Autoinhibition of CYP3A4 Leads to Important Role of CYP2C8 in Imatinib Metabolism: Variability in CYP2C8 Activity May Alter Plasma Concentrations and Response

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ABSTRACT

Recent data suggest that the role of CYP3A4 in imatinib metabolism is smaller than presumed. This study aimed to evaluate the quantitative importance of different cytochrome P450 enzymes in imatinib pharmacokinetics. First, the metabolism of imatinib was investigated using recombinant P450 enzymes and human liver microsomes with P450 isoform-selective inhibitors. Thereafter, an in silico model for imatinib was constructed to perform pharmacokinetic simulations to assess the roles of P450 enzymes in imatinib elimination at clinically used imatinib doses. In vitro, CYP2C8 inhibitors and CYP3A4 inhibitors inhibited the depletion of 0.1 μM imatinib by 45 and 80%, respectively, and the formation of the main metabolite of imatinib, N-desmethylimatinib, by >50%. Likewise, recombinant CYP2C8 and CYP3A4 metabolized imatinib extensively, whereas other isoforms had minor effect on imatinib concentrations.

In the beginning of imatinib treatment, the fractions of its hepatic clearance mediated by CYP2C8 and CYP3A4 were predicted to approximate 40 and 60%, respectively. During long-term treatment with imatinib 400 mg once or twice daily, up to 65 or 75% of its hepatic elimination was predicted to occur via CYP2C8, and only about 35 or 25% by CYP3A4, due to dose- and time-dependent autoinactivation of CYP3A4 by imatinib. Thus, although CYP2C8 and CYP3A4 are the main enzymes in imatinib metabolism in vitro, in silico predictions indicate that imatinib inhibits its own CYP3A4-mediated metabolism, assigning a key role for CYP2C8. During multiple dosing, pharmacogenetic polymorphisms and drug interactions affecting CYP2C8 activity may cause marked interindividual variation in the exposure and response to imatinib.

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ABBREVIATIONS: CLint, intrinsic clearance; CLH, hepatic clearance; DDC, diethyldithiocarbamate; GEM-G, gemfibrozil 1-O-β-glucuronide; HLM, human liver microsomes; ISEF, intersystem extrapolation factor; 8-M-P, 8-methoxy-psoralen; MBI, mechanism-based inhibition; N-DMI, N-desmethylimatinib; P450, cytochrome P450; PBPK, physiologically based pharmacokinetic.
mechanism-based inhibitor of this enzyme in vitro, and clinically relevant imatinib concentrations were predicted to cause up to 90% inhibition of hepatic CYP3A4 activity (Filipula et al., 2012). These findings suggest that imatinib can affect its own CYP3A4-mediated metabolism, which may reduce the significance of this enzyme in its elimination in vivo. In fact, strong CYP3A4 inhibitors have had only little effect on imatinib pharmacokinetics in the beginning of therapy, and no effect at all during long-term treatment. In healthy volunteers, the CYP3A4-inhibiting antifungal agent ketoconazole increased the AUC of imatinib after single-dose administration by 40% only (Dutreix et al., 2004); in patients, steady-state imatinib pharmacokinetics were unchanged by ritonavir, a CYP3A4-inhibiting antiretroviral drug (van Erp et al., 2007).

Recent in vitro data suggest that in addition to CYP3A4, the CYP2C8 enzyme also contributes to the formation of N-DMI (Nebot et al., 2010); recombinant human CYP2C8 catalyzed the N-demethylation of imatinib at a much higher rate than did CYP3A4 and CYP3A5. However, the significance of CYP2C8 to the human metabolism of imatinib is difficult to estimate because the recombinant CYP2C8 and CYP3A5 enzymes used in this previous study were produced in insect cells, whereas the recombinant CYP3A4 originated from human lymphoblastoid cells, which typically show a several-fold lower activity than enzymes from insect cells. Furthermore, the contributions of P450 enzymes to the overall metabolism of imatinib, including both its N-demethylation and other metabolic pathways, were not investigated, nor was the role of P450 enzymes in the further metabolism of N-DMI; consequently, the clinical significance of the previous in vitro results cannot be estimated.

Using recombinant human P450 enzymes, human liver microsomes (HLM) and chemical P450 inhibitors, we carefully examined the contributions of different P450 enzymes, particularly those of CYP2C8 and CYP3A4, to the main metabolic pathway of imatinib and the further metabolism of N-DMI. Furthermore, to translate our laboratory findings to clinical relevance, we used our data for pharmacokinetic and drug–drug interaction simulations by constructing a physiologically based model of imatinib pharmacokinetics, incorporating the time-dependent inhibitory effect of imatinib on its own CYP3A4-mediated metabolism.

Materials and Methods

In vitro study

Chemicals and Microsomes. Imatinib mesilate (mesylate salt), clopidogrel, and montelukast were purchased from Sequoia Research Products Ltd. (Pangbourne, UK). N-DMI and N-DMI-d8 were procured from SynFine Research Inc. (Richmond Hill, ON, Canada), and imatinib-d8 mesilate and gemfibrozil 1-O-β-glucuronide (GEM-G) were purchased from Toronto Research Chemicals Inc. (North York, ON, Canada). Diethylthiocarbamate (DDC), furafylline, 8-methoxy-psoralen (8-M-P), omeprazole, quinidine, sulfaphenazole, trocleandomycin, and β-NADPH were obtained from Sigma-Aldrich (St. Louis, MO). Ketoconazole was purchased from Janssen Biotech (Olen, Belgium). Pooled HLM and Supersomes (recombinant human P450 enzymes and control supernatants) were obtained from BD Biosciences (Woburn, MA). Other chemicals were from Merck (Darmstadt, Germany).

Incubation Conditions. Incubations were carried out in a shaking water bath (37°C) in triplicates (mean value used as the result). The incubations contained HLM or recombinant P450 enzymes in 0.1 M sodium phosphate buffer (pH 7.4). To keep the possible nonspecific binding of imatinib equal in the experiments and to enable precise comparisons of results with different P450 isoforms, an equal protein concentration (0.5 mg/ml unless otherwise indicated) was used in parallel experiments, resulting in variable P450 contents in recombinant isoform studies. Except for inhibition studies, experiments were started by premixing imatinib for 3 minutes with microsomes, followed by addition of β-NADPH (final concentration 1 mM) to initiate the reaction. In competitive inhibition studies, imatinib and inhibitor or buffer control were simultaneously premixed with HLM for 3 minutes before β-NADPH addition. In mechanism-based inhibition (MBI) studies, except for that with GEM-G, the inhibitor or buffer control was first premixed with HLM for 3 minutes before addition of β-NADPH. After a 15-minute preincubation, including β-NADPH, imatinib was added to start the reaction. Inhibition by GEM-G (60 μM) was investigated by premixing it with 10 mg/ml HLM in buffer. After addition of β-NADPH, the solution was preincubated for 20 minutes. An aliquot of 25 μl was then moved to another tube containing β-NADPH in buffer, and imatinib was immediately added to start the reaction in a final incubation volume of 0.5 ml. Thus, the protein and inhibitor concentrations had been diluted 20-fold to avoid possible competitive inhibition of other enzymes by the inhibitor.

After incubation, reactions were stopped by moving incubation mixture to acetonitrile containing the internal standards imatinib-d8 and N-DMI-d8, 10% MeOH and 0.1% HCOOH, diluting the incubation mixture 3-fold. Samples were immediately vortexed, put on ice for at least 10 minutes, and vortexed two additional times before centrifugation at 20,800g for 10 minutes. All stock solutions of imatinib and N-DMI were prepared in methanol. All incubations (including controls) contained the same concentration of organic solvent (1% methanol or 0.5:0.5% methanol:acetonitrile). As appropriate, the incubation time was optimized within the linear range for metabolism depending on the turnover conditions of each specific experiment. The unbound fraction of 0.1 μM imatinib in microsomal incubations had previously been determined (Filipula et al., 2012), and the nonspecific binding of N-DMI to microsomes was assumed to equal that of imatinib.

Measurement of Imatinib and Its Metabolites. Imatinib and N-DMI concentrations were quantified by use of an API 3000 liquid chromatography-tandem mass spectrometry system (Sciex Division of MDS Inc. Toronto, ON, Canada). Concentrations of imatinib and N-DMI were measured in positive turbo ion spray mode. Chromatography was performed on an Atlantis HicSilica analytic column (2.1 × 100 mm, 3.0 μm) (Waters, Milford, MA) by use of gradient elution. The mobile phase was A (10 mM ammonium formate in 0.1% HCOOH) and B (0.1% HCOOH in acetonitrile:MeOH 10:1, v/v, and the gradient comprised 0 minutes at 95% (B), 15 minutes to 50% (B), 5 minutes at 50% (B), 0.1 minute to 95% (B), and finally 14.9 minutes at 95% (B). The flow rate was 0.2 ml/min. The mass spectrometer was operated in multireaction mode (MRM), and ion transitions monitored were m/z (mass-to-charge ratio) 494.3 to 394.3 for imatinib, 480.2 to 394.3 for N-DMI, 502.2 to 394.3 for imatinib-d8 and 488.2 to 394.3 for N-DMI-d8. The peaks of a hydroxy benzyl metabolite (M5), piperidine N-oxide imatinib (M6) and pyridine N-oxide imatinib (M8) were monitored during the assays based on ion transitions reported (Marull and Rochat, 2006; Rochat et al., 2008), and their quantities were measured as arbitrary units relative to the ratio of the peak height of the metabolite to the peak height of N-DMI. The limit of quantification was 0.005 μM for imatinib, 0.01 μM for N-DMI, and a signal-to-noise ratio of 10:1 was used as the limit of quantification for M5, M6, and M8. For imatinib and N-DMI, the between-day coefficient of variation (CV) was <15% at relevant concentrations.

Recombinant P450 Isoform Studies. First, the depletion of 0.1 μM imatinib by CYP1A2 (50 pmol/ml), CYP2A6 (30 pmol/ml), CYP2B6 (40 pmol/ml), CYP2C8 (158 pmol/ml), CYP2C9 (120 pmol/ml), CYP2C19 (174 pmol/ml), CYP2D6 (72 pmol/ml), CYP2E1 (296 pmol/ml), CYP3A4 (66 pmol/ml), and CYP3A5 (50 pmol/ml) was investigated in a 30-minute incubation. Then, metabolite formation by these enzymes was studied by incubating 1 μM imatinib with each enzyme for up to 60 minutes. Finally, the enzyme kinetics of N-DMI formation was determined by incubating imatinib (0.10–320 μM) with CYP2C8 (33 pmol/ml) for 4 minutes, CYP3A4 (13 pmol/ml) for 3 minutes, and CYP3A5 (10 pmol/ml) for 30 minutes. The protein concentration was 0.5 mg/ml in the depletion and metabolite formation studies, and 0.1 mg/ml in the enzyme kinetic incubations.

Effects of P450-Selective Inhibitors on Imatinib Metabolism. To confirm the results from the recombinant P450 studies, inhibition studies with HLM were carried out. Montelukast (5 μM), sulfaphenazole (10 μM), omeprazole (10 μM), quinidine (10 μM), and ketoconazole (1 μM) were tested as competitive inhibitors of CYP2C8, CYP2C9, CYP2C19, CYP2D6, and CYP3A4, respectively (Baldwin et al., 1995; Newton et al., 1995; Bourrie et al., 1996; Ko et al., 1997; Eagling et al., 1998; Walsky et al., 2005). Furafylline (20 μM), 8-M-P (0.5 μM), clopidogrel (1 μM), GEM-G (60 μM), DDC (100 μM), and...
Intrinsic clearance for N-DMI formation (CL\text{int, N-DMI form}) was calculated as CL\text{int, dep} = \frac{\text{metabolic pathways, their intrinsic clearance in depletion experiments was based on the Akaike information criterion, on SigmaPlot software (version 9.01; Systat Software, Inc., San Jose, CA). Selection by CYP2C8, CYP3A4, and CYP3A5 was examined in detail.}

In vitro incubation of CYP2C8 (50 pmol/ml), CYP2C9 (72 pmol/ml), CYP3A4 (66 pmol/ml), CYP3A5 (50 pmol/ml), and an enzyme mix containing CYP2A6 (59 pmol/ml), CYP2B7 (7.7 pmol/ml), CYP2C9 (24 pmol/ml), CYP2C19 (35 pmol/ml), and CYP2E1 (25 pmol/ml), wherein the total protein concentration was 0.5 mg/ml. Finally, the depletion of 0.05 µM N-DMI by CYP2C8, CYP3A4, and CYP3A5 was examined in detail.

**Data Analysis.** The kinetics of N-DMI metabolism were analyzed using SigmaPlot software (version 9.01; Systat Software, Inc., San Jose, CA). Selection of the best-fit enzyme model was based on the Akaikes information criterion, on R², and on the examination of Michaelis-Menten plots. For CYP2C8 and CYP3A4, the results were best described by an uncompetitive substrate inhibition model: \( v = \frac{V_{\text{max}} \cdot [S] \cdot [K_m \cdot S]}{K_m + [S]} \), where \( v \) is velocity (pmol/min/mmol), \( V_{\text{max}} \) is the maximal velocity (pmol/min/mmol), \( S \) is substrate concentration (\( \mu \)M), \( K_m \) is the Michaelis-Menten constant (\( \mu \)M), and \( K_i \) is the inhibitory constant (\( \mu \)M). CYP3A5-mediated N-demethylation was best described by traditional Michaelis-Menten kinetics: \( v = \frac{V_{\text{max}} \cdot [S]}{K_m + [S]} \). Intrinsic clearance for N-DMI formation (CL\text{int, N-DMI form}) was calculated according to CL\text{int, N-DMI form} = \frac{V_{\text{max}} \cdot [K_m \cdot S]}{K_i \cdot S}. Pseudo-first-order depletion rate constants (\( k_{\text{dep}} \)) were determined for the depletion of 0.1 µM imatinib, and 0.05 and 0.1 µM N-DMI in HLM and recombinant enzyme incubations using nonlinear regression analysis (SigmaPlot). Inhibitory \( k_{\text{dep}} \) values were calculated on the basis of the time points at 0–8 minutes for CYP2C8, 0–4 minutes for CYP3A4, and 0–30 minutes for the other P450 isoforms and HLM. N-DMI \( k_{\text{dep}} \) values were estimated based on time points at 0–30 minutes for all P450 isoforms and 0–60 minutes for HLM. Percent inhibition of imatinib depletion was calculated by comparing \( k_{\text{dep}} \) values to those of control incubations. Assuming that imatinib and N-DMI concentrations were \( <K_m \) for their metabolic pathways, their intrinsic clearance in depletion experiments was expressed as CL\text{int, dep} = \frac{k_{\text{dep}}}{[M]} \), where \([M]\) is the microsomal protein concentration or P450 concentration in recombinant enzyme incubations (Venkatadrikrishnan et al., 2003). In addition, an intrinsic clearance value for the formation of all primary metabolites of imatinib other than N-DMI was defined as CL\text{int, N-DMI form} for each P450 isoform, where CL\text{int, N-DMI form} and CL\text{int, u,M} denote the unbound intrinsic clearance values for imatinib depletion and N-DMI formation, respectively. To estimate the relative contributions of different P450 enzymes to imatinib and N-DMI metabolism, the CL\text{int, N-DMI form} values, adjusted for nonspecific binding in microsomes, were multiplied with intersystem extrapolation factors (ISEFs) (Proctor et al., 2004) of each P450 isoform and with average P450 isoform abundance (pmol/mg microsomal protein) (Table 1). The obtained values were then scaled to in vivo using 40 mg of microsomal protein per gram liver (Houston and Galetin, 2008) and 25.7 g of liver weight per kilogram body weight (Davies and Morris, 1993). Hepatic blood clearance (CL\text{H, N-DMI}) values were calculated using the well-stirred model: CL\text{H, N-DMI} = \frac{Q_h \cdot f_{b,p}}{CL\text{int, N-DMI form} \cdot (1 + \frac{Q_h \cdot f_{b,p}}{CL\text{int, in vitro}})} \), where \( Q_h \) is the hepatic blood flow (20.7 ml/min/kg) (Houston and Galetin, 2008), \( f_{b,p} \) is the unbound fraction of imatinib or N-DMI in blood, and CL\text{int, in vitro} is the scaled CL\text{int, N-DMI form}.

**In Silico Study.**

**Construction and Validation of a Simcyp Model for Imatinib.** Based on the present in vitro investigations and literature data, compound files for imatinib and N-DMI (see Supplementary Tables 1 and 2 for data) were constructed within the Simcyp Population-Based Simulator (V11.00; Simcyp Limited, UK). Using physiologically based pharmacokinetic (PBPK) modeling, Simcyp simulates change in drug concentration over time. The software generates virtual populations reflecting variability in genetic, physiologic, and demographic variables using Monte Carlo methods so that interindividual variability in drug elimination and the importance of different metabolizing P450 isoforms in a population can be assessed (Howgate et al., 2006; Rostami-Hodjegan and Tucker, 2007; Jamei et al., 2009; Rowland Yeo et al., 2010).

The models for imatinib and N-DMI comprised first-order oral absorption from the intestine (for imatinib); intestinal metabolism; a minimal physiologically based distribution model, including a single adjusting compartment; and elimination by hepatic P450-mediated and additional (non-P450-mediated) metabolism and by renal excretion. The hepatic elimination input parameters were obtained from the present in vitro studies. ISEF factors in Tables 1 and 2 and other parameters provided by the software were used to scale CL\text{int, N-DMI} to CL\text{H, N-DMI} and CL\text{H, u,M} values were then predicted using the well-stirred model. Renal clearance was estimated from literature values of systemic clearance and amount excreted unchanged in the urine (Bornhauser et al., 2005; Gschwind et al., 2005). Then, hepatic and renal clearances were combined with additional clearance to derive the total clearance. Furthermore, the compound files for imatinib and N-DMI included values for direct inhibition of different P450 enzymes, and the final model for imatinib also included kinetic constants for MBI of CYP3A4. When the literature and experimental values had been entered into the compound files, the model was refined by adjusting the additional clearances and the volume of the single adjusting compartment so that

### TABLE 1

<table>
<thead>
<tr>
<th>P450 Isoform</th>
<th>Pathway</th>
<th>CL\text{int}</th>
<th>V\text{max}</th>
<th>K\text{m}</th>
<th>f\text{b,p}</th>
<th>ISEF</th>
<th>ISEF and P450 Abundance Adjusted CL\text{int}\text{,}\text{scaled}</th>
<th>CL\text{H, scaled}</th>
<th>% Total CL\text{H}\text{,}\text{scaled}</th>
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</thead>
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<td>CYP1A2 Metabolism</td>
<td>0.03</td>
<td>—</td>
<td>—</td>
<td>0.80</td>
<td>BD Sup</td>
<td>0.84</td>
<td>3.6</td>
<td>0.14</td>
<td>1.1</td>
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<td>—</td>
<td>—</td>
<td>0.80</td>
<td>BD Sup</td>
<td>0.66</td>
<td>2.9</td>
<td>0.11</td>
<td>0.83</td>
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<tr>
<td>CYP2C8 N-DMI</td>
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<td>4.28</td>
<td>0.90</td>
<td>User</td>
<td>295</td>
<td>127</td>
<td>4.8</td>
<td>40</td>
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<tr>
<td>Other metabolites</td>
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<td>—</td>
<td>—</td>
<td>0.80</td>
<td>BD Sup</td>
<td>0.34</td>
<td>1.5</td>
<td>0.059</td>
<td>0.43</td>
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<td>CYP3A4 Other metabolites</td>
<td>2.78</td>
<td>—</td>
<td>—</td>
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<td>User</td>
<td>13</td>
<td>56</td>
<td>2.2</td>
<td>57</td>
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<td>14.40</td>
<td>0.90</td>
<td>User</td>
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<td>151</td>
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<tr>
<td>Other metabolites</td>
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<td>—</td>
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<td>BD Sup</td>
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<td>2.0</td>
<td>0.081</td>
<td>0.79</td>
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</table>

\( f_{b,p} \) unbound fraction of imatinib in microsomal incubations.

1. Intersystem extrapolation factors used in the Simcyp compound file and in the static model calculations; ‘BD Sup’ indicates default values within Simcyp for incubations conducted with microsomes from BD Biosciences, whereas ‘User’ denotes in-house values: 1.16 for CYP2CS, 0.09 for CYP3A4, and 0.06 for CYP3A5. Because the P450 activity between different recombinant enzyme lots may vary, in-house ISEF factors for the key enzymes in imatinib metabolism were preferred. Furthermore, the best accuracy in CYP3A4 interaction predictions was obtained using these values. The in-house ISEF factors are based on Vmax, for amodiaquine N-deethylation and midazolam 1'-hydroxylation in recombinant CYP2C8, CYP3A4, CYP3A5, and in pooled HLM.

2. The average P450 hepatic abundance values used were 52 pmol/mg protein for CYP1A2, 17 pmol/mg protein for CYP2B6, 24 pmol/mg protein for CYP3A4, 8 pmol/mg protein for CYP2D6, 137 pmol/mg protein for CYP3A4, and 103 pmol/mg protein for CYP3A5 (these are average values of the North European Caucasian population within Simcyp).

3. Calculated contributions of each P450 enzyme to the total hepatic clearance of imatinib.

4. The unbound fractions of imatinib had previously been determined (Filppula et al., 2012), and vary between 0.8 and 0.9, depending on the protein concentration used in the experiment (0.5 or 0.1 mg/ml, respectively). The CL\text{int, u,M} values for “other metabolites” were calculated as the difference between CL\text{int, u,M} and CL\text{int, N-DMI form} of 1 entered in Simcyp in this case.
Enzyme kinetic parameters N-DMI metabolism determined on the basis of recombinant P450 enzyme studies and prediction of the hepatic clearance of N-DMI by use of the static ISEF model

<table>
<thead>
<tr>
<th>P450 Isoform</th>
<th>Pathway</th>
<th>CLint (\text{µl/min/mg protein})</th>
<th>(f_{\text{unb}})</th>
<th>ISEF (^a)</th>
<th>ISEF and P450 Abundance Adjusted CLint (b)</th>
<th>Scalled CLint (\text{µl/min/mg protein})</th>
<th>CLint (\text{µl/min})</th>
<th>% Total CLint (c)</th>
</tr>
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<tbody>
<tr>
<td>CYP1A2</td>
<td>Metabolism</td>
<td>0.03</td>
<td>0.80</td>
<td>BD Sup</td>
<td>0.84</td>
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<td>User</td>
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<td>9.2</td>
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<tr>
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<td>0.80</td>
<td>BD Sup</td>
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<tr>
<td>CYP3A5</td>
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<td>0.80</td>
<td>User</td>
<td>0.76</td>
<td>3.3</td>
<td>0.065</td>
<td>3.9</td>
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</tbody>
</table>

\(f_{\text{unb}}\), unbound fraction of N-DMI in microsomal incubations.

\(^a\)ISEF and P450 Abundance Adjusted CLint denotes in-house values; 1.16 for CYP2C8, 0.09 for CYP3A4, and 0.06 for CYP3A5.

Important Role for CYP2C8 in Imatinib Metabolism

Imatinib Metabolism by Recombinant Enzymes. Recombinant CYP2C8 and CYP3A4 metabolized 0.1 and 1 \(\mu M\) imatinib rapidly, and <13% of the parent drug remained after a 30-minute incubation (Figs. 1A and 2A). In CYP3A5 incubations, ~80% of imatinib was left at 30 minutes, whereas the other P450 isoforms tested had a minor effect on imatinib concentrations (>90% of parent drug was left). At 1 \(\mu M\) imatinib, N-demethylation was mediated by CYP2C8, CYP3A4, and CYP3A5, and very small amounts of N-DMI were formed also by CYP2D6, CYP2C19, and CYP2C9 (Fig. 1B). However, at 0.1 \(\mu M\) imatinib, only CYP2C8, CYP3A4, and CYP3A5 formed detectable amounts of N-DMI (Fig. 1B and 2B). At 1 \(\mu M\) imatinib, CYP2C8 also catalyzed formation of M5, whereas CYP3A4 formed both M5 and M6 (data not shown). The enzyme kinetics of N-DMI formation in humans over time. The clearances of imatinib and N-DMI were predicted on the basis of the present in vitro data together with literature data on renal and additional clearance, and the final model included MBI of CYP3A4 by imatinib. The simulated concentration-time curves, as well as the mean pharmacokinetic parameters of imatinib and N-DMI, matched well with published data on imatinib single-dose pharmacokinetics in healthy volunteers (Fig. 3, A and B, Supplementary Table 3). Compared with when only direct inhibition of CYP3A4 by imatinib was considered, the final model simulated the peak concentrations, AUC_{0-24h}, and trough concentrations of imatinib on day 30 that were, on average, 32, 58, and 113% higher, respectively, and those of N-DMI were, on average, 5, 16, and 24% higher, respectively (Fig. 4, A and B). The final model also matched well with observed trough and peak concentrations of imatinib during treatment with 400 mg once...
daily, averaging 910–1530 ng/ml and 2200–3405 ng/ml, respectively, and with trough and peak concentrations of N-DMI averaging 170–301 and 290–556 ng/ml, respectively (Peng et al., 2004b; van Erp et al., 2007; Gibbons et al., 2008; Demetri et al., 2009; Kim et al., 2011; Teng et al., 2012) (Fig. 4, A and B; Supplementary Table 4). Similarly, the simulations predicted well the effects of ketoconazole, rifampicin, and ritonavir on the pharmacokinetics of imatinib (Supplementary Table 5).

The validation simulation of gemfibrozil pharmacokinetics is presented in Supplementary Fig. 2.

Role of CYP2C8 in Imatinib Metabolism Is Important during Prolonged Treatment. With the final model, the inactivation of intestinal and hepatic CYP3A4 by imatinib proceeded time- and dose-dependently (Fig. 4). For example, at steady-state, imatinib 100 mg once daily, 400 mg once daily, and 400 mg twice daily were predicted to reduce the amount of active CYP3A4 to 55–59, 22–29, and 13–15% of its normal amount in the liver, respectively. At the commencement of imatinib treatment, the fractions metabolized by hepatic CYP3A4 and CYP2C8 were predicted to average 59 and 39% of the total hepatic clearance of imatinib, equaling those estimated with the static ISEF model. After multiple doses of imatinib 400 mg once daily, the majority of the hepatic metabolism of imatinib was predicted to occur by CYP2C8 (61–65%) and a smaller proportion to occur by CYP3A4 (31–37%) (Fig. 4E). The corresponding values for treatment with 400 mg twice daily were 71–74% and 22–25% for CYP2C8 and CYP3A4, respectively.

An otherwise typical 60-year-old man whose CYP2C8 liver activity was 2-fold higher than average was predicted to have a markedly increased steady-state imatinib metabolism (Fig. 5, A and B). His plasma concentrations of imatinib were, for most of the 24-hour dosing interval, below the suggested effectiveness threshold of about 1000 ng/ml (Fig. 5A). Conversely, a low-activity CYP2C8 genotype (50% reduction in CYP2C8 activity) decreased imatinib metabolism, leading to increased imatinib concentrations and reduced N-DMI concentrations.

According to drug–drug interaction predictions, a strong CYP3A4 inhibitor (itraconazole) increased the AUC0– of imatinib and N-DMI by 38 and 6%, respectively, after a single dose of imatinib 400 mg (Fig. 5, C and D, Supplementary Table 8), and the dosing interval AUC by 18 and 6%, respectively, following multiple imatinib doses (Fig. 5, E and F). A strong CYP2C8 inhibitor (gemfibrozil) was predicted to increase the AUC0– of a single dose of imatinib 1.8-fold and the dosing interval AUC after multiple imatinib doses 2.3-fold, whereas it reduced the AUC of N-DMI by 59–84%. The inhibition of both CYP2C8 and CYP3A4 was predicted to markedly increase imatinib AUC by 2.9-fold and almost completely inhibit N-DMI formation (by >79%).

Discussion

According to the present in vitro findings, imatinib metabolism is almost exclusively mediated by CYP2C8 and CYP3A4 at clinically relevant imatinib concentrations. Formation of the active metabolite of imatinib, N-DMI, accounted for the majority of imatinib metabolism
by CYP2C8, whereas more than two thirds of imatinib metabolism mediated by CYP3A4 occurred via other metabolic pathways. Moreover, the further biotransformation of N-DMI was mainly catalyzed by CYP3A4. Pharmacokinetic simulations based on these results and on recent data indicate that imatinib is an irreversible mechanism-based inhibitor of CYP3A4 (Filppula et al., 2012), predicting that the role of CYP3A4 in imatinib metabolism is important mainly in the beginning of therapy but diminishes thereafter, because of time-dependent autoinhibition of CYP3A4-mediated metabolism of imatinib. Consequently, CYP2C8 is likely to be the most important enzyme in imatinib N-demethylation at steady-state during long-term treatment.

Imatinib biotransformation occurs via multiple metabolic pathways in addition to the N-demethylation pathway (Gschwind et al., 2005; Marull and Rochat, 2006; Rochat et al., 2008). Therefore, we used a depletion approach to estimate the contributions of different P450 enzymes to the total elimination of imatinib at low, therapeutic concentrations. The depletion rates and inhibition experiments showed that CYP2C8 and CYP3A4 almost exclusively mediate the hepatic microsomal metabolism of imatinib with other isoforms contributing to a minor extent (~5%). For example, CYP3A5 metabolized imatinib to N-DMI, but the total elimination CL_{int} of CYP3A5 was small (~10% of that of CYP2C8). Comparison of CL_{int} values obtained from the depletion of 0.1 µM imatinib and N-demethylation kinetics indicated that N-demethylation accounts for the majority of imatinib metabolism by CYP2C8. On the contrary, CYP3A4 seemed to produce more than twice as much other metabolites as its produced N-DMI, in line with previous data (Rochat et al., 2008). In our incubations, CYP3A4 formed M5 and M6, but due to lack of authentic standards, the quantitative evaluation of these metabolites was not possible. CYP2D6 also formed a small amount of M5, but the depletion experiment with 0.1 µM imatinib indicated a negligible significance for CYP2D6 in its metabolism. Also, CYP2C9, CYP2C19, CYP1A1, CYP1B1, and CYP4F may play minor roles in imatinib biotransformation (http://www.accessdata.fda.gov/drugsatfda_docs/nda/2001/21335_Gleevec.cfm) (Rochat et al., 2008), but the contributions of CYP2C9 and CYP2C19 were negligible at therapeutic concentrations in our study.

Fig. 2. Experiments with recombinant P450 enzymes. (A) Depletion of 0.1 µM imatinib and (B) the subsequent formation of N-DMI by CYP2C8, CYP3A4, and CYP3A5. (C) the enzyme kinetics of N-DMI formation by CYP2C8, CYP3A4, and CYP3A5. (D) depletion of 0.05 µM N-DMI by CYP2C8, CYP3A4, and CYP3A5. The protein concentration was 0.5 mg/ml in all incubations, except in the enzyme kinetic study, where it was 0.1 mg/ml, resulting in variable P450 concentrations in the incubations (see Materials and Methods for exact P450 concentrations). The data points represent mean ± S.D. values of triplicate incubations.
enzymes to imatinib metabolism. Therefore, we constructed a dynamic PBPK model for imatinib and N-DMI pharmacokinetics, incorporating previous data on time-dependent inactivation of CYP3A4 by imatinib. Interaction simulations with ketoconazole, rifampicin, and ritonavir, based on this model, generally showed a good agreement with their reference studies (Bolton et al., 2004; Dutreix et al., 2004; van Erp et al., 2007). Thus, it seems that our in vitro data for CYP3A4 generated reliable predictions of its role in imatinib pharmacokinetics. Compared with a model without MBI of CYP3A4 by imatinib, steady-state simulations based on the final model corresponded much better, with clinical data showing that trough and peak concentrations average 910–1530 ng/ml and 2200–3405 ng/ml, respectively, after multiple doses of imatinib 400 mg once daily (Peng et al., 2004b; van Erp et al., 2007; Gibbons et al., 2008; Demetri et al., 2009; Kim et al., 2011; Teng et al., 2012).

MBI of P450 enzymes proceeds in a time- and concentration-dependent manner because it requires that the inhibitor is metabolized by the enzyme to an intermediate, which immediately binds covalently to the enzyme (Lin and Lu, 1998). Thus, unlike reversible inhibitors, mechanism-based inhibitors inactivate their victim enzymes permanently, and enzyme activity can be regained only by synthesis of new enzyme. Clinically, these characteristics can lead to a slow onset of inhibition and a long-lasting duration of inhibition. MBI poses a particular problem when in vitro studies are carried out to estimate the contributions of P450 enzymes to the metabolism of a drug, which is a mechanism-based inhibitor of a P450 form participating in its own metabolism. Failure to consider MBI leads to overestimation of the role of this enzyme. To overcome this problem with imatinib, we used very short incubations and low imatinib concentrations to minimize MBI and obtain reliable initial rates of in vitro metabolism. We then applied a dynamic PBPK model for extrapolation of our in vitro data to in vivo.

According to our simulations, autoinhibition of the CYP3A4-mediated metabolism of imatinib may attribute a key role for CYP2C8 in imatinib elimination. The fraction of hepatic clearance mediated by CYP2C8 was simulated to increase from 40% in the beginning of treatment to over 60% after multiple doses of imatinib 400 mg once daily. Conversely, the fraction eliminated by CYP3A4 decreased from 60% in the beginning to < 40% during multiple dosing. The significance of CYP2C8 in steady-state imatinib pharmacokinetics became apparent in interaction simulations, where a strong CYP2C8 inhibitor like gemfibrozil (Backman et al., 2002; Honkalanni et al., 2012) was predicted to increase imatinib AUC by 80% following a single imatinib dose and by 130% after multiple imatinib doses. By contrast, a strong CYP3A4 inhibitor like itraconazole (Olkola et al., 1994) was predicted to increase imatinib AUC by 40% after a single dose of imatinib, and by only 20% after multiple imatinib doses. This result is comparable to clinical findings from interaction studies with ketoconazole and ritonavir (Dutreix et al., 2004; van Erp et al., 2007). According to our simulations, gemfibrozil could reduce the plasma exposure to N- DMI by up to 85%, whereas itraconazole could increase it by ~ 5%. Of note, the combination of gemfibrozil and itraconazole was predicted to increase imatinib AUC by almost 200% during multiple dosing, highlighting the potential dangers of multiple interacting medications.

Simcyp has been associated with overpredictions of the magnitude of time-dependent drug-drug interactions. For CYP3A4, the former default degradation rate constant of 0.0077 l/h has been recognized as an important source for overpredictions, whereas the value of 0.019 l/h, used in version 11, has generated relatively reliable predictions (Rowland Yeo et al., 2011). Other possible factors impairing prediction accuracy of drug–drug interactions are failure to consider transporter mechanisms, gut metabolism or other simultaneous mechanisms, such as concurrent inhibition and induction of enzymes (Peters et al.,

**Fig. 3.** Pharmacokinetic simulations of the single-dose pharmacokinetics of imatinib. Mean simulated and observed imatinib (A) and N-DMI (B) plasma concentrations in 33 healthy volunteers after a single oral dose of imatinib 400 mg. Lines are simulated mean concentration time-profiles of 10 trials (dotted lines represent standard deviations), whereas the circles refer to clinical data from Nikolova et al. (2004).
In the present work, as evident from steady-state simulations and interaction simulations with the CYP3A4 inhibitors, Simcyp did not appear to overpredict the impact of autoinhibition of CYP3A4 on imatinib pharmacokinetics. However, the effect of imatinib on the pharmacokinetics of other CYP3A4 substrates was not investigated in this work and needs to be addressed in future studies. Furthermore, given the aforementioned uncertainties, clinical studies are needed to evaluate the prediction accuracy concerning the role of CYP2C8 in imatinib pharmacokinetics and interactions.

There is a wide interindividual variability in imatinib plasma concentrations, associated with nonresponse and disease progression, even in the absence of interacting comedications (Peng et al., 2004b; Picard et al., 2007; Teng et al., 2012). Differences in CYP3A4 activity have been suggested to partly explain this variability (Peng et al., 2005; Apperley, 2007). Our findings contrast this suggestion and raise the possibility that pharmacogenetic polymorphisms of CYP2C8 can affect imatinib plasma concentrations, especially during long-term medication. For example, the CYP2C8*3 allele has been associated with a considerably increased clearance of several drugs, such as rosiglitazone and pioglitazone (Kirchheiner et al., 2006; Tornio et al., 2008; Aquilante et al., 2012). In our simulations, a high activity CYP2C8 genotype was predicted to result in an increased imatinib metabolism, leading to mean plasma levels of imatinib below the threshold concentration of 1000 ng/ml, suggesting that genetic polymorphisms of CYP2C8 could possibly affect the pharmacokinetics of imatinib to a clinically relevant degree. It should be noted, however, that the effect of the CYP2C8*3 polymorphism seems to be substrate-dependent and therefore clinical studies with imatinib are needed. Moreover, imatinib is a substrate and inhibitor of several transporters in vitro, but their clinical significance in imatinib pharmacokinetics has not yet been established, apart from the role of organic cation transporter 1 (OCT1) in uptake of imatinib to leukocytes and leukemic cells (Eechoute et al., 2011; Wang et al., 2012). Our interaction simulations (Fig. 5, C through F) did not account for possible co-effects of P450 inhibitors on different transporter functions, which could influence imatinib pharmacokinetics. Thus, an inhibition or induction of relevant transporters affecting imatinib pharmacokinetics could modify the effect of CYP2C8 and CYP3A4 inhibitors on imatinib plasma and tissue concentrations.

In this work, we used an integrated approach of carefully optimized in vitro experiments, comprising both depletion and enzyme kinetic experiments, and pharmacokinetic simulations to evaluate the clinical relevance of CYP2C8 and CYP3A4 in imatinib elimination. Although clinical studies are necessary to confirm our in vitro and in silico findings, it is likely that imatinib time-dependently inhibits its own CYP3A4-mediated metabolism, leading to an important role for
CYP2C8 in its elimination. Thus, during multiple dosing, both pharmacogenetic polymorphisms and drug interactions affecting CYP2C8 activity may cause marked interindividual variability in the exposure and response to imatinib. Overall, the present findings highlight the need to carefully evaluate the implications of MBI using integrated in vitro and modeling/simulation approaches.

**Authorship Contributions**

- **Participated in research design:** Filppula, M. Neuvonen, Laitila, P. J. Neuvonen, Backman.
- **Conducted experiments:** Filppula, M. Neuvonen, Laitila, Backman.
- **Performed data analysis:** Filppula, P. J. Neuvonen, Backman.
- **Wrote or contributed to the writing of the manuscript:** Filppula, M. Neuvonen, Laitila, P. J. Neuvonen, Backman.

**References**


