Short Communication

The Intestine As an Important Contributor to Prasugrel Active Metabolite Formation In Vivo

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ABSTRACT:

Prasugrel [2-acetoxy-5-(α-cyclopropylcarbonyl-2-fluorobenzyl)]-4,5,6,7-tetrahydrothieno[3,2-c]pyridine, a thienopyridine antplatelet agent, undergoes rapid hydrolysis in vivo to a thiolactone intermediate, 2-[2-oxo-6,7-dihydrothieno[3,2-c]pyridin-5(4H)-yl]-1-cyclopropyl-2-(2-fluorophenyl)ethanone (R-95913), which is further converted to a pharmacologically active metabolite, 2-[1-2-cyclopropyl-1-(2-fluorophenyl)-2-oxoethyl]-4-mercapto-3-piperidinylidine acetic acid (R-138727), by oxidation via cytochromes P450. In this study, we investigated how much the intestine and liver contribute to the formation of R-95913 and R-138727 after intraduodenal administration of prasugrel (1 mg/kg) to portal vein- and hepatic vein-cannulated dogs. The areas under the plasma concentration-time curve up to 2 h of R-95913 in the portal, hepatic, and systemic veins were 525, 32, and 17 ng · h/ml, respectively, and those of R-138727 were 564, 529, and 495 ng · h/ml, respectively. The dose of prasugrel was absorbed and then converted to R-95913 and R-138727 by 93 and 13%, respectively, in the intestine. In the liver, 23% of the R-95913, which passed through the intestine, was converted to R-138727. In conclusion, this is the first report to directly demonstrate that the conversion of prasugrel to R-138727 in the intestine is comparable to that converted in the liver of dogs.

Introduction

Prasugrel [2-acetoxy-5-(α-cyclopropylcarbonyl-2-fluorobenzyl)]-4,5,6,7-tetrahydrothieno[3,2-c]pyridine; Efient in the United States and Efient in the European Union, clopidogrel (Plavix/Iscover), and ticlopidine (Ticlid) are thienopyridine antiplatelet agents. Prasugrel is indicated to reduce the rate of thrombotic cardiovascular events and stent thrombosis in patients with acute coronary syndrome who are undergoing percutaneous coronary intervention (Wiviott et al., 2007; Effient package insert, Eli Lilly and Company, Indianapolis, IN). The thienopyridines are prodrugs that are converted in vivo to their pharmacologically active metabolites possessing a thiol group via a corresponding thiolactone metabolite (Farid et al., 2010). In clinical trials, prasugrel achieved a greater and faster antiplatelet effect than clopidogrel (Payne et al., 2007; Wallentin et al., 2008). Such responses to prasugrel are attributed to indirectly demonstrate that the conversion of prasugrel to R-138727 in the intestinal and hepatic vein to the formation of R-95913 and R-138727 after intraduodenal administration of prasugrel (1 mg/kg) to portal vein- and hepatic vein-cannulated dogs. The areas under the plasma concentration-time curve up to 2 h of R-95913 in the portal, hepatic, and systemic veins were 525, 32, and 17 ng · h/ml, respectively, and those of R-138727 were 564, 529, and 495 ng · h/ml, respectively. The dose of prasugrel was absorbed and then converted to R-95913 and R-138727 by 93 and 13%, respectively, in the intestine. In the liver, 23% of the R-95913, which passed through the intestine, was converted to R-138727. In conclusion, this is the first report to directly demonstrate that the conversion of prasugrel to R-138727 in the intestine is comparable to that converted in the liver of dogs.

Materials and Methods

Materials. Prasugrel, prasugrel thiolactone (R-95913), and prasugrel active metabolite (R-138727), shown in Fig. 1, were synthesized by Ube Industries, Ltd. (Ube, Japan). Phenacetin and N,N-dimethylacetamide were purchased from Sigma-Aldrich (St. Louis, MO). Polyethylene glycol 400 was obtained from Wako Pure Chemicals (Osaka, Japan). Methoxyphenacetyl bromide was from Tokyo Kasei Kogyo Co., Ltd. (Tokyo, Japan). Human intestinal...
microsomes, dog intestinal microsomes, and dog liver microsomes were purchased from Tissue Transformation Technologies Inc. (Edison, NJ), Biopredic International (Rennes, France), and XenoTech, LLC (Lenexa, KS), respectively. All other chemicals and reagents were commercially available and of the highest grade.

Preparation of Dosing Formulations. Prasugrel was dissolved in 5% N,N-dimethylacetamide-95% polyethylene glycol 400 (v/v) solution at concentrations of 3 mg/ml. The solution was prepared immediately before use.

Experimental Animals. Male beagle dogs (n = 6) at age 2 to 3 years were obtained from Nosan Corporation (Yokohama, Japan) and were acclimatized in a controlled animal area set at 23 ± 2°C (acceptable range, 20–26°C) and relative humidity of 55 ± 5% (acceptable range, 30–70%) under a 12-h light/dark cycle of artificial lighting (lighting time, 7:00 AM–7:00 PM). Food (DS-A; Oriental Yeast Co., Ltd., Tokyo, Japan) and water were provided freely. Dogs, weighing 9 to 12 kg, that underwent the portal- and hepatic-vein cannulating surgery were used in the experiments and were fasted for approximately 19 h before prasugrel administration. All animal experiments were performed according to the guidelines provided by the Institutional Animal Care and Use Committee of Daichi Sankyo Co., Ltd.

Portal Vein- and Hepatic Vein-Cannulated Dogs. Under pentobarbital anesthesia, the abdomen was incised on the median line. The portal vein was clamped onto the liver side and intestinal side of the cannulation point, into which the catheter (Medicut LCV-UK kit, single lumen, outer diameter 16 gauge, length 70 cm; Sherwood Medical Company, St. Louis, MO) was inserted. A purse-string ligature was applied, and the clamps were released. After the portal vein cannulation, the same catheter was also inserted into the hepatic vein and a purse-string ligature was applied. The catheters were conjugated with each injection port, which was embedded subcutaneously.

Animal Experiments. From the jugular vein, 2 ml of blood was extracted before dosing. The dosing solution of prasugrel was intraduodenally administered to the cannulated dogs (n = 6) at a dose level of 1 mg/kg. After approximately 1 ml of blood drainage from the portal and hepatic veins via the injection port, the syringes were changed to another one, and 1 ml of blood was collected with the heparinized syringe at 1, 5, 10, 15, 30, 60, and 120 min postdose. The blood in the cannula was pushed back by the injection of 2 ml of heparin solution in saline (100 units/ml). At each time point, 1 ml of blood was also collected from the jugular vein. The blood samples were immediately centrifuged at 14,000 rpm for 3 min at 4°C (Hitachi Koki Co., Ltd., Tokyo, Japan) to collect plasma samples. A total of 50 µl of plasma was mixed with 100 µl of acetonitrile and 50 µl of the internal standard solution (4 µM phenacetin in acetonitrile), and the mixture was centrifuged at 14,000 rpm for 3 min at 4°C (Hitachi Koki Co., Ltd.). A total of 10 µl of the supernatant was injected into the LC-MS system.

Quantitation of R-95913 and R-138727. Quantitation of R-95913 and R-138727 in dog plasma was performed on an Alliance HPLC system consisting of a 2690 Separations Module (Waters, Milford, MA) coupled to a Quattro LC-MS system (Micromass Ltd., Milford, MA) with the electrospray ionization source in positive ion mode. The mobile phase containing acetonitrile, 5 mM ammonium acetate, and formic acid (32:68:0.2, v/v/v) was applied onto the column. A total of 10 µl of each sample was injected onto a CAPCELL PAK C18 column (5 µm, 150 mm × 1.5 mm; Shiseido Co., Ltd., Tokyo, Japan). The operating parameters of the MS detector were set as follows: capillary voltage, 3.5 kV; ion source temperature, 120°C; and desolvation temperature, 350°C. Detection was performed in the multiple reaction monitoring mode. The concentrations of each analyte in the samples were calculated using the computer software MassLynx (version 3.4; Micromass Ltd.).

Pharmacokinetic Analysis. The pharmacokinetic parameters were calculated using the computer program WinNonlin Professional (version 4.0.1; Pharsight, Mountain View, CA) on the basis of the noncompartmental method. The area under the plasma concentration-time curve up to 2 h (AUC0–2h) was calculated by the trapezoidal method, and values are expressed as means ± S.D.

Calculation of Availability of R-95913. The availability of R-95913 was calculated using eqs. 1 and 2:

\[ F_{\text{g}_{\text{pras}}} \times F_{\text{g}_{\text{pr-as-913}}} = \frac{Q_{\text{g}_{\text{sys}}}[\text{R-913}] - \text{AUC}_{\text{sys}, 913}}{\text{dose}} \]

\[ F_{h_{913}} = \frac{\text{AUC}_{\text{sys}, 913}}{\text{AUC}_{\text{sys}, 913}} \]

where \( F_{\text{g}_{\text{pras}}} \), \( F_{\text{g}_{\text{pr-as-913}}} \), and \( F_{h_{913}} \) are fraction of intestinal absorption of prasugrel, fraction of prasugrel hydrolysis to R-95913 in the intesti-
time, and availability of R-95913 in the liver, respectively. AUC_{por, 913}, AUC_{hep, 913}, and AUC_{sys, 913} indicate the AUC_{0–2 h} values of R-95913 in the portal, hepatic, and systemic veins, respectively. Q_{p} is portal blood flow, and R_{b} is the blood/plasma concentration ratio. F_{p} to F_{b} are set as 0.968 (Hagihara et al., 2007), 521 ml/min (Hoshino et al., 1986), and 0.597 (in-house data, Daiichi Sankyo Co., Ltd.), respectively.

**Calculation of Availability of R-138727.** The availability of R-138727 was calculated using eqs. 3 to 5:

\[
F_{p} \cdot \frac{F_{b, pras-727}}{F_{b, pras-913}} = Q_{p} \cdot R_{b} \cdot \left( AUC_{por, 727} - AUC_{hep, 727} \right) \text{dose}
\]

(3)

\[
F_{b, 913} \cdot \frac{F_{h, 727} + F_{b, pras-913}}{F_{b, pras-913}} \cdot F_{h, 913} - F_{h, 727} = \text{relative BA}
\]

(5)

where \( F_{p, pras-727}, F_{b, 913}, F_{h, 727} \), and \( F_{h, 727} \) are fraction of prasugrel conversion to R-138727 in the intestine, fraction of R-95913 conversion to R-138727 in the liver, and availability of R-138727 in the liver, respectively. AUC_{por, 727}, AUC_{hep, 727}, and AUC_{sys, 727} indicate the AUC_{0–2 h} values of R-138727 in the portal, hepatic, and systemic veins, respectively. Relative BA represents the relative bioavailability of R-138727 after oral dosing of prasugrel to dogs and was set as 24.8% (Hagihara et al., 2009).

**Formation of R-95913 in Dog and Human Intestinal S9.** The mixture (total volume, 247.5 μl) in triplicate contained potassium phosphate buffer (7 mM, pH 7.4); an NADPH-generating system containing 2.5 mM β-NADP, 25 mM glucose 6-phosphate, 0.5 units/ml glucose-6-phosphate dehydrogenase, and 10 mM MgCl₂; 5 mM glutathione; and dog or human intestinal S9 (10 mg of protein/ml each). The mixture was preincubated at 37°C for 15 min, and 2.5 μl of prasugrel (final concentration: 250 μM) was added to the mixture, which was incubated at 37°C for 5 min and 2.5 μl of prasugrel (final concentration: 250 μM) was added to the mixture. After incubation at 37°C for 5 min, 5 μl of the internal standard solution (5:12:83:0.01, v/v/v/v) was added to 30 μl of 5 mM methoxyphenacyl bromide solution and 100 μl of the reaction mixture to stop the reaction, and the mixture was left for 10 min at room temperature to derivatize a thiol moiety of R-138727. The mixture was extracted by a solid-phase extraction column (Captive; Varian, Inc., Palo Alto, CA). The assay of R-138727 was performed following the methods reported previously (Hagihara et al., 2009). Separation of the analytes by HPLC was conducted using an Alliance 2690 Separations Module (Waters). Mass spectra were determined using a Quattro LC-MS/MS system (Micromass Ltd.) in the positive ion detection mode using an electrospray ionization interface. A lower limit of quantification was set at 1.6 nM. Data acquisition and analyses were performed using MassLynx software (version 4.0).

**Data Handling.** The formation pattern of R-138727 in human or dog intestinal or dog liver microsomes appeared monophasic in each Eadie-Hofstee plot (data not shown). Therefore, the data were fitted to eq. 6 using WinNonlin Professional (version 4.0.1).

\[
V = V_{\text{max}} \times S/(K_{m} + S)
\]

(6)

where \( S, K_{m}, \) and \( V_{\text{max}} \) are the substrate concentration, Michaelis-Menten constant, and maximal formation rate, respectively. The intrinsic clearance (CL_{int}) was calculated as a ratio of \( V_{\text{max}} \) to \( K_{m} \). These parameters are expressed as means ± S.D.

**Results**

**Plasma Concentrations and AUC_{0–2 h} Values after Intraduodenal Administration of Prasugrel to Cannulated Dogs.** The plasma concentrations of R-95913 and R-138727 were determined by LC-MS/MS.

### TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>R-95913</th>
<th>R-138727</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_{p} \cdot F_{b, pras-913}</td>
<td>0.80</td>
<td>0.88</td>
</tr>
<tr>
<td>F_{b, 913}</td>
<td>0.23</td>
<td>0.06</td>
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<tr>
<td>F_{b, pras-913}</td>
<td>0.08</td>
<td>0.83</td>
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### TABLE 2

<table>
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<tr>
<th></th>
<th>R-95913</th>
<th>R-138727</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_{p} \cdot F_{b, pras-727}</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>F_{b, 727}</td>
<td>0.23</td>
<td>0.06</td>
</tr>
<tr>
<td>F_{b, pras-913}</td>
<td>0.08</td>
<td>0.75</td>
</tr>
<tr>
<td>F_{b, 727}</td>
<td>0.75</td>
<td>0.21</td>
</tr>
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</table>

Fig. 4. Availability of R-95913 and R-138727 in the intestine and the liver in dogs.

Fig. 5. Formation of R-95913 from prasugrel in dog and human intestinal S9. Prasugrel (250 μM) was incubated in dog and human intestinal S9 and the concentrations of R-95913 were determined.
after intraduodenal administration of prasugrel to the portal vein- and hepatic vein-cannulated dogs at a dose of 1 mg/kg. Plasma concentrations of prasugrel were not analyzed because prasugrel was not detected unmodified even in the portal vein in a previous study (Hagihara et al., 2009). The plasma concentration-time profiles of R-95913 and R-138727 are shown in Figs. 2 and 3, respectively. The AUC₀–₂₅₉₉₉₉ value of R-95913 in the portal vein (525 ± 234 ng · h/ml) was much higher than those in hepatic and systemic veins (32 ± 17 and 17 ± 8 ng · h/ml, respectively). The AUC₀–₂₅₉₉₉₉ values of R-138727 in the portal, hepatic, and systemic veins were 564 ± 187, 529 ± 136, and 495 ± 233 ng · h/ml, respectively. The bimodal peaks were detected in the plasma concentration-time profiles of R-95913 (Fig. 2). This finding may indicate reabsorption of R-95913 from the intestine as in the case of rats, which showed enterohepatic circulation of [¹⁴C]prasugrel (Hagihara et al., 2007).

Availability of R-95913 and R-138727 in the Intestine and the Liver. The $F_\text{a}$, $F_\text{g-pras}$, and $F_{h,R}$ values were 0.80 ± 0.23 and 0.08 ± 0.06, respectively (Table 1). The $F_\text{a}$, $F_\text{g-pras}$, and $F_{h,R}$ values were 0.13 ± 0.13, 0.23 ± 0.06, and 0.75 ± 0.21, respectively (Table 2). The dose of prasugrel was absorbed and converted to R-95913 by 93% ($F_\text{a}$, $F_\text{g-pras}$, and $F_{h,R}$) and to R-138727 by 13% in the intestine. R-95913 that passed through the intestine was converted to R-138727 by 23% in the liver (Fig. 4).

Formation of R-95913 in Dog and Human Intestinal S9. Prasugrel was almost completely hydrolyzed to R-95913 at 5 min in dog and human intestinal S9 (Fig. 5). The results indicated comparable hydrolytic activities of prasugrel by dog and human intestinal enzymes.

### TABLE 3

<table>
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<tr>
<th>Incubation Time</th>
<th>$K_m$ (µM)</th>
<th>$V_{max}$ (pmol per min/mg)</th>
<th>$CL_{int}$ (µl per min/mg)</th>
<th>$CL_{int}$ Ratio (Liver/Intestine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog Intestinal microsomes</td>
<td>15</td>
<td>42.7 ± 1.0</td>
<td>49.8 ± 2.0</td>
<td>1.2 ± 0.0</td>
</tr>
<tr>
<td>Liver microsomes</td>
<td>15</td>
<td>18.5 ± 0.6</td>
<td>379.9 ± 20.7</td>
<td>20.6 ± 0.5</td>
</tr>
<tr>
<td>Human Intestinal microsomes</td>
<td>15</td>
<td>80.4 ± 11.5</td>
<td>89.2 ± 1.3</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>Liver microsomes</td>
<td>15</td>
<td>26</td>
<td>247</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Data from Rehmel et al. (2006).
be an important contributor to R-138727 formation in vivo. In general, it is difficult to perform quantitative kinetic analyses of a prodrug and its metabolites in vivo, because complex models are required to describe respective concentration profiles (Tsukamoto et al., 2001). Therefore, we evaluated the availability of each metabolite using a simple calculation method without any differential equations. The results in the present study demonstrated a quantitatively important contribution of the intestine to R-138727 formation in dogs, where 13% of the dose of prasugrel was converted to R-138727. Because the availability of R-138727 in the liver was 75%, approximately 10% (13 × 75%) of the dose of prasugrel is thought to reach the circulation as R-138727 via bioactivation in the intestine. The relative bioavailability of R-138727 after oral administration of prasugrel to dogs is 25% (Hagiwara et al., 2009), and therefore approximately 40% (10.25%) of exposure to R-138727 in the circulation is probably attributable to intestinal bioactivation.

In this study, the dose of prasugrel was calculated to be substantially converted to R-95913 (by 93%) during the absorption process through the intestine, which is consistent with the previous clinical and nonclinical observations. In human plasma, prasugrel was not detected unmodified because of rapid hydrolysis by carboxylesterases (Farid et al., 2007b; Williams et al., 2008). In addition, a Caco-2 cell study showed the complete conversion of prasugrel to R-95913 during absorption (Williams et al., 2008). In the current study, carboxylesterase inhibitors were not added during blood sampling, indicating the possibility of hydrolysis of prasugrel in the extracted blood samples. However, prasugrel is rapidly hydrolyzed in dog intestinal S9 (Fig. 5), and therefore prasugrel administered to dogs is thought to be hydrolyzed in the intestine in vivo.

We used dogs to evaluate respective fractions of prasugrel bioactivation in the intestine and liver. Because CYP3A activities have been reported in the intestine and liver in dogs (Komura et al., 2002; Sahi et al., 2002), it is considered reasonable to use dogs for assessment of active metabolite formation of prasugrel, which is mediated mainly by CYP3A. Indeed, prasugrel was metabolized to R-138727 in dog intestinal and liver microsomes with Clint values comparable to those in human intestinal and liver microsomes, respectively (Table 3). The ratios of Clint (liver/intestine) were 17.2 and 8.7 in dogs and humans, respectively, and these were relatively higher than that of the fraction of R-138727 formation in dogs (Fr int:913–727 g p gras–727 1.8). This discrepancy between in vitro and in vivo might be explained by the difference in physiological conditions in intestine and liver (i.e., more absolute exposure to the substrate in the intestine during absorption) or possibly a higher unbound fraction of the substrate in the intestine. In dog small intestine, no carboxylesterases were found in the previous report (Taketani et al., 2007). However, prasugrel was hydrolyzed in dog intestinal S9 to the same degree as in human intestinal S9 (Fig. 5), indicating the existence of complementary esterases in dog intestine. This concept is also supported by the previous observation that prasugrel was not detected unmodified in the portal vein after oral administration of prasugrel to dogs (Hagiwara et al., 2009). Thus, a fraction of R-138727 similar to that formed in the intestine in dogs could be expected in humans.

Clopidogrel seems not to be converted to either a thiolactone intermediate or an active metabolite in the intestine (Kazu et al., 2005; Hagiwara et al., 2009). This could be the reason for the slower onset of an inhibitory effect on platelet aggregation by clopidogrel than by prasugrel in the clinical studies (Payne et al., 2007; Wallentijn et al., 2008).

In conclusion, a significant portion of R-95913 was oxidized to R-138727 during intestinal absorption in dogs. This is the first report to quantitatively evaluate the contribution of the intestine and liver to the formation of R-95913 and R-138727, and the calculation method used in this study may provide a useful tool for evaluation of the bioactivation of other prodrugs in the liver and intestine.

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References


Kazui M, Kurihara A, Hagiwara K, Farid NA, and Ikeda T (2005) Prasugrel (CS-747, LY640315), a novel thienopyridine antiplatelet agent, more efficiently generates active me-


Sahi et al., 2002), it is considered reasonable to use dogs for assess-


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