Drug Interactions of Thalidomide with Midazolam and Cyclosporine A: Heterotropic Cooperativity of Human Cytochrome P450 3A5

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ABSTRACT:

There is growing clinical interest of thalidomide because of its immunomodulatory and antiangiogenic properties, despite its teratogenicity. However, little information about thalidomide has been reported regarding its precise effects on drug-metabolizing enzymes. We investigated the effects of thalidomide on cytochrome P450 (P450) enzymes in human liver microsomes to clarify the potential for possible drug interactions. Thalidomide inhibited S-mephenytoin 4′-hydroxylation activities of recombinant P450 2C19 and human liver microsomes: the apparent concentration of thalidomide producing 50% inhibition was approximately 270 μM for P450 2C19. Midazolam 4-hydroxylation activities were suppressed by thalidomide, but activities of 1′-hydroxylation and total midazolam oxidation and testosterone 6β-hydroxylation were enhanced in the presence of thalidomide. Recombinant P450 3A5 was found to have altered kinetics at clinically relevant concentrations of thalidomide (10–30 μM). P450 3A4 was also affected, but only at higher thalidomide concentrations. Enhanced midazolam hydroxylation by thalidomide was also seen in liver microsomal samples harboring the CYP3A5*1 allele. Similarly enhanced rates of cyclosporine A clearance were observed in P450 3A5 and liver microsomes expressing P450 3A5 in the presence of thalidomide. A proposed effector constant for thalidomide corresponded roughly to its clinical plasma levels. Docking studies with a P450 3A5 homology model, based on the published structure of P450 3A4, revealed close interaction between thalidomide and the heme of P450 3A5. The present results suggest that total midazolam metabolism or cyclosporine A clearance may be increased by thalidomide in a dose-dependent manner. Unexpected drug interactions involving thalidomide might occur via heterotropic cooperativity of polymorphic P450 3A5.

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ABBREVIATIONS: P450, cytochrome P450; HL, human liver.
and an apparently observed $K_i$ treatment theory for drug interaction studies. A proposed model for heterotropic cooperativity of P450 3A5 is presented.

**Materials and Methods**

**Chemicals.** (+)-Thalidomide was purchased from Sigma-Aldrich (St. Louis, MO). Cyclosporine A and midazolam were obtained from Wako Pure Chemicals (Osaka, Japan). Other chemicals and reagents used in this study were obtained from the sources described previously (Yamazaki et al., 2002, 2006) or were of the highest qualities commercially available.

**Enzyme Preparations.** Human liver microsomes were prepared in 10 mM Tris-HCl buffer (pH 7.4) containing 0.10 mM EDTA and 20% (v/v) glycerol as described previously (Yamazaki et al., 2006). The use of the human livers for this study was approved by the Ethics Committees of Vanderbilt University and Showa Pharmaceutical University. Each reconstituted human cytochrome P450, coexpressed in *Escherichia coli* membranes with human NADPH-P450 reductase, was prepared as described earlier (Yamazaki et al., 2002). Genomic DNA samples from livers were genotyped for the CYP2C19 and CYP3A5 genes as described previously (Inoue et al., 1997; Yamaori et al., 2004).

**Enzyme Assays.** Midazolam 1'- and 4-hydroxylation activities were determined using high-performance liquid chromatography (Emoto et al., 2008). Cyclosporine A oxidation was determined by the disappearance of parent compound (Dai et al., 2004). In brief, a typical incubation mixture (total volume of 0.25 ml) contained microsomal protein (0.25 mg/ml) or recombinant CYP3A5 and 7-ethoxycoumarin (100 μM) (recombinant P450 1A1 and 1A2), 7-ethoxycoumarin (100 μM) (recombinant P450 2B6), and diclofenac (50 μM) (recombinant P450 2C9) were not affected by thalidomide (up to 500 μM) under these conditions (results not shown). P450 2C19 S-mephenytoin 4'-hydroxylation activity was suppressed by thalidomide in a concentration-dependent manner (Fig. 1A); 50% inhibition was observed with a thalidomide concentration of 270 μM. Similar inhibitory effects of thalidomide on S-mephenytoin hydroxylase activity were seen in liver microsomal preparations (genotyped as *CYP2C19*/*C19*/1*/*1* (Fig. 1B).

On the contrary, testosterone 6β-hydroxylation (Fig. 2, A and B) by P450 3A4A or P4503A5 was enhanced by thalidomide. Midazolam 1'-hydroxylation activities (Fig. 2D) of P450 3A5 were highly enhanced in the presence of low concentrations of thalidomide. These activities were less affected by thalidomide with P450 3A4 than P450 3A5 (Fig. 2C). The minor pathway, midazolam 4-hydroxylation, was slightly suppressed by thalidomide (with P450 3A4 or 3A5), but rates of formation of the major product (1'-hydroxylation) and total oxidative products of midazolam were stimulated in the presence of thalidomide.

**Kinetic Analysis.** Kinetic analysis was done using nonlinear regression analysis programs [KaleidaGraph (Synergy Software, Reading, PA) and Prism (GraphPad Software Inc., San Diego, CA)] using the following equations. Inhibition by thalidomide (concentration [I]) of midazolam 1'-hydroxylation activity ($v$) of P450 3A as a function of substrate concentration [S] with a maximum velocity ($V_{max}$) was analyzed for competitive inhibition with the usual eqs. 1 and 2:

$$v = V_{max} \cdot [S](K_{mobs} + [S])$$  

and an apparently observed $K_m$ value ($K_{mobs}$), namely (eq. 2)

$$K_{mobs} = K_m^1 \cdot (1 + [I]/K_i)$$

where $K_i$ is the inhibition constant (Ito et al., 2004). On the other hand, midazolam 1'-hydroxylation activity ($\nu$) shows a substrate-inhibition manner with the eq. 3 formula, including the substrate inhibition constant $K_i$ (Dai et al., 2004):

$$\nu = V_{max} \cdot [S](K_{mobs} + [S] + [S]^2)/K_i$$

When the enzyme activities ($\nu$) are increased by thalidomide (concentration [E]), resulting apparent $V_{max}$ values multiplied by [1 + [E]/$K_i$ (effector constant)] or deceased $K_{mobs}$ divided by (1 + [E]/$K_i$) are proposed using the eq. 3 formula. In the present study, apparent $V_{max}$ values were not affected, but $K_{mobs}$ values were decreased in the presence of thalidomide; therefore, eqs. 3 and 4, including a novel parameter for effector concentration $K_e$, were proposed in this study:

$$K_{mobs} = K_m^1/(1 + [E]/K_e)$$

Docking Simulation of Thalidomide into Reported Structure of P450 3A4 and a Homology Model of P450 3A5. The human P450 3A5 primary sequence was aligned with human P450 3A4 (Protein Data Bank code 1TQN) in the MOE software (version 2007.09; Chemical Computing Group, Montreal, Canada) for modeling of a three-dimensional structure (Pearson et al., 2007). Before docking, the energy of the P450 3A4 or 3A5 structure was minimized using the CHARMM22 force field. Docking simulations were carried out for thalidomide binding to the reported P450 3A4 or a homology model of P450 3A5 using the MMFF94x force field distributed in the MOE Dock software. Twenty solutions were generated for each docking experiment and ranked according to total interaction energy ($S$ value).

**Results**

**Inhibitory or Enhancing Effects of Thalidomide on Activities of Human P450 Enzymes.** Because P450 2C19 has already been shown to be the major enzyme involved in the oxidative metabolism of thalidomide (Ando et al., 2002), we first investigated the inhibitory effects of thalidomide on the typical marker activities of a series of P450 enzymes. The oxidation activities measured with the substrates ethoxyresorufin (10 μM) (recombinant P450 1A1 and 1A2), 7-ethoxycoumarin (100 μM) (recombinant P450 2B6), and diclofenac (50 μM) (recombinant P450 2C9) were not affected by thalidomide (up to 500 μM) under these conditions (results not shown). P450 2C19 S-mephenytoin 4'-hydroxylation activity was suppressed by thalidomide in a concentration-dependent manner (Fig. 1A); 50% inhibition was observed with a thalidomide concentration of 270 μM. Similar inhibitory effects of thalidomide on S-mephenytoin hydroxylase activity were seen in liver microsomal preparations (genotyped as *CYP2C19*/*C19*/1*/*1* (Fig. 1B).

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**Modifications of Kinetic Parameters for P450 3A-Dependent Drug Oxidation Activities by Thalidomide.** It was of interest to describe the enhancing effects of thalidomide in terms of an effector concentration. Midazolam 1'- and 4-hydroxylation activities were plotted against substrate concentrations in the presence of various concentrations of thalidomide (Fig. 3). Only small effects of thalidomide on the midazolam hydroxylation activities of P450 3A4 were observed (Fig. 3A). In the contrast, midazolam 1'-hydroxylation activities of P450 3A5 at low substrate concentrations were enhanced in

($K_i$) (Ito et al., 2004). However, there is little information about inhibition by thalidomide thus far.

The purpose of this study was to clarify the inhibitory potential of thalidomide with human P450 enzymes, to understand possible drug interactions. We investigated the effects of thalidomide on P450 activities and found that thalidomide inhibited P450 2C19-dependent S-mephenytoin 4'-hydroxylation at high concentrations but enhanced P450 3A5-dependent midazolam hydroxylation and cyclosporine A clearance at clinically relevant concentrations. Although there are reports on ligand cooperativity with P450 3A5 (Niwa et al., 2008b), we report a proposed effector constant for thalidomide in the heterotropic cooperativity of P450 3A5 in human liver microsomes, adapting 1 + [I]/$K_i$ treatment theory for drug interaction studies. A proposed model for heterotropic cooperativity of P450 3A5 is presented.

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the presence of thalidomide; however, midazolam 4-hydroxylation was suppressed (Fig. 3B). Human liver microsomes were also used as the enzyme source. The midazolam hydroxylation activities of liver microsomal sample HL-3 (Fig. 3C), genotyped as CYP3A5*3/*3, were not extensively affected, as in the case of recombinant P450 3A4. Midazolam 1′-hydroxylation activities in liver microsomal sample HL-1 (Fig. 3D), genotyped as CYP3A5*1/*3, were also enhanced by the low concentrations of thalidomide.

Apparent \( K_{\text{m}} \) values (\( K_{\text{m,obs}} \)) for midazolam 1′-hydroxylation activities of P450 3A5 using the Michaelis-Menten equation were reduced from 5.5 \( \mu \text{M} \) to 3.0, 1.8, 1.2, 0.97, and 0.77 \( \mu \text{M} \) in the presence of 10, 50, 100, 250, and 500 \( \mu \text{M} \) thalidomide, respectively (Fig. 3B). We adopted a new parameter, \( K_{\text{v}} \), for modified \( K_{\text{m,obs}} \) values as \( K_{\text{v}}(1 + [E]/K_{\text{I}}) \), in the same way as \( K_{\text{v}} \) for \( K_{\text{m,obs}}(1 + [I]/K_{\text{I}}) \) (Table 1). The \( K_{\text{v}} \) value of thalidomide enhancement of midazolam 1′-hydroxylation catalyzed by recombinant P450 3A5 was calculated to be 40 ± 7 \( \mu \text{M} \). Similar reduced \( K_{\text{m,obs}} \) values for midazolam 1′-hydroxylation activities by increasing concentrations of thalidomide were obtained in the human liver microsomes expressing P450 3A5 protein (CYP3A5*1/*3): the \( K_{\text{v}} \) value was 62 ± 24 \( \mu \text{M} \) using the equation of \( K_{\text{m,obs}} = K_{\text{m}}/(1 + [E]/K_{\text{v}}) \). In the case of P450 3A4, >10-fold higher \( K_{\text{v}} \) values of thalidomide were obtained (Table 1).

To confirm the enhancing effects of thalidomide on liver microsomal P450 3A5, the oxidation of cyclosporine A was also used as a test reaction (Fig. 4). P450 3A4-catalyzed cyclosporine A oxidation was not affected by thalidomide (Fig. 4A). P450 3A5-catalyzed cyclosporine A oxidation (substrate concentrations of 2 and 10 \( \mu \text{M} \)) was enhanced by increasing concentrations (2–30 \( \mu \text{M} \)) of thalidomide (Fig. 4B). Similar enhancement of cyclosporine A oxidation by thalidomide was seen in liver microsomes expressing P450 3A5 and 3A4 (Fig. 4D) but not in other liver microsomes mainly expressing P450 3A4 (Fig. 4C). Thalidomide (10–30 \( \mu \text{M} \)) enhanced cyclosporine A oxidation mediated by P450 3A5 in human liver microsomes approximately 2-fold.

**Docking Simulation of Thalidomide into P450s 3A4 and 3A5.** The human P450 3A4 crystal structures allowed generation of a homology model of P450 3A5 using the MOE program. The top-rank docking model of thalidomide in P450 3A4 or 3A5 was adopted. In the P450 3A4 model, the aromatic ring of thalidomide was found far away from the heme of P450 3A4 (Fig. 5A). In contrast, in the P450 3A5 model, the cycloalkane ring of thalidomide was closely oriented to the center of the heme of P450 3A5 (Fig. 5B).

**Discussion**

In the course of screening the inhibitory potential of thalidomide with human P450 enzymes, thalidomide inhibition of P450 2C19-mediated activity and enhancement of P450 3A activities were seen (Figs. 1 and 2). Thalidomide inhibited P450 2C19-dependent activity of testosterone 6β-hydroxylation activity in recombinant P450 2C19 (A and C) and human liver microsomes (B). S-Mephenytoin (200 \( \mu \text{M} \)) was incubated with P450 2C19 and human liver microsomal sample HL-1 (genotyped as CYP2C19*1/*1) in the absence or presence of thalidomide. Results are presented as means and ranges of duplicate determinations.
M. S-mephenytoin 4'-hydroxylation activity only at high concentrations but enhanced P450 3A5-dependent midazolam 1'-hydroxylation activity at low concentrations. P450s 2C9 and 2C19 have both been shown to have a smaller substrate pocket than P450 3A4 (Yano et al., 2004; Locuson and Wahlstrom, 2005; Ahlström and Zamora, 2008). The thalidomide inhibition constant for P450 2C19 was similar to the substrate concentration used for S-mephenytoin. Thus, the active site area of P450 2C19 may be blocked by a similar concentration of thalidomide, resulting in half-maximal inhibition of P450 2C19 function.

Polymorphic P450 3A5s have been suggested to contribute as much as 50% of the liver P450 3A in one third of white and one half of African-Americans (Kuehl et al., 2001; Koch et al., 2002) or Japanese (Yamaori et al., 2004). Because P450 3A5 is 83% identical to P450 3A4, it is generally believed that the substrate specificity of P450 3A5 is similar to that of P450 3A4, although some differences in catalytic properties have been found (Daly, 2006; Niwa et al., 2008a,b). Less activation of P450 3A4 by thalidomide was observed under our conditions. On the other hand, midazolam 4'-hydroxylation (minor pathway) was inhibited but 1'-hydroxylation and total disappearance of midazolam (as well as cyclosporine A) were enhanced by thalidomide, presumably mediated via a cooperativity mechanism in P450 3A5 (Figs. 3 and 4). In our preliminary experiments, preincubation of thalidomide with P450 3A5 in the presence of NADPH resulted in decreases in enhanced midazolam 1'-hydroxylation (results not shown), suggesting the involvement of thalidomide itself, not a product (tentatively 5'-hydroxythalidomide), in the activation. Similar activation of P450 3A5-mediated midazolam 1'-hydroxylation was also observed in another liver microsomal sample, HL-130, harboring CYP3A5*1/*3 but not in HL-127 (CYP3A5*3/*3) (results not shown). Because the apparent K\textsubscript{m} values for midazolam 1'-hydroxylation in recombinant P450 3A5 and human liver microsomes were similarly decreased in the presence of thalidomide, the proposed K\textsubscript{v} values of thalidomide (approximately 40 µM) for P450 3A5 and liver microsomes are consistent and are one order of magnitude less than those for P450 3A4 (Table 1). These results suggest the hypothesis that thalidomide preferentially binds to P450 3A5. To further address this hypothesis, docking simulations of thalidomide into P450 3A4 and 3A5 models were performed (Fig. 5). Thalidomide could closely dock to the P450 3A5 heme region in silico analysis (Fig. 5B). These results and findings may be collectively relevant to a different preferable substrate orientation for P450 3A5, explaining the P450 3A5 activation.

This activation phenomenon is generally termed heterotropic cooperativity, involving two different ligands in the active site of a P450 enzyme (McConnell et al., 2004; Isin and Guengerich, 2006). A proposed model for heterotropic cooperativity of P450 3A5 is shown in Fig. 5C. When thalidomide docks near the heme iron and/or suitable substrate binding area (Roberts and Atkins, 2007; Skopalk et al., 2008), the proposed substrate pocket of P450 3A5 would be affected, resulting in a large active site. On the other hand, because thalidomide apparently does not dock closely to the heme of the P450 3A4 structure (Fig. 5A), the substrate binding area might not be strongly affected (Fig. 5C). This proposed mechanism could be derived from the several differences in reported important amino residues (positions at 210–214) of the F-helix of P450 3A4, remote from the heme of the P450 3A4 catalytic center (Szklarz and Halpert, 1997; Harlow and Halpert, 1998; Fowler et al., 2002), and a characterized Ser239 residue in substrate recognition site-3 (Pearson et al., 2007) (Fig. 5D). The Leu211 residue in both P450 3A4 and 3A5 has been suggested to be an important residue for homotropic cooperativity in P450 3A4 (Skolarch and Halpert, 1997; Harlow and Halpert, 1998; Fowler et al., 2002). Lys212 of P450 3A5 seems to have a similar property, corresponding to Arg212, in P450 3A4 forming the roof of the active site (Harlow and Halpert, 1998). Amino acid differences at positions Leu210, Asp214, and Ser239 in P450 3A4 and Phe210, Gly214, and Cys239 in P450 3A5 might produce a more flexible site and higher lipophilicity in the P450 3A5 active site, to show different phenomena with P450 3A4 for thalidomide. These residues might be key determinants for the specificity of thalidomide activation of P450 3A5. Consequently, a thalidomide molecule shifts P450 3A5 into a

#### Table 1

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<tr>
<th>Enzyme</th>
<th>Midazolam Hydroxylation</th>
<th>Thalidomide</th>
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<tr>
<td></td>
<td>V\textsubscript{max} (nmol/min/mol P450)</td>
<td>K\textsubscript{m}, µM</td>
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<tr>
<td>P450 3A4</td>
<td>1'-</td>
<td>8.6 ± 0.3</td>
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<td></td>
<td>4-</td>
<td>3.4 ± 0.1</td>
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<tr>
<td>P450 3A5</td>
<td>1'-</td>
<td>18 ± 1</td>
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<td>4-</td>
<td>2.2 ± 0.1</td>
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#### Figure 4

Enhanced cyclosporine oxidation activity with recombinant P450 3A4 (A) and 3A5 (B) and human liver microsomes (C and D) in the absence (□) or presence of 2 (□), 10 (□), and 30 µM (bl) thalidomide. Human liver samples HL-3 (C) and HL-1 (D) were genotyped for the CYP3A5*3/*3 and CYP3A5*1/*3, respectively. Results are presented as means ± S.D. from triplicate determinations.
conformation, such that the proximal binding niche exists near the heme, leading to the stimulation of the cyclosporine and midazolam oxidative activation observed in the present study.

In terms of the clinical consequences of drug interactions with thalidomide, the present results suggest that a more rapid drug clearance might be due to thalidomide via a P450 3A5 contribution. The reported plasma concentrations of thalidomide (Vogelsang et al., 1992) are similar to the proposed $K_e$ constants estimated in the present study. Adapting $1/\left[\frac{I}{K_i}\right]$ theory to the $1/(1 + [E]/K_e)$ equation, thalidomide concentrations could reach levels similar to calculated $K_e$ constant and, in principal, approximately 1.5-fold enhanced elimination of other drugs mediated by P450 3A5. We propose the $K_e$ value as a general constant, whereas it is highly likely to be dependent upon an exact pairing of effector and substrate. Vincristine has been reported to be a P450 3A5 substrate (Dennison et al., 2006). Therefore, we investigated interactions between thalidomide and vincristine in vitro. In preliminary experiments, however, low concentrations of thalidomide did not activate the oxidative cleavage of vincristine (catalyzed by P450 3A5 or liver microsomes with CYP3A5*1/*3) (results not shown). The $K_m$ values (for the major oxidative cleavage of vincristine catalyzed by P450 3A5) have been reported to be 13 to 17 µM (Dennison et al., 2006). Because vincristine is a large molecule and has high P450 3A5 affinity, these present results may be interpreted that thalidomide could not dock in P450 3A5 before vincristine.

In conclusion, the present study suggests that total midazolam metabolism or cyclosporine clearance may be increased by thalidomide with clinical relevant concentrations through the heterotropic cooperativity of human P450 3A5. Because of the high frequency of polymorphic P450 3A5 expression in Asians and Africans, a relatively high frequency of unexpected drug interactions involving thalidomide might occur via P450 3A5 contribution in drug metabolism.

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References

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