Absorption, Metabolism, and Excretion of [14C]Vildagliptin, a Novel Dipeptidyl Peptidase 4 Inhibitor, in Humans

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ABSTRACT:
The absorption, metabolism, and excretion of [14C]vildagliptin, an orally active, highly selective dipeptidyl peptidase 4 inhibitor developed for the treatment of type 2 diabetes, were evaluated in four healthy male subjects after a single p.o. 100-mg dose of [14C]vildagliptin. Serial blood and complete urine and feces were collected for 168 h postdose. Vildagliptin was rapidly absorbed, and peak plasma concentrations were attained at 1.1 h postdose. The fraction of drug absorbed was calculated to be at least 85.4%. Unchanged drug and a carboxylic acid metabolite (M20.7) were the major circulating components in plasma, accounting for 25.7% (vildagliptin) and 55% (M20.7) of total plasma radioactivity area under the curve. The terminal half-life of vildagliptin was 2.8 h. Complete recovery of the dose was achieved within 7 days, with 85.4% recovered in urine (22.6% unchanged drug) and the remainder in feces (4.54% unchanged drug). Vildagliptin was extensively metabolized via at least four pathways before excretion, with the major metabolite M20.7 resulting from cyano group hydrolysis, which is not mediated by cytochrome P450 (P450) enzymes. Minor metabolites resulted from amide bond hydrolysis (M15.3), glucuronidation (M20.2), or oxidation on the pyrrolidine moiety of vildagliptin (M20.9 and M21.6). The diverse metabolic pathways combined with a lack of significant P450 metabolism (1.6% of the dose) make vildagliptin less susceptible to potential pharmacokinetic interactions with comedinations of P450 inhibitors/inducers. Furthermore, as vildagliptin is not a P450 inhibitor, it is unlikely that vildagliptin would affect the metabolic clearance of comediations metabolized by P450 enzymes.

Dipeptidyl peptidase 4 (DPP-4, DPP-IV) is a highly specialized aminopeptidase that is present in plasma, the kidney, and the intestinal brush-border membranes, as well as on the surface of capillary endothelial cells, hepatocytes, and a subset of T lymphocytes (Deacon et al., 1995; Mentlein, 1999). DPP-4 is responsible for the rapid inactivation of the incretin glucagon-like peptide 1 (GLP-1) and glucose-dependent insulintropic peptide. GLP-1, which is released postprandially, stimulates meal-induced insulin secretion and contributes to glucose homeostasis (Gutniak et al., 1997; Kieffer and Habener, 1999). Circulating GLP-1 is rapidly degraded and inactivated by DPP-4 (Deacon et al., 1995; Mentlein, 1999). With the inhibition of the DPP-4 enzyme activity, GLP-1 activity increases markedly, improving glycemic control in experimental and human studies (Balkan et al., 1999; Ahren et al., 2002, 2004; Reimer et al., 2002). Therefore, administration of a DPP-4 inhibitor to diabetic patients augments endogenous GLP-1 activity, which in turn produces a clinically significant lowering of diabetic glycaemia comparable with that observed when GLP-1 is administered by direct infusion (Gutniak et al., 1992; Drucker, 2003; Mest and Mentlein, 2005).

Vildagliptin (Galvus, Novartis, East Hanover, NJ; (1-[3-hydroxy-1-adamantyl] amino) acetyl]-2-cyano-(S)-pyrrolidine) is a potent, orally active, highly selective inhibitor of DPP-4 (Villhauer et al., 2003) and is marketed as an antidiabetic drug in this novel class of action mechanisms (He et al., 2007b). Based on an in vitro recombinant DPP-4 assay, the IC50 for vildagliptin is 2 nM. In humans, the efficacy of vildagliptin against the DPP-4 enzyme also shows a low in vivo inhibitory constant (IC50 4.5 nM), a value that suggests higher potency than that reported for another DPP-4 inhibitor, sitagliptin (IC50 26 nM) (Herman et al., 2005; He et al., 2007b). Vildagliptin has shown the ability to inhibit DPP-4, increase plasma concentrations of intact GLP-1 and glucose-dependent insulintropic peptide, decrease fasting and postprandial glucose, and suppress plasma glucagon in clinical trial in patients with type 2 diabetes. The pharmacokinetics and pharmacodynamics of vildagliptin after various dosing regimens in healthy volunteers and patients with type 2 diabetes have been previously reported (He et al., 2007a,b, 2008; Sunkara et al., 2007).

The purpose of this study was to investigate the disposition and

ABBREVIATIONS: DPP-4, dipeptidyl peptidase 4; GLP-1, glucagon-like peptide 1; vildagliptin, (1-[3-hydroxy-1-adamantyl] amino) acetyl]-2-cyano-(S)-pyrrolidine; [14C]vildagliptin, (1-[3-hydroxy-adamant-1-yl-amino)-acetyl]-pyrrolidine-2(S)-carbonitrile; LSC, liquid scintillation counting; LC/MS/MS, liquid chromatography/tandem mass spectrometry; IS, internal standard; ESI, electrospray ionization; HPLC, high-performance liquid chromatography; LC/MS, liquid chromatography/mass spectrometry; DMSO, dimethyl sulfoxide; CID, collision-induced dissociation; P450, cytochrome P450; UGT, UDP glucuronosyltransferase; AUC, area under the curve; amu, atomic mass unit.
biotransformation of vildagliptin in healthy male volunteers after a single 100-mg (47 μCi) p.o. dose of [14C]vildagliptin ([1-[3-hydroxyadamant-1-yl-amino]-acetyl]-pyrrolidin-2(S)-carbonitrile]. A daily dose of 100 mg is the recommended human efficacious dosing regimen for vildagliptin, and no pharmacokinetic gender difference has been observed (He et al., 2007b, 2008). [14C]Vildagliptin has been shown to be highly absorbed in both rats and dogs (He et al., 2009). Vildagliptin was mainly metabolized before excretion in rats and dogs. One major metabolite in excreta involved hydrolysis at the cyano moiety to yield a carboxylic acid metabolite (M20.7) in rats and dogs. Another predominant metabolic pathway included the hydrolysis of the amide bond (M15.3) in the dog.

Materials and Methods

Study Drug. [14C]Vildagliptin (specific activity 0.47 μCi/mg, radiochemical purity >99%) was synthesized by the Isotope Laboratory of Novartis Pharmaceuticals Corporation (East Hanover, NJ). The chemical structure of vildagliptin and the position of the radiolabel are shown in Fig. 1.

Metabolites. Synthetic standards of metabolites M20.2, M20.7, and M15.3 were also obtained from Novartis Pharmaceuticals Corporation.

Human Studies. The study protocol and the informed consent document were approved by an independent institutional review board. The written informed consent was obtained from all the subjects before enrollment.

Four healthy, nonsmoking, male white subjects, age 18 to 45 years, with weights ranging from 77 to 93 kg, participated in the study. Subjects were confined to the study center for at least 20 h before administration of the study drug until 168 h (7 days) postdose. After an overnight fast, informed consent was obtained from all the subjects before enrollment. The study protocol and the informed consent document were approved by an independent institutional review board. The written informed consent was obtained from all the subjects before enrollment.

Radioactivity Analysis of Blood, Plasma, Urine, and Feces Samples. Radioactivity was measured in plasma and blood by liquid chromatography/tandem mass spectrometry (LC/MS/MS) assay. Aliquots of plasma (200 μl) or human urine (100 μl diluted with 100 μl of water) and 200 μl of internal standard (IS) solution ([3H]N-vildagliptin) were transferred to individual wells in a 1-ml, 96-well polypropylene plate. Extraction of the samples was performed using a Quadra-96 model 320 workstation (TomTec, Hamden, CT). Before extraction of samples, a 10-μg Oasis HLB 96-well solid-phase extraction plate (Waters, Milford, MA) was conditioned with 300 μl of methanol, followed by 300 μl of water. The samples were applied to the preconditioned extraction plate. The plate was washed with 300 μl of 5% methanol (containing 2% ammonium hydroxide), 300 μl of 20% methanol (containing 2% ammonium hydroxide), and 300 μl of water. After vacuum-drying each well, the samples were eluted with 2 × 75 μl of 80% methanol (containing 0.1% trifluoroacetic acid) and evaporated under nitrogen (35°C) to a volume of ~50 μl using an Evaporex solvent evaporator (Apicot Designs, Monrovia, CA). The samples were diluted with 50 μl of 15% methanol (containing 0.5% ammonium hydroxide) and mixed before injection.

Sample Preparation of Plasma, Urine, and Feces for Metabolite Investigation. Semiquantitative determination of main and trace metabolites was obtained for plasma, urine, and feces (based on peak areas) using high-performance liquid chromatography (HPLC)-radiodetection with off-line microplate solid scintillation counting and structural characterization by liquid chromatography/mass spectrometry (LC/MS). Plasma samples (3.5–4.5 ml) from each subject at 0.5, 1, 2, 3, 6, 12, 16, and 24 h postdose were protein-precipitated with acetonitrile/ethanol (90:10 v/v) containing 0.1% acetic acid and removed by centrifugation. Recoveries of radioactivity after plasma sample preparation averaged 95%. The supernatant was evaporated to near dryness under a stream of nitrogen using the Zymark Turbo-Vap LV (Zymark Corp., Hopkinton, MA), and the residues were reconstituted in acetonitrile/5 mM ammonium acetate containing 0.1% trifluoroacetic acid (10/90 v/v). Aliquots (80–85 μl) of concentrated plasma extracts were injected onto the HPLC column. For urine analysis, a pool of equal percent volume from the 0- to 48-h fractions (10% of urine volume from each time point, e.g., 0–24 and 24–48 h) was prepared for each subject. An aliquot was centrifuged, and 100 μl was injected onto the HPLC column without further purification. Recoveries of radioactivity after centrifugation of urine samples were 100%. Feces homogenates were pooled from 0 to 96 h at equal percent weight for each subject (10% of feces homogenates from each time point, e.g., 0–24, 24–48, and 48–72 h) and extracted twice with methanol by vortexing and centrifugation. The average recovery of sample radioactivity in the methanolic extracts was 87%. Aliquots of combined supernatant (5 ml) were evaporated to dryness under a stream of nitrogen using the Zymark Turbo-Vap LV, and the residues were reconstituted in 0.2 ml of acetonitrile/5 mM ammonium acetate containing 0.1% trifluoroacetic acid (10/90 v/v). Aliquots (60–80 μl) of concentrated fecal extracts were injected onto the HPLC column.

HPLC Instrumentation for Metabolite Pattern Analysis. Vildagliptin and its metabolites in urine, plasma, and feces were analyzed by HPLC with off-line radioactivity detection using a Waters Alliance 2690 HPLC system equipped with a Phenomenex (Torrance, CA) Synergy Hydro-RP column.
Wisconsin solution but was rejected for transplantation. The incubations were obtained through the Association of Human Tissue Users (Tucson, AZ). Bated with liver slice preparations from one human subject. The human tissue was considered as semiquantitative only, unlike those determined by the methods. The values are derived from the radiochromatograms (metabolite patterns) by dividing the peak areas of the metabolites by the peak areas of the parent compound.

For the radioactivity analysis, an aliquot of blood containing [14C]vildagliptin was pipetted for radioactivity analysis. Then the blood samples were incubated at 37°C for 30 min and centrifuged at approximately 40,000 g for 10 min at 20°C. The pellet was re-extracted with methanol, and the resultant supernatant was evaporated to dryness and combined with the pooled sample.

**Structural Characterization of Metabolites by LC/MS/MS.** Metabolite characterization was conducted with a Finnigan LCQ ion-trap mass spectrometer (Thermo Fisher Scientific, Waltham, MA) equipped with an ESI source. The effluent from the HPLC column was split, and approximately 500 μl/min was introduced into the atmospheric ionization source after diverting to waste during the first 4 min of each run to protect the mass spectrometer from nonvolatile salts. The electrospray interface was operated at 5000 V, and the mass spectrometer was operated in the positive ion mode. Collision-induced dissociation (CID) studies were performed using helium gas at the collision energy of 35% (arbitrary unit).

**Metabolism of Vildagliptin in Human Liver Microsomes and by Recombinant Cytochromes P450.** The metabolism of [14C]vildagliptin (specific activity of 154.5 μCi/mg) was examined in pooled human liver microsomes (n = 46 donors, mixed gender) and in microsomal preparations from baculovirus-infected insect cells expressing recombinant human cytochrome P450 (P450) enzymes (BD Gentest, Woburn, MA). The recombinant P450 enzymes examined in this study were CYP1A1, CYP1A2, CYP1B1, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C18, CYP2C19, CYP2D6, CYP2E1, CYP2J2, CYP3A4, CYP3A5, and CYP4A11. Human liver microsomes (1 mg of microsomal protein/ml) or recombinant P450 enzymes (100 pmol of P450/ml) were preincubated with [14C]vildagliptin (47 M, 0.5% final DMSO concentration, v/v) in 100 mM potassium phosphate buffer, pH 7.4, and 5 mM MgCl2, final concentrations, at 37°C for 3 min. The reactions were initiated by the addition of NADPH (1 mM, final concentration) and incubated for 30 min; the reactions were then quenched by the addition of cold acetonitrile. The precipitated protein was removed by centrifugation, and an aliquot of each sample was analyzed by HPLC with in-line radioactivity detection as described above.

**P450 Inhibition Assay by Vildagliptin and M207.** The ability of vildagliptin and its metabolite M207 to inhibit P450 enzyme activity was assessed using pooled human liver microsomes (n = 50 donors, mixed gender; Xenotech, LLC, Lenexa, KS). To determine individual P450 activities, several probe substrate activities that were used to be known that are P450 enzyme-selective. The reactions used and corresponding probe substrate concentrations included phenacetin O-deethylation (5 μM, CYP1A2), bupropion hydroxylation (25 μM, CYP2B6), paclitaxel 6α-hydroxylation (10 μM, CYP2C8), diclofenac 4′-hydroxylation (5 μM, CYP2C9), S-mephentoin 4′-hydroxylation (15 μM, CYP2C19), bufuralol 1′-hydroxylation (5 μM, CYP2D6), chloroxazone 6-hydroxylation (10 μM, CYP2E1), and midazolam 1′-hydroxylation (5 μM, CYP3A4/5). The probe concentrations used were less than or approximately equal to their reported Km values. The conditions for each probe reaction were previously established to ensure linearity with time and protein concentration and to limit probe substrate turnover to ~<10% (results not shown). Increasing concentrations of the vildagliptin or authentic synthetic M207 (up to 100 μM) were incubated at 37°C individually with human liver microsomes (0.2 or 0.5 mg/ml) and one probe substrate in (final concentration)
100 mM potassium phosphate buffer, pH 7.4, 1 mM NADPH, 5 mM MgCl2, 1 mM EDTA, and 0.2% DMSO. After incubation, the reactions were quenched by addition of an equal volume of cold acetonitrile. Probe substrate turnover was determined by LC/MS/MS analysis (PE Sciex API300 mass spectrometer; Applied Biosystems, Foster City, CA; Shimadzu LC, Shimadzu, Kyoto, Japan) of metabolite formation. Reference standards for probe metabolites were obtained from commercial sources as follows: acetalopin (Sigma-Aldrich, St. Louis, MO); 1'-hydroxybufuralol, hydroxybufpropion, 6-hydroxychloroxazone, 4'-hydroxy-S-mephenytoin, and 1'-hydroxymidazolam (Ultrafine Chemicals, Manchester, UK); and 6-hydroxypaclitaxel and 4'-hydroxydocetaxel (BD Biosciences, San Jose, CA). Chromatographic separation was achieved on a Supelco (Bellefonte, PA) Discovery DP-Amide C16 column (50 × 2.1 mm, 4 μm, 0.3 ml/min flow rate, 25°C). The chromatographic solvents were as follows: A = 0.1% formic acid in 10 mM ammonium acetate, pH 4.7, B = acetonitrile; the gradient elution program (%B) was A:0→1 min (5%), 1→4 min (from 5% to 95%), 4→6 min (from 95% to 5%). Probe metabolites derived from phenacetin, bupropion, midazolam, bufuralol, and paclitaxel were analyzed using ESI in positive ion mode, whereas the metabolites of the remaining probes (diclofenac, chloroxazone, S-mephenytoin) were analyzed in negative ion mode.

**UDP Glucuronosyltransferase Enzyme Involvement in the Glucuronidation of Vildagliptin.** The enzymes involved in the glucuronidation of vildagliptin to form M20.2 were determined using a panel of recombinant human UDP glucuronosyltransferase (UGT) enzymes, including UGT1A1, UGT1A3, UGT1A4, UGT1A6, UGT1A7, UGT1A8, UGT1A9, UGT1A10, UGT2B4, UGT2B7, UGT2B15, and UGT2B17 (BD Gentest). In the initial assessment, incubations (100 μl, 37°C) consisted of (final concentrations): vildagliptin (20 μM), UDP-glucuronic acid (5 mM), alamethicin (0.25 mg/mg protein), enzyme protein (1 mg/ml), MgCl2 Tris-HCl buffer (pH 7.6, 50 mM), and acetonitrile (<0.2%). The enzyme protein had been preincubated with the alamethicin for 15 min on ice immediately before the experiments. The reactions were initiated by the addition of UDP-glucuronic acid after a 3-min preincubation and terminated after 60 min by the addition of acetonitrile (200 μl). The incubation samples were evaporated, reconstituted in 100 μl of 10:90 (v/v) acetonitrile/water, and centrifuged at ~4000g (10 min). A 25-μl aliquot was analyzed by LC/MS. The chromatographic separation was achieved using an Ace3 C18 (50 mm, 0.25 ml/min flow rate, 35°C). The chromatographic solvents were as follows: A = 0.1% formic acid in 10 mM ammonium acetate, pH 4.7, B = acetonitrile; the gradient elution program (%B) was A:0→1 min (5%), 1→4 min (from 95% to 5%), 4→6 min (from 95% to 5%). Probe metabolites derived from phenacetin, bupropion, midazolam, bufuralol, and paclitaxel were analyzed using ESI in positive ion mode, whereas the metabolites of the remaining probes (diclofenac, chloroxazone, S-mephenytoin) were analyzed in negative ion mode.

**Plasma and Blood Distribution of Vildagliptin.** The mean plasma protein binding of vildagliptin in humans was 49.0% (30.0–70.0%). The mean plasma protein binding of vildagliptin in human recombinant DPP-IV (expressed in Sf9 cells; Sigma-Aldrich) in Tris-HCl buffer (50 mM, pH 8.0) at 37°C. After 60 min, the reaction was terminated by the addition of acetonitrile (200 μl). The incubation samples were evaporated, reconstituted in 100 μl of 10:90 (v/v) acetonitrile/water, and centrifuged at ~4000g (10 min). A 25-μl aliquot was analyzed by LC/MS. The LC/MS method was as described above (see UGT involvement).

**Pharmacokinetic Analysis.** The following pharmacokinetic variables were determined by fitting the concentration-time profiles to a noncompartmental model with an iterative nonlinear regression program (WinNonlin software version 4.0; Pharsight, Mountain View, CA): area under the curve or plasma drug concentration-time curve between time 0 and time t (AUC0-t); until time AUC0-∞; t1/2; until time highest observed drug concentration (tmax); apparent terminal half-life (t1/2); apparent volume of distribution of parent drug (Vz/F) calculated as dose/AUC × k0, where F is bioavailability and k0 is the terminal rate constant; and apparent clearance (CL/F), calculated as dose/AUC0-∞.

**Results**

**In Vitro Human Blood Distribution and Protein Binding.** The mean human blood/plasma ratio (Cb/Cp) and fraction of [14C]vildagliptin bound to red blood cells (fBC) were 1.0 and 0.44, respectively, indicating approximately equal distribution between plasma and blood cells. The blood distribution was independent of concentration between 10 and 10,000 ng/ml.

The mean plasma protein binding of vildagliptin in humans was low (9.3%) and also independent of concentration. The nonspecific binding of the compound to centrifuge tubes and/or membranes was low (<1%), suggesting that ultrafiltration is a suitable method. In addition, M20.7 showed no plasma protein binding in humans over the concentration range of 10 to 1000 ng/ml and was independent of concentration.

**Absorption.** The absorption of vildagliptin was rapid after oral administration, with the peak plasma concentration of vildagliptin observed at an average of 1.1 h (range, 0.5–2 h). The percentage of drug absorbed was estimated to be at least 85.4%, because this amount of the radioactivity was recovered in urine.

**Pharmacokinetics of Vildagliptin and Total Radioactivity.** The mean plasma concentration-time profiles and pharmacokinetic parameters of total radioactivity and unchanged vildagliptin in healthy male volunteers after a single oral dose of [14C]vildagliptin are shown in Fig. 2 and Table 1, respectively. The highest concentrations in plasma (Cmax) were achieved at 2.1 h postdose with the mean value 594 ng-Eq/ml (total radioactivity) and at 1 h postdose with the mean value of 397 ng/ml (vildagliptin) in all four subjects. Radioactivity and parent levels at 48 h were below the limit of quantification. The terminal elimination half-life (t1/2) of radioactivity and vildagliptin averaged 4.6 and 2.8 h, respectively. Based on AUC0-∞ values, approximately 25.7 and 55% of the circulating radioactivity were attributable to unchanged vildagliptin and its major metabolite M20.7.
respectively. In addition, mean blood-to-plasma ratios of radioactivity calculated at specific time points (between 0.25 and 1 h) averaged near 1.1, indicating that vildagliptin distributed almost equally between blood cells and plasma as the main circulating component was the parent drug at the early time points, consistent with the in vitro finding (Cp/Cv ratio of vildagliptin ~1). However, the total radioactivity AUCl/AUCp ratio was 0.64, suggesting that metabolite(s) should be distributed more to plasma than blood cells. The CL/F and Vz/F values of vildagliptin were 65.2 l/h and 269 liters, respectively. In addition, mean blood-to-plasma ratios of radioactivity were calculated (41 h/L) by (He et al., 2007a). A measured Vc value has not been reported in the literature, but Vc can be estimated to be 229 liters based on data from this study.

Excretion and Mass Balance in Urine and Feces. After a single p.o. 100-mg dose of [14C]vildagliptin, radioactivity was excreted predominantly in the urine (Table 2). At 168 h after dosing, the excretion in urine and feces averaged 85.4 ± 4.4 and 14.8 ± 3.5% of the administered dose, respectively. In total, the cumulative excretion of radioactivity was complete in all four subjects, averaging 100 ± 1.10%. Elimination of radioactivity was rapid. More than 90% of the entire radioactivity recovered in urine and feces was excreted in the first 48 h after dose administration.

Metabolite Profiling. Tables 3 and 4 summarize the pharmacokinetics of vildagliptin and its metabolites in plasma and percentage of vildagliptin and its metabolites in excreta, respectively, after a single p.o. 100-mg dose of [14C]vildagliptin to humans. A representative HPLC radiochromatogram of circulating metabolites is shown in Fig. 3A. In plasma, major circulating components were unchanged drug and M20.7 (a carboxylic metabolite), accounting for 25.7% (vildagliptin) and 55% (M20.7) of the total plasma exposure. At early time points (up to 1 h) postdose, the predominant radiolabeled plasma component was vildagliptin, accounting for 70.2 to 88.3% of the total radioactivity. At later time points (12–24 h), the predominant component was M20.7, accounting for 78.4 to 89.9% of the total radioactivity. Other metabolites detected in plasma included M15.3 (carboxylate metabolite formed from hydrolysis of the amide bond) and M20.2 (glucuronic acid conjugate of vildagliptin), accounting for 8.1 and 9.3%, respectively, of the total plasma exposure.

Representative HPLC radiochromatograms for metabolites in urine and feces are shown in Fig. 3, B and C, respectively. Approximately 27.1% of the administered dose was excreted as unchanged drug in urine and feces. In addition to the unchanged drug, five metabolites were radiochemically quantifiable in the urine or feces. In urine, M20.7 represented the major metabolite (49.6% of the administered dose), and all the other metabolites were minor (each <4.5% of the dose). Unchanged vildagliptin in urine averaged at 22.6% of the dose. In the feces, M20.7 was also the major metabolite, accounting for 6.89% of the dose; unchanged vildagliptin accounted for 4.54% of the dose. In summary, the urinary and fecal metabolites totally accounted for >90% of the total radioactivity recovered.

In Vitro Metabolism in Human Liver Slices. Incubation of [14C]vildagliptin with human liver slices formed three metabolites: M15.3, M20.7, and M20.2 (formed at late time points in the incubations at 20 μM substrate concentration).

Metabolite Characterization by Mass Spectrometry. Metabolite structures were characterized by LC/MS/MS using a combination of full and product ion scanning techniques. The structure of major metabolites, where possible, was supported by comparisons of their retention times on HPLC and mass spectra with those of synthetic standards (vildagliptin, M20.2, M20.7, and M15.3).

Vildagliptin displayed a protonated molecular ion (MH+ at m/z 304. The product ion spectrum of m/z 304 showed major fragment ions at m/z 97 and 154 (Fig. 4). The ion at m/z 154 corresponded to the amino acyl pyrrolidine carbonitrile moiety, and m/z 97 corresponded to the pyrrolidine carbonitrile moiety.

Metabolite M15.3. M15.3 was found in urine, feces, and plasma. Mass spectral analysis showed a protonated molecular ion at m/z 226 [78 atomic mass units (amu) lower than the parent drug]. The product ion mass spectrum of m/z 226 showed fragment ions at m/z 76 and 151. The ion at m/z 151 corresponded to the hydroxy adamantyl moiety, suggesting modification had occurred at the other half of vildagliptin. Based on comparison of the HPLC retention time and CID spectrum with the synthetic standard, M15.3 was identified as the carboxylic acid metabolite resulting from hydrolysis of the amide bond.

Metabolite M20.2. M20.2 was found in urine, feces, and plasma. Its full-scan mass spectrum displayed a protonated molecular ion at m/z 480, 176 amu higher than that of the parent drug, suggesting that it was a glucuronide conjugate. Based on comparison of the HPLC retention time and CID spectrum with the synthetic standard, M20.2 was identified as the O-glucuronide of vildagliptin.

Metabolite M20.7. M20.7 was found in urine, feces, and plasma. Its full-scan mass spectrum displayed a protonated molecular ion at m/z 323, 19 amu higher than that of the parent drug. The product ion mass spectrum of m/z 323 showed fragment ions at m/z 305, 173, and 116. The ion at m/z 305 occurred from the loss of water in the molecule. The ions at m/z 173 and 116 were 19 amu higher than those observed in the parent drug (m/z 154 and 97, respectively), suggesting modification had occurred at the pyrrolidine carbonitrile moiety. Based on comparison of the HPLC retention time and CID spectrum with the synthetic standard, M20.7 was identified as the glucuronic acid conjugate from hydrolysis of the amide bond.

TABLE 2
Cumulative excretion of [14C] radioactivity in urine and feces after a single p.o. 100-mg dose of [14C]vildagliptin to humans, mean ± S.D.

<table>
<thead>
<tr>
<th>Time Period (h)</th>
<th>Urine</th>
<th>Feces</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–24</td>
<td>72.7 ± 4.8</td>
<td>1.37 ± 2.0</td>
<td>73.7 ± 4.8</td>
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<tr>
<td>0–48</td>
<td>81.6 ± 4.2</td>
<td>9.33 ± 8.0</td>
<td>90.9 ± 4.2</td>
</tr>
<tr>
<td>0–72</td>
<td>83.6 ± 4.4</td>
<td>13.2 ± 4.8</td>
<td>95.4 ± 4.4</td>
</tr>
<tr>
<td>0–96</td>
<td>84.7 ± 4.4</td>
<td>14.3 ± 3.7</td>
<td>96.6 ± 4.4</td>
</tr>
<tr>
<td>0–168</td>
<td>85.4 ± 4.4</td>
<td>14.8 ± 3.5</td>
<td>100 ± 1</td>
</tr>
</tbody>
</table>

TABLE 3
Pharmacokinetic parameters (mean ± S.D.) of vildagliptin and its metabolites in plasma after a single p.o. 100-mg dose of [14C] vildagliptin

<table>
<thead>
<tr>
<th>Pharmacokinetic Parameters</th>
<th>M15.3</th>
<th>M20.2</th>
<th>M20.7</th>
<th>Vildagliptin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cmax (ng/ml)</td>
<td>54.9 ± 20.4</td>
<td>90.9 ± 23.1</td>
<td>230 ± 50</td>
<td>399 ± 100</td>
</tr>
<tr>
<td>tmax (h)</td>
<td>3.8 ± 1.5</td>
<td>1.8 ± 0.5</td>
<td>6.0 ± 0.0</td>
<td>1.3 ± 0.5</td>
</tr>
<tr>
<td>AUCl-168 h (ngEq · h/ml)</td>
<td>489 ± 166</td>
<td>559 ± 120</td>
<td>3310 ± 1900</td>
<td>1550 ± 520</td>
</tr>
<tr>
<td>AUCl0–168 (ng/ml)</td>
<td>490 ± 164</td>
<td>572 ± 124</td>
<td>3350 ± 970</td>
<td>1550 ± 510</td>
</tr>
<tr>
<td>AUC (%)</td>
<td>8.1 ± 0.3</td>
<td>9.3 ± 0.5</td>
<td>55 ± 2.5</td>
<td>25.7</td>
</tr>
</tbody>
</table>

a The abbreviation definitions for pharmacokinetic parameters, e.g., Cmax, tmax, and AUC are denoted in the Pharmacokinetic Analysis under Materials and Methods.

b Vildagliptin and its metabolites were determined by HPLC with radio detection.
standard, M20.7 was identified as the carboxylic acid metabolite resulting from hydrolysis of the cyano moiety.

Metabolite M20.9. M20.9 was found in urine and plasma. Its full-scan MS displayed a protonated molecular ion at \( m/z \) 336, 32 amu higher than that of the parent drug. The product ion mass spectrum of \( m/z \) 336 showed fragment ions at \( m/z \) 318, 186, and 129. The ion at \( m/z \) 318 occurred from the loss of water in the molecule. The ions at \( m/z \) 186 and 129 were 32 amu higher than those observed in the parent drug (\( m/z \) 154 and 97, respectively), suggesting modification (dioxygenation) had occurred at the pyrrolidine carbonitrile moiety. Based on these data, M20.9 was tentatively identified as dihydroxy vildagliptin.

Metabolite M21.6. M21.6 was found in urine and plasma. Its full-scan MS displayed a protonated molecular ion at \( m/z \) 311, 7 amu higher than that of the parent drug (\( m/z \) 304). The product ion mass spectrum of \( m/z \) 311 showed fragment ions at \( m/z \) 293, 186, and 129. The ion at \( m/z \) 186 occurred from the loss of water in the molecule. The ions at \( m/z \) 129 were 32 amu higher than those observed in the parent drug (\( m/z \) 97), suggesting modification (dioxygenation) had occurred at the pyrrolidine carbonitrile moiety. Based on these data, M21.6 was tentatively identified as dihydroxy vildagliptin.

**TABLE 4**

<table>
<thead>
<tr>
<th>Matrices</th>
<th>M15.3</th>
<th>M20.2</th>
<th>M20.7</th>
<th>M20.9</th>
<th>M21.6</th>
<th>Vildagliptin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine</td>
<td>3.40 ± 1.1</td>
<td>4.40 ± 0.47</td>
<td>49.6 ± 3.6</td>
<td>0.95 ± 0.18</td>
<td>0.64 ± 0.50</td>
<td>22.6 ± 5.3</td>
</tr>
<tr>
<td>Feces</td>
<td>0.26 ± 0.07</td>
<td>—</td>
<td>6.89 ± 2.0</td>
<td>—</td>
<td>—</td>
<td>4.54 ± 2.9</td>
</tr>
<tr>
<td>Urine + feces</td>
<td>3.7 ± 1.1</td>
<td>4.4 ± 0.5</td>
<td>56.5 ± 3.5</td>
<td>1.0 ± 0.2</td>
<td>0.6 ± 0.5</td>
<td>27.1 ± 2.5</td>
</tr>
</tbody>
</table>

—, not detected.

FIG. 3. Representative radiochromatograms of vildagliptin in plasma 6 h postdose (A), urine 0 to 48 h (B), and feces 0 to 96 h (C) after a single oral dose of \( [1^4C] \)vildagliptin to humans. Note that M15.3, M20.2, and M20.7 were identified by retention times and CID product ion spectra that were similar to those of their synthetic standards, whereas the other metabolite structures were tentatively assigned as described under Results.
higher than that of the parent drug. Because its protonated molecular ion is an odd number, the molecule must contain an even number of nitrogen. The product ion mass spectrum of $m/z$ 311 showed fragment ions at $m/z$ 293, 161, and 143. The ion at $m/z$ 161 was 7 amu higher than that observed in the parent drug ($m/z$ 154), suggesting modification had occurred at the pyrrolidine carbonitrile moiety. Based on these data, M21.6 was identified as the carboxylic acid metabolite resulting from opening of the pyrrolidine moiety.

**Identification of P450 Enzymes Involved in the Metabolism of Vildagliptin.** The oxidative metabolism of $[^{14}C]$vildagliptin at 47 Ci/H9262 M was evaluated in human liver microsomes and by individual P450 enzymes. The results indicated that $[^{14}C]$vildagliptin was not metabolized in human liver microsomes nor by any P450 enzymes examined to any quantifiable extent in the presence of NADPH.

**DPP-4-Catalyzed Conversion of Vildagliptin to Form M20.7.** Incubation of vildagliptin (0.1 Ci/H9262 M) with recombinant human DDP-4 (0.1 mg/ml) for 60 min resulted in approximately 1.5% turnover to the carboxylic acid metabolite, M20.7, supporting the contribution of this enzyme to this metabolic pathway.

**Identification of the UGT Enzymes Involved in Formation of M20.2.** Incubation of vildagliptin (20 $\mu$M) with a panel of recombinant UGT enzymes indicated that vildagliptin O-glucuronide (M20.2) seems to be primarily catalyzed by UGT2B7. Minor contributions of UGT enzymes UGT2B17 and UGT2B4 were also observed (Fig. 6).

**Inhibition of P450 by Vildagliptin and M20.7.** Vildagliptin and M20.7 showed little or no inhibition of P450 enzyme activities (IC$_{50}$ values >100 $\mu$M), including CYP1A2, CYP2B6, CYP2C8, CYP2C9, CYP2C19, CYP2D6, CYP2E1, and CYP3A4/5, when tested at concentrations of up to 100 $\mu$M.

**Discussion**

In the present study, the absorption and disposition of vildagliptin were investigated in four male healthy volunteers after a single p.o. 100-mg dose of $[^{14}C]$vildagliptin (47 $\mu$Ci), which was well tolerated in all the subjects. Vildagliptin was rapidly absorbed with a short mean $t_{\text{max}}$ of 1.1 h. Based on the amount of dose recovered in urine (85.4%) and with the finding of only a small amount of unchanged drug in feces (4.54% of the dose), vildagliptin absorption in humans was estimated to be at least 85.4%. This result is in agreement with the high absolute oral bioavailability of vildagliptin determined in healthy volunteers (85%) based on the single i.v. 25-mg dose (He et al., 2007a), suggesting a low first-pass metabolism and high intestinal absorption.

At $t_{\text{max}}$ for the radioactivity, vildagliptin accounted for approximately 67% of the radioactivity in plasma. Thereafter, the parent drug concentrations decreased more rapidly than the total radioactivity, reflecting the increasing presence of metabolites in the circulation, predominantly metabolite M20.7. The terminal half-lives of both parent drug (average $t_{1/2}$ 2.8 h) and radioactivity (average $t_{1/2}$ 4.6 h) in plasma were short, consistent with previous findings in healthy volunteers and patients (He et al., 2007b). However, this short half-life does not affect the DPP-4 inhibition as vildagliptin inhibited DPP-4 up to 24 h (90%) (He et al., 2007b).

Four metabolic pathways are involved in the in vivo biotransformation of vildagliptin (Fig. 5): 1) cyano group hydrolysis, leading to
formulation of M20.7; 2) amide bond hydrolysis, leading to formation of M15.3; 3) glucuronidation, leading to formation of M20.2; and 4) oxidation on the pyrrolidine, leading to the formation of M20.9 and M21.6. The latter is thought to be derived from the decarboxylation of M20.7 and/or the loss of cyano group of the parent drug.

The primary route of elimination of radioactivity was via urinary excretion (85.4%), and vildagliptin was mainly eliminated in humans through hydrolysis reactions and excretion of unchanged drug. Hydrolysis of the cyano group, resulting in the M20.7, accounted for elimination of 56.5% of the dose (49.6% in urine and 6.89% in feces). M20.7 was not detected in the liver microsome incubation in the presence of NADPH, suggesting P450 is not involved in the hydrolysis of the cyano group. However, M20.7 was observed in the human liver slice, confirming the hydrolysis occurs in liver, possibly in the cytosolic fraction. Furthermore, based on findings from the in vivo metabolism data in DPP-4-deficient rats (He et al., 2009), approximately 20% of the cyano group hydrolysis reaction (formation of main metabolite M20.7) may be attributable to the DPP-4 enzyme. Indeed, the formation of M20.7 was found to be catalyzed by human recombinant DDP-IV in vitro, supporting the contribution of this enzyme to this metabolic transformation.

Approximately 27.1% of vildagliptin was excreted as unchanged (22.6% in urine and 4.54% in feces). Given negligible protein binding (9.3% for vildagliptin and no binding for M20.7), the renal clearance was estimated to be 14.6 and 15.0 l/h for vildagliptin and M20.7, respectively, using the ratio of the total amount in urine (22.6 mg for vildagliptin and 49.6 mg for M20.7) relative to total AUC in plasma (1550 ng·h/ml for vildagliptin and 3350 ng·h/ml for M20.7). Similar renal clearances of vildagliptin (13.4 l/h) have also been reported after an intravenous dose (He et al., 2007a). With the protein binding correction (fu = 90.7% for vildagliptin and 100% for M20.7), the unbound renal clearance of vildagliptin and M20.7 was estimated to be 16 and 15 l/h, respectively. Thus, the unbound renal clearance of vildagliptin and M20.7 was 167 and 150% higher than the glomerular filtration rate (6.0 l/h) in healthy humans, respectively (Rule et al., 2004), suggesting possible involvement of renal transporters in the elimination process.

Vildagliptin was also metabolized to form M20.2 (vildagliptin O-glucuronide), only accounting for 4.4% of the dose. The direct glucuronidation of vildagliptin was found to be primarily catalyzed by UGT2B7, with minor contributions by UGT2B17 and UGT2B4 (Fig. 6). The formation of minor metabolites, M20.9 and M21.6, is probably mediated by P450s. However, these pathways accounted for only approximately 1.6% of the dose, indicating a lack of significant P450 involvement. The oxidative metabolism of vildagliptin was confirmed in human liver microsomes and by individual human recombinant P450 enzymes. Consistent with the in vivo findings, results from the in vitro studies indicated that vildagliptin was not metabolized by P450 enzymes to any quantifiable extent. Therefore, it is unlikely that inhibitors or inducers of P450 enzymes would have a significant drug-drug interaction effect on the metabolic clearance of vildagliptin in humans. Moreover, as both vildagliptin and M20.7 showed no inhibition on P450 isoenzyme activities (IC_{50} values \( \geq 100 \mu M \)) and given that the plasma C_{max} values of vildagliptin and M20.7 in humans after a single oral dose of 100 mg (the clinical efficacious dose) is much lower (2–10 \( \mu M \)) than the IC_{50} values, it is unlikely that vildagliptin and M20.7 would inhibit the metabolic clearance of potential comedication metabolized by P450 enzymes.

The elimination of vildagliptin in humans was comparable with that in rats and dogs, being primarily metabolized to M20.7 and excreted as unchanged drug (He et al., 2009). The other major pathway in dogs was the hydrolysis at the amide bond (M15.3). Overall, all the metabolites observed in human plasma and excreta were also found in rat and dog.

In summary, vildagliptin is rapidly absorbed in fasting humans after a single oral dose of 100 mg; the absorption was high (\( > 85.4% \)), and dose recovery was complete. The major circulating components in the plasma were unchanged drug and metabolite M20.7. Elimination of vildagliptin in humans mainly involved renal excretion of unchanged parent drug and cyano group hydrolysis with little P450 involvement, suggesting a low potential for drug-drug interaction when coadmini-
istered with P450 inhibitors/inducers. Moreover, vildagliptin is unlikely to inhibit the metabolic clearance of comedication metabolized by P450 enzymes.

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References
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