Ablation of Both Organic Cation Transporter (Oct)1 and Oct2 Alters Metformin Pharmacokinetics but Has No Effect on Tissue Drug Exposure and Pharmacodynamics

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ABSTRACT:

Organic cation transporter (OCT)1 and OCT2 mediate hepatic uptake and secretory renal clearance of metformin, respectively. Pharmacokinetic/pharmacodynamic (PK/PD) implications of simultaneous impairment of both transporters, such as by systemic pan-OCT inhibition, have not been studied directly. At present metformin PK/PD, distribution, and excretion were studied in Oct1/Oct2-knockout mice. Metformin clearance was reduced 4.5-fold from renal blood flow to unbound glomerular filtration rate, and volume of distribution was reduced 3.5-fold in Oct1/Oct2-knockout mice. Oral bioavailability was not affected (F = 64 ± 4 versus 59 ± 11; knockout versus wild type). Liver- and kidney-to-plasma concentration ratios were decreased in Oct1/Oct2-knockout mice 4.2- and 2.5-fold, respectively. The 2.9-fold increase in oral metformin exposure and reduced tissue partitioning yielded little to no net change in tissue drug concentrations. Absolute kidney exposure was unchanged (knockout/wild type = 1.1 ± 0.2), and liver exposure was only modestly decreased (knockout/wild type = 0.6 ± 0.1). Oral glucose area under the curve (AUC) lowering by metformin was not impaired in Oct1/Oct2-knockout mice at the five dose levels tested (ED50 = 151 versus 110 mg/kg; glucose lowering at highest dose = 42 ± 1 versus 39 ± 4%; knockout versus wild type); however, higher systemic metformin exposures were necessary in knockout mice to elicit the same effect (half-maximal efficacious AUC = 70 versus 26 μg·h/ml). Despite major changes in metformin clearance and volume of distribution in Oct1/Oct2-knockout mice, tissue drug exposure and PD were not affected. These findings challenge the presumption that systemic OCT inhibition will affect metformin pharmacology.

Introduction

Organic cation transporters (OCTs) mediate the electrogenic uptake of hydrophilic type I organic cations (Gründemann et al., 1994; Sweet and Pritchard, 1999). Three OCT isoforms have been identified, and the clinical importance of OCT1 and OCT2 in pharmacokinetics (PK) and/or drug interactions has been documented (Somogyi et al., 1987; Shu et al., 2007, 2008; Chen et al., 2009). OCT1 is present on the sinusoidal (basolateral) membrane of hepatocytes and is responsible for hepatic uptake of substrates (Jonker et al., 2001; Nishimura and Naito, 2005). Human OCT2 is expressed primarily on the basolateral membrane of renal tubules; in rodents in addition to Oct2, Oct1 is coexpressed in the kidney (Gründemann et al., 1994; Jonker et al., 2003). Considerable substrate and inhibitor overlap exists between OCT1 and OCT2. For example, prototypic substrates metformin and 1-methyl-4-phenylpyridinium are transported by both OCT1 and OCT2 (König et al., 2011); cimetidine, amantadine, quinidine, and procainamide are equipotent inhibitors of both OCT isoforms (Minematsu et al., 2010).

Murine knockout models have been developed to interrogate the PK/pharmacodynamic (PK/PD) relevance of OCT transport (De-Gorter and Kim, 2011). Studies with Oct1-knockout mice demonstrated the importance of this isoform in hepatic distribution of several prototypic substrates, including TEA, meta-iodobenzylguanide, 1-methyl-4-phenylpyridinium, and metformin (Jonker et al., 2001; Wang et al., 2002). However, no apparent impairment in the renal clearance of these compounds was observed in Oct1-knockout mice, presumably because of compensation by Oct2 (Jonker et al., 2001; Wang et al., 2002). Pronounced PK consequences of genetic ablation of Oct2 in mice were not observed (Jonker et al., 2003). As expected, hepatic distribution of TEA was not affected in Oct2-knockout mice, but surprisingly neither was renal clearance, because apical urinary secretion via multidrug and toxin extrusion (Mate) proteins appears to determine the overall rate of TEA tubular secretion even when only Oct1 uptake is maintained (Schäli et al., 1983; Jonker et al., 2003; Tanihara et al., 2007). Thus, to better understand the importance of OCTs, the Oct1/Oct2 double-knockout mouse was developed (Jonker et al., 2003). Systemic exposure to TEA was increased significantly in Oct1/2-knockout mice, and clearance was decreased from renal blood flow in wild-type mice to unbound glomerular filtration rate (GFR) in the double knockouts, consistent with elimination of the secretory component of renal clearance (Jonker et al., 2003).

Metformin is a commonly used antidiabetic drug, whose PK is influenced by OCT transport (Shu et al., 2007, 2008; Chen et al., 2009). Initial studies in Oct1-knockout mice indicated that metformin...
hepatic exposure may be reduced as much as 30-fold (Wang et al., 2002), although subsequent reports estimated a less pronounced decrease of 2.5- to 8-fold in liver partitioning (Wang et al., 2003; Shu et al., 2007). Because hepatic distribution of metformin is necessary for its inhibition of gluconeogenesis, Oct1-knockout mice exhibited markedly attenuated metformin PD, including metformin-insensitive hepatocyte gluconeogenesis, abolished fasting glucose-lowering effects, and reduced lactic acidosis (Wang et al., 2003; Shu et al., 2007). Systemic PK and renal clearance of metformin were not altered in Oct1-knockout mice (Wang et al., 2002, 2003; Shu et al., 2007), although a significantly higher initial concentration after intravenous bolus administration suggested a decreased volume of distribution (Wang et al., 2002). Clinically, the oral volume of distribution of metformin was reduced 2.2-fold in subjects with functional OCT1 variants (Shu et al., 2007, 2008). Although metformin PK and/or PD studies in Oct1-knockout models are lacking, because humans do not express OCT1 along with OCT2 in the kidney, secretory renal clearance of metformin can be reduced up to 2.6-fold in people with functional OCT2 variants (Song et al., 2008; Chen et al., 2009).

Previous literature reports established the isolated importance of OCT1 in metformin hepatic distribution/PD and OCT2 in its secretory renal clearance. However, the effect of combined OCT1 and OCT2 impairment on metformin PK/PD and tissue distribution has not been studied systematically, even though nonspecific OCT inhibitors will impair both isoforms. For example, cimetidine, an equipotent inhibitor of OCT1 and OCT2 (Minematsu et al., 2010), increased metformin exposure 50% because of inhibition of secretory renal clearance (Somogyi et al., 1987; Wang et al., 2008), but lactic acidosis was not attenuated overall and was actually significantly enhanced at one of four time points (Somogyi et al., 1987). These findings are surprising because clinically notable inhibition of metformin renal clearance by cimetidine would also be expected to reduce hepatic distribution and, in turn, impair PD. To understand PK/PD alterations during combined impairment of both OCT1 and OCT2, metformin PK/PD were for the first time studied in Oct1/Oct2 double-knockout mice.

Materials and Methods

Chemicals. TEA and dextrose were purchased from Sigma-Aldrich (St. Louis, MO). Metformin-HCl and D6-metformin-HCl were purchased from Toronto Research Chemicals (North York, ON, Canada). [14C]Urinulin was obtained from PerkinElmer Life and Analytical Sciences (Waltham, MA). All other chemicals were of reagent grade and were readily available from commercial sources.

Animals. Age-matched Oct1/Oct2 double-knockout and wild-type FVB male mice were purchased from Taconic Farms (Germantown, NY). Mice were delivered to Covance (Greenfield, IN), where they were acclimated for at least 72 h before initiation of PK studies or 2 weeks before PK/PD studies to ensure the same normal diet. In all cases, mice were between 6 and 8 weeks of age at the time of study. All animal procedures were approved by the Institutional Animal Care and Use Committee at Covance.

Intravenous PK and Excretion. TEA was dissolved in phosphate-buffered saline (pH = 7.4) and was administered to mice as a tail vein injection (10 mg/kg; 10 ml/kg). Blood samples were collected at the following times: 3, 6, 10, 15, 20, 30, 40, 50, and 60 min after dose administration. Metformin was dissolved in phosphate-buffered saline (pH = 7.4) and was administered to mice as a tail vein injection (5 mg/kg; 10 ml/kg). Blood samples were collected at the following times: 3, 6, 10, 20, 30, 45, 60, 90, and 120 min after dose administration. In all intravenous PK studies, three time points were collected per mouse. The first two were retro-orbital bleeds, and the third blood draw was performed by cardiac puncture. As such, the plasma concentration-time profiles are a composite of three groups of four mice (n = 4 mice/group per time point) at the time of terminal blood collection (90, 120, and 150 min), liver and kidneys were excised for analysis of tissue metformin levels. Likewise, the tissue concentration-time profiles are a composite of three groups of four mice (n = 4 mice/group per time point).

Bioanalysis. TEA and metformin in plasma, urine, cage wash, liver, and kidney tissue homogenate were analyzed by liquid chromatography/tandem mass spectrometry (LC-MS/MS). All samples were mixed with an organic internal-standard solution to precipitate protein and were centrifuged. The resulting supernatants were analyzed directly. TEA and its internal standard, N,N-trimethyl-phenylalaninamide, were eluted from a C18 column [Aqualis 2.1 × 20 mm, 5 μm (Thermo Fisher Scientific, Waltham, MA)] with a mobile phase gradient. Metformin and its internal standard, D6-metformin, were eluted from a C18 column [Betalis Sil 2.1 × 50 mm, 5 μm (Thermo Fisher Scientific)] with a mobile phase gradient optimized for each matrix. Analytes were detected in positive ion mode using multiple reaction monitoring [Sciex API 4000 triple quadrupole mass spectrometer equipped with a TurboIonSpray interface (Applied Biosystems/MDM Sciex, Foster City, CA)]; 130.1 → 86.1 m/z; and N,N-trimethyl-phenylalaninamide 207.1 → 148.1 m/z; metformin 130.1 → 71.1 and D6-metformin 136.1 → 77.1 m/z. The dynamic range of the assays was 1 to 5000 ng/ml for both TEA and metformin in all relevant matrices. Samples with analyte concentrations above the upper limit of quantification were diluted with matrix to within the assay range; concentrations below the lower limit of quantification were reported as such.

Data Analysis. Noncompartmental composite PK parameters were calculated using Watson version 7.4 (Thermo Fisher Scientific). All renal clearances...
were calculated as the ratio of total amount excreted in urine and systemic exposure measured over the corresponding urine collection time interval. The simple \(E_{\text{max}}\) model was fitted to the PD data using WinNonlin version 5.3 (Pharsight, Mountain View, CA). Because PK parameters were calculated from mean values in composite concentration-time datasets, only mean parameter estimates are reported without variability estimates and significance testing. Otherwise, all data are reported as mean ± S.E.M., with the corresponding \(n\) noted. S.E.M. was selected as the variability descriptor, because many reported parameters represent the mean of means (e.g., oral bioavailability).

Significance testing was performed in SigmaPlot version 11.0 (Systat Software, Inc., San Jose, CA). The Student’s two-tailed \(t\) test was used to assess statistical significance between two groups. In cases where variance was different between compared groups (\(F\) test, \(p < 0.05\)), the unequal-variance \(t\) test was used. Significance of changes in composite tissue exposures, knockout relative to wild type, was assessed with a one-sample \(t\) test. Significance of PD data, which were affected by two factors [mouse type (knockout or wild type) and drug treatment (metformin or vehicle)], was assessed with a two-way analysis of variance with Tukey’s post hoc test. In all cases, the minimal criterion for significance was \(p < 0.05\).

Results

TEA concentration-time profiles in wild-type and Oct1/2-knockout mice after administration of a 10 mg/kg TEA i.v. bolus dose are presented in Fig. 1; corresponding PK parameters are summarized in Table 1. Knockout mice exhibited significantly higher TEA systemic concentrations at all nine time points; overall systemic exposure was 3.8-fold higher. TEA systemic clearance in wild-type mice was rapid and comparable to renal blood flow but was reduced 3.5-fold in Oct1/2-knockout mice to approximately unbound GFR (Davies and Morris, 1993; Jonker et al., 2003). Volume of distribution was 5-fold lower in Oct1/2-knockout mice. Because of both decreased clearance and volume, the terminal half-life was not markedly different in knockout mice but was nonetheless reduced 30%, reflecting the greater magnitude of decrease in volume than clearance. TEA urinary excretion over 2 h was only 16% lower in knockout mice; considering the 3.8-fold higher systemic exposure, renal clearance was reduced from 5 times GFR in wild-type mice to approximately GFR. With the functional absence of Oct1 and Oct2 in the commercially obtained Oct1/2-knockout mice, which confirmed (Jonker et al., 2003), metformin studies were commenced.

Metformin intravenous PK were studied in wild-type and Oct1/2-knockout mice after administration of a 5 mg/kg i.v. bolus dose (Fig. 2A; Table 2). Knockout mice exhibited significantly higher metformin systemic concentrations at all nine time points; systemic exposure was on average 4.4-fold higher. Systemic clearance in wild-type mice was slightly higher than renal blood flow but was reduced 4.5-fold in Oct1/2-knockout mice to approximately unbound GFR [Davies and Morris, 1993; metformin hydrochloride (Glucophage) prescribing information, Bristol-Meyers Squibb Co., Stamford, CT]. Volume of distribution was 3.5-fold lower in knockout mice. Terminal half-life was comparable between wild-type and Oct1/2-knockout mice, which is consistent with a similar magnitude of decrease in both clearance and volume. Over 2 h after intravenous dose administration, metformin urinary excretion was only 24% lower in Oct1/2-knockout mice; however, because of the 4.5-fold higher systemic exposure, renal clearance was reduced from 4 times GFR in wild-type mice to approximately GFR.

Metformin oral PK were studied in wild-type and Oct1/2-knockout mice at five dose levels (Fig. 2, B–D; Table 2). Metformin concentration-time curve after administration of a 10 mg/kg oral dose (Fig. 2B) was strikingly different in appearance from the intravenous profile (5 mg/kg i.v., comparable exposure to 10 mg/kg p.o.; Fig. 2A) and was characterized by apparent protracted absorption. Concentrations at 5- and 10-min after oral dose were not significantly increased, but all plasma concentrations at subsequent time points were higher in Oct1/2-knockout mice (\(p < 0.05\)). Oral exposure increased in a dose-proportional manner between 10 and 300 mg/kg (Fig. 2C) and was on average 2.9 ± 0.2-fold higher in Oct1/2-knockout mice (\(p < 0.05\)). Likewise, \(C_{\text{max}}\) increased in a dose-proportional manner (Fig. 2D) and was 2.4 ± 0.2-fold higher in Oct1/2-knockout mice (\(p < 0.05\)). Oral bioavailability and \(T_{\text{max}}\) values showed no apparent dose dependence in the 10 to 300 mg/kg range tested and were comparable between wild-type and Oct1/2-knockout mice (Table 2).

Metformin liver and kidney tissue-to-plasma concentration ratios were markedly decreased in Oct1/2-knockout mice (Figs. 3 and 4). Significant differences were noted in the tissue-to-plasma concentration ratios with respect to time and dose level, so these values are presented individually. Liver metformin partitioning was significantly reduced in Oct1/2-knockout mice in 13 of 15 measurements. Overall, liver-to-plasma ratio was significantly decreased with a median 4.2-fold reduction (Fig. 3). At all time points, a consistent trend of decreased liver metformin partitioning was noted in both wild-type and Oct1/2-knockout mice at the highest 300 mg/kg dose relative to the four lower dose levels, suggesting saturation of hepatic uptake.

![Figure 1](image)

**FIG. 1.** TEA plasma concentration-time profiles in wild-type (closed symbols) and Oct1/2-knockout (open symbols) mice after administration of a 10 mg/kg TEA i.v. bolus dose. Concentration-time profiles are a composite of three groups of four mice, \(n = 4\) mice/group per time point; mean ± S.E.M., *, \(p < 0.05\) knockout versus wild-type mice; where error bars are not visible, they are contained within the symbol.

**TABLE 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wild Type</th>
<th>Oct1/2 Knockout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraocular dose, mg/kg</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>AUC(\text{0-}\tau), pg · h/ml</td>
<td>2.41</td>
<td>9.10</td>
</tr>
<tr>
<td>AUC(\text{0-}\infty), pg · h/ml</td>
<td>3.28</td>
<td>9.84</td>
</tr>
<tr>
<td>(C_{\text{max}}), pg/ml</td>
<td>22.7</td>
<td>67.4</td>
</tr>
<tr>
<td>CL, ml · min(^{-1}) · kg(^{-1})</td>
<td>58.7</td>
<td>16.9</td>
</tr>
<tr>
<td>(V_{\text{dss}}), ml/kg</td>
<td>1520</td>
<td>318</td>
</tr>
<tr>
<td>T(_{1/2})</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>Urinary excretion, % dose(^{a})</td>
<td>35 ± 4</td>
<td>30 ± 6</td>
</tr>
<tr>
<td>Creatinine renal CL, ml/min</td>
<td>0.09 ± 0.01</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>Inulin renal CL, ml/min</td>
<td>0.12 ± 0.03</td>
<td>0.19 ± 0.06</td>
</tr>
<tr>
<td>Corrected urinary recovery, % dose(^{a})</td>
<td>95 ± 11</td>
<td>62 ± 12</td>
</tr>
<tr>
<td>TEA renal CL/GFR ratio</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^{a}\) Noncomparitional parameters were calculated using mean concentrations in composite PK datasets, so variability and \(p\) values were not calculated.

\(^{b}\) Urinary excretion was measured in a separate set of mice with four metabolic cages each containing three mice per group; mean ± S.E.M. for \(n = 4\) metabolic cages; no statistically significant differences were observed between groups.

\(^{c}\) Urinary recovery was corrected on the basis of the ratio of nominal-to-observed murine GFR (Bingham and Cummings, 1985). Nominal murine GFR is 0.28 ml/min (Davies and Morris, 1993), and observed GFR was measured by creatinine and inulin renal clearance.
The magnitude of decrease in kidney partitioning was less pronounced. Kidney-to-plasma metformin concentration ratio was significantly reduced in Oct1/2-knockout mice in 7 of 15 measurements; overall, this ratio was significantly decreased with a median decrease of 2.5-fold (Fig. 4). A trend of decreased kidney metformin partitioning was noted in both wild-type and Oct1/2-knockout mice at the highest 300 mg/kg dose, suggesting saturation of renal uptake. Note that in Figs. 3 and 4, unusually high tissue concentrations were observed in some animals at the 100 mg/kg dose level, so the mean values are skewed upwards, and the associated variability is high at this dose.

The absolute liver and kidney tissue metformin exposures were not markedly reduced in Oct1/2-knockout mice (Fig. 5). Hepatic exposure was modestly lower in Oct1/2-knockout mice at each dose level tested (Fig. 5A), but on average this decrease was only 42 ± 6%. Although the decrease itself was statistically significant, both absolute and dose-normalized liver metformin exposures were not significantly different between wild-type and Oct1/2-knockout mice. Kidney drug exposure was comparable at all five dose levels tested between wild-type and Oct1/2-knockout mice (Fig. 5B); on average, the knockout/wild-type exposure ratio was 1.1 ± 0.2.

The effects of metformin on blood glucose levels after an oral tolerance test in wild-type and Oct1/2-knockout mice are summarized in Fig. 6. At the lowest 10 mg/kg dose, metformin did not significantly lower blood glucose concentrations (Fig. 6A); however, at the highest 300 mg/kg dose, metformin significantly decreased blood glucose levels at all time points after the oral tolerance test and maintained them close to baseline (Fig. 6B). Glucose AUC lowering by metformin was not impaired in Oct1/2-knockout mice at any of the five dose levels tested (ED$_{50}$ = 151 versus 110 mg/kg, knockout versus wild type), and the effect on blood glucose levels over the tested dose range was generally comparable (Fig. 6C). Likewise, the observed metformin maximal effect was not attenuated in Oct1/2-knockout mice (glucose AUC lowering at the highest 300 mg/kg dose = 42 ± 1 versus 39 ± 4%, knockout versus wild type; Fig. 6B and C). Although the glucose-lowering effect-dose relationship was unchanged between wild-type and Oct1/2-knockout mice, higher systemic metformin exposures were necessary to achieve the same effect in knockouts (half-maximal efficacious AUC = 70 versus 26 µg·h/ml, knockout versus wild type; Fig. 6D).

### TABLE 2

<table>
<thead>
<tr>
<th>Metformin pharmacokinetic parameters</th>
<th>Wild Type</th>
<th>Oct1/2 Knockout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intravenous dose, mg/kg</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>AUC$_{max}$, µg·h/ml</td>
<td>0.991</td>
<td>4.39</td>
</tr>
<tr>
<td>AUC$_{0-t}$, µg·h/ml</td>
<td>1.02</td>
<td>4.64</td>
</tr>
<tr>
<td>C$_{max}$, µg/ml</td>
<td>6.25</td>
<td>23.5</td>
</tr>
<tr>
<td>CL, ml·min$^{-1}$·kg$^{-1}$</td>
<td>81.7</td>
<td>18.0</td>
</tr>
<tr>
<td>V$_{dav}$, ml/kg</td>
<td>1840</td>
<td>530</td>
</tr>
<tr>
<td>T$_{max}$, h</td>
<td>0.50</td>
<td>0.62</td>
</tr>
<tr>
<td>Urinary excretion, % dose$^a$</td>
<td>18 ± 2</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>Creatinine renal CL, ml/min</td>
<td>0.09 ± 0.01</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>Inulin renal CL, ml/min</td>
<td>0.12 ± 0.03</td>
<td>0.19 ± 0.06</td>
</tr>
<tr>
<td>Corrected urinary recovery, % dose$^b$</td>
<td>49 ± 5</td>
<td>29 ± 4</td>
</tr>
<tr>
<td>Renal CL/GFR ratio</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Oral dose, mg/kg$^c$</td>
<td>10, 30, 60, 100, 300</td>
<td>10, 30, 60, 100, 300</td>
</tr>
<tr>
<td>F, %</td>
<td>59 ± 11</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>T$_{max}$, h</td>
<td>1.4 ± 0.5</td>
<td>1.0 ± 0.3</td>
</tr>
</tbody>
</table>

$^a$ Noncompartmental parameters were calculated using mean concentrations in composite PK datasets, so variability and $p$ values were not calculated.

$^b$ Urinary excretion was measured in a separate set of mice with four metabolic cages each containing three mice per group; mean ± S.E.M. for $n$ = 4 metabolic cages; no statistically significant differences were observed between groups.

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$^d$ Oral bioavailability and T$_{max}$ values are presented as the mean ± S.E.M. of the five oral dose levels; no dose-dependent trends in bioavailability or T$_{max}$ were observed in the 10 to 300 mg/kg dose range. Individual bioavailabilities at each dose level were calculated using systemic AUC values based on the mean concentrations in composite intravenous and oral PK datasets ($n$ = 4 mice/group per time point). No statistically significant differences were observed between groups.

The magnitude of decrease in kidney partitioning was less pronounced. Kidney-to-plasma metformin concentration ratio was significantly reduced in Oct1/2-knockout mice in 7 of 15 measurements; overall, this ratio was significantly decreased with a median decrease of 2.5-fold (Fig. 4). A trend of decreased kidney metformin partitioning was noted in both wild-type and Oct1/2-knockout mice at the highest 300 mg/kg dose, suggesting saturation of renal uptake. Note that in Figs. 3 and 4, unusually high tissue concentrations were observed in some animals at the 100 mg/kg dose level, so the mean values are skewed upwards, and the associated variability is high at this dose.

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The effects of metformin on blood glucose levels after an oral tolerance test in wild-type and Oct1/2-knockout mice are summarized in Fig. 6. At the lowest 10 mg/kg dose, metformin did not significantly lower blood glucose concentrations (Fig. 6A); however, at the highest 300 mg/kg dose, metformin significantly decreased blood glucose levels at all time points after the oral tolerance test and maintained them close to baseline (Fig. 6B). Glucose AUC lowering by metformin was not impaired in Oct1/2-knockout mice at any of the five dose levels tested (ED$_{50}$ = 151 versus 110 mg/kg, knockout versus wild type), and the effect on blood glucose levels over the tested dose range was generally comparable (Fig. 6C). Likewise, the observed metformin maximal effect was not attenuated in Oct1/2-knockout mice (glucose AUC lowering at the highest 300 mg/kg dose = 42 ± 1 versus 39 ± 4%, knockout versus wild type; Fig. 6B and C). Although the glucose-lowering effect-dose relationship was unchanged between wild-type and Oct1/2-knockout mice, higher systemic metformin exposures were necessary to achieve the same effect in knockouts (half-maximal efficacious AUC = 70 versus 26 µg·h/ml, knockout versus wild type; Fig. 6D).
To confirm that the observed metformin glucose-lowering effects (Fig. 6) were not mediated by insulin modulation, plasma insulin concentrations were monitored. As expected, insulin levels after the glucose tolerance test were not markedly different between wild-type and Oct1/2-knockout mice (Fig. 7). Although metformin significantly decreased insulin exposure in wild-type relative to Oct1/2-knockout mice at the highest 300 mg/kg dose level, no other significant differences or overall trends were otherwise noted.

**Discussion**

Previous literature reports established the importance of OCT1 in metformin hepatic distribution, necessary for its pharmacological
activity, and OCT2 in its secretory renal clearance (Wang et al., 2002, 2003, 2008; Shu et al., 2007, 2008; Song et al., 2008); however, the PK/PD relevance of each OCT isoform was evaluated independently. These studies are sufficient to support the interpretation of OCT1 or OCT2 functional variants in the context of metformin distribution/pharmacology or renal clearance. However, many OCT inhibitors are nonspecific (Minematsu et al., 2010), and the effect of pan-OCT inhibition on metformin PK/PD and tissue distribution has not been thoroughly evaluated. To gain insight into this issue, at present metformin PK/PD were studied in a model with genetic ablation of both Oct1 and Oct2.

Oct1/Oct2-double knockout phenotype was confirmed with TEA PK and urinary excretion properties reported previously by Dr. Alfred H. Schinkel’s laboratory, who initially generated the mice used in the current studies (Jonker et al., 2003). The present results are in agreement with the previous report and confirm the Oct1/Oct2 double-knockout phenotype, which with respect to TEA disposition is distinctly different from Oct1/Oct2(+/+), as well as Oct1 and Oct2 single-knockout phenotypes (Jonker et al., 2003). Considering the unexpected findings with respect to absolute metformin tissue exposure and PD, confirmation of the functional absence of both Oct genes was necessary.

Oct1/Oct2-knockout mice demonstrated the expected alterations in metformin systemic PK, as well as liver and kidney distribution (Wang et al., 2002, 2003, 2008; Shu et al., 2007, 2008; Song et al., 2008). Knockout mice exhibited significantly higher metformin systemic concentrations because of a 4.5-fold decrease in systemic clearance to approximately GFR and a 3.5-fold decrease in the volume of distribution. These observations are consistent with up to 2.6-fold reduction in secretory renal clearance in humans with a functional OCT2 variant (Song et al., 2008; Chen et al., 2009), as well as a 2.2-fold decrease in oral volume of distribution in people with a functional OCT1 variant (Shu et al., 2007, 2008).

In Oct1/Oct2-knockout mice, hepatic and renal tissue partitioning of metformin was reduced 4.2- and 2.5-fold, respectively. Metformin liver-to-plasma concentration ratio has been suggested to be 30-fold decreased in Oct1-knockout mice (Wang et al., 2002), but this measurement was made during the distributional phase. Subsequent studies properly estimated the extent of attenuation in hepatic metformin...
distribution in Oct1-knockout mice to be 2.5-, 4-, and 8-fold (Wang et al., 2003; Shu et al., 2007), which is consistent with the 4.2-fold reduction in the present study. Direct reference for the 2.5-fold decrease in kidney-to-plasma concentration ratio in the Oct1/2-knockout mouse does not exist in the literature, but it is consistent with up to 2.6-fold reduction in secretory renal clearance in humans with a functional OCT2 variant (Song et al., 2008; Chen et al., 2009).

On the basis of the observed decreases in liver and kidney partitioning, and assuming no compensatory changes in other metformin hepatic and renal transport mechanisms in the Oct1/2-knockout mouse, the fraction excreted calculation (Zamek-Gliszczynski et al., 2009) can be used to estimate the contribution of OCTs to hepatic and renal uptake of metformin. Thus, Oct1 is estimated to mediate 76% of metformin hepatic uptake in mice, whereas Oct1 and Oct2 together account for 60% of metformin renal uptake. These estimates are consistent with the existing literature supporting these transporters as the major hepatic and renal uptake pathways for metformin (Giacomini et al., 2010). However, they also highlight the existence of additional non-Oct1/2 uptake mechanism(s), which may account for as much as 24% of hepatic and 40% of renal metformin uptake. Passive diffusion into hepatocytes and cells of the renal proximal tubule is highly unlikely; metformin is very polar (log D = −6.13) and exhibited artificial membrane permeability that was too low to quantify (<0.27 × 10⁻⁶ cm/s) (Saitoh et al., 2004). Although OCT3 has not been reported to be an important determinant of drug PK (Giacomini et al., 2010), it is capable of transporting metformin in vitro and is expressed in the liver and kidney (Nishimura and Naito, 2005; Nies et al., 2009; Chen et al., 2010). Oct3 is the most logical mechanism behind the observed residual non-Oct1/2 uptake of metformin, although additional pathways cannot be ruled out.

A common concern with knockout animal models are the expression changes that may occur to compensate for the absent protein (Giacomini et al., 2010). In the case of metformin PK in the Oct1/2-knockout mice, potential changes to Mate proteins are most relevant (Kusuhara et al., 2011). In the present study both metformin renal tissue exposure and urinary recovery were essentially unchanged in Oct1/2-knockout mice. Because dX(tissue)/dt = CL(tissue) × C(tissue), the only way both renal tissue exposure (C(tissue)) and urinary recovery (X(tissue)) can remain unchanged is if the excretory clearance for transport between tubular cells and urine (CL(tissue)) is not altered in the knockout mice. Because urinary recovery and kidney tissue concentration were similar in the knockouts, renal Mate function was not altered to a notable extent.

Metformin pharmacology is complex and multifaceted (Bailey and Turner, 1996). Three major mechanisms of action are involved: inhibition of hepatic gluconeogenesis, stimulation of peripheral glucose uptake and utilization, and inhibition of intestinal glucose absorption (metformin hydrochloride prescribing information). These complexities raise the question of whether mice are a representative species of metformin clinical PK/PD. Key metformin systemic PK parameters are in good agreement between mice and humans: clinical oral bioavailability was 50 to 60% versus 59 to 64% in mice; metformin was well distributed in both species with a volume of distribution of 4.7 ± 2.6 l/kg in humans (oral V/F × F) versus 1.5 l/kg in mice (i.v.); renal clearance was 3.5 times unbound GFR in humans versus 4 times in mice (metformin hydrochloride prescribing information). In both mice and humans, hepatic distribution of metformin is largely dependent on OCT1/Oct1 uptake (Wang et al., 2002; Shu et al., 2007). At a gross PD level, metformin elicits its distinct hepatic, peripheral, and intestinal effects in rodents with progressively greater blood glucose lowering with the route of metformin administration: intravenous infusion < portal infusion < oral administration (Stepensky et al., 2002). More mechanistic studies in mice demonstrated that this species is representative of human pharmacology in that metformin decreases murine intestinal glucose absorption (Wilcock and Bailey, 1991), inhibits murine hepatic gluconeogenesis (Shu et al., 2007), and promotes murine peripheral glucose uptake and utilization (Wilcock and Bailey, 1990). Thus, mice are reasonably representative of metformin PK/PD in humans.

In the present study, the marked reduction in metformin clearance and distribution in Oct1/2-knockout mice ultimately did not result in impaired PD effects. The present findings are conceptually consistent with the presumption that systemic pan-OCT inhibition will affect metformin pharmacology (metformin hydrochloride prescribing information). The putative PD and toxicodynamic implications of such drug interactions are based on the observed increase in metformin systemic exposure by the equipotent OCT1 and OCT2 inhibitor, cimetidine (Somogyi et al., 1987; Wang et al., 2008; König et al., 2011). However, cimetidine concentrations sufficient to inhibit metformin renal clearance would also be expected to inhibit hepatic uptake, such that the net product of increased systemic metformin concentrations and decreased hepatic uptake would yield little net change in hepatic drug exposure (dX(systemic)/dt = C(systemic) × CL(systemic)). Although metformin hepatic concentrations are not available clinically, cimetidine did not affect metformin lactic acidosis; the blood lactate/pyruvate ratio was comparable at two of four time points tested and was increased and then decreased to a similar extent at the other two times (Somogyi et al., 1987). The concern of enhanced metformin effects due to inhibition of renal clearance and subsequent increase in systemic exposure would be more relevant for a selective OCT2 inhibitor, for example, amantadine or amphetamine exhibit 20-fold greater selectivity for OCT2 over OCT1 (Amphoux et al., 2006). Despite major changes in metformin clearance and distribution in Oct1/Oct2 double-knockout mice, hepatic drug exposure was not reduced to an appreciable extent, and metformin PD effects were not diminished. These findings challenge the presumption that impair-
ment of both renal and hepatic OCT transport is expected to result in altered metformin PD. Furthermore, present studies provided additional evidence that Oct1 is not the sole mechanism of metformin hepatic uptake necessary for inhibition of gluconeogenesis.

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Authorship Contributions

Participated in research design: Higgins, Bedwell, and Zamek-Gliszczynski.
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Wrote or contributed to the writing of the manuscript: Higgins, Bedwell, and Zamek-Gliszczynski.

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