Pharmacokinetics and Metabolism in Rats, Dogs, and Monkeys of the Cathepsin K Inhibitor Odanacatib: Demethylation of a Methylsulfonyl Moiety as a Major Metabolic Pathway


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ABSTRACT:

Odanacatib is a potent cathepsin K inhibitor that is being developed as a novel therapy for osteoporosis. The disposition and metabolism of odanacatib were evaluated in rats, dogs, and rhesus monkeys after intravenous and oral administration of [14C]odanacatib. Odanacatib was characterized by low systemic clearance in all species and by a long plasma half-life in monkeys (18 h) and dogs (64 h). The oral bioavailability was dependent on the vehicle used and ranged from 18% (monkey) to 100% (dog) at doses of 1 to 5 mg/kg, using nonaqueous vehicles. After intravenous and oral administration to intact rats and monkeys >90% of the dose was recovered, mainly in the feces. Studies in bile duct-cannulated animals indicated that biliary secretion was the major mode of elimination of radioactivity; odanacatib also underwent some intestinal secretion. In monkeys, odanacatib was almost completely eliminated by metabolism; metabolism also played a major role in the clearance of odanacatib in rats and dogs. The major metabolic pathways were methyl hydroxylation (formation of M8 and its derivatives), methyl sulfone demethylation (formation of M4 and its derivative M5), and glutathione conjugation (formation of the cyclized cysteinylglycine adduct M6 after addition of glutathione to the nitrile group of odanacatib). The major metabolites in rats [M4 (parent-14 Da) and M5 (oxygenated derivative of M4)] were determined to arise from a novel pathway that involved oxidative demethylation of the methylsulfonyl moiety of odanacatib. Overall, odanacatib displayed species-dependent metabolism, which explains, at least in part, the divergent plasma half-life observed.

Introduction

Osteoporosis, a disease in which bone resorption exceeds bone formation, is associated with a high fracture risk. Osteoporosis affects more than 10 million individuals in the United States alone and is prevalent in postmenopausal women (Poole and Compston, 2006; US Health and Human Services, 2004). Bone resorption involves the acidic dissolution of bone mineral and the proteolytic degradation of bone matrix, primarily of type I collagen. The most abundant collagenase in osteoclasts, the cells responsible for bone resorption, is cathepsin K, a cysteine protease active at acidic pH (Drake et al., 1996; Zhao et al., 2009).

Odanacatib is a cathepsin K inhibitor under development for the treatment of osteoporosis (Gauthier et al., 2008; Stoch et al., 2009). Odanacatib is orally active with an in vitro EC50 of 0.2 nM, a selectivity of ≥300-fold against other known human cathepsins, and a half-life suitable for weekly dosing. Odanacatib prevents loss of bone mineral density in ovariectomized rabbits (Pennypacker et al., 2011) and rhesus monkeys (Masarachia et al., 2007). Histomorphometric analyses in both species suggested that odanacatib treatment preserved normal bone biomechanical properties. In a dose-finding clinical study, odanacatib increased bone mineral density and reduced biochemical markers of bone resorption in postmenopausal women over a period of 3 years (Eisman et al., 2011). Unlike other antiresorptive treatments, odanacatib only transiently inhibited the activity of markers of bone formation, which returned to baseline after approximately 2 years. The effects on biochemical markers (urinary N-telopeptide and C-telopeptide cross-linked collagen type I) were reversible after discontinuation of treatment. There were similar overall rates of adverse experiences between patients treated with odanacatib compared with those treated with placebo.

Understanding the metabolism and disposition of a new drug is an important element in its safety and efficacy evaluation. In the present report, the pharmacokinetics, metabolism, and routes of excretion of odanacatib in rats, dogs, and monkeys are reported.

Materials and Methods

Chemicals. [14C]Odanacatib and authentic standards of metabolites M4, M5, and M8 and the hydroxymethylsulfone derivative of odanacatib were synthesized at Merck Research Laboratories (Rahway, NJ) and Merck-Frosst (Montreal, QC, Canada); the synthesis methods for M4, M5, and M8 can be found at http://dmd.aspetjournals.org.

ABBREVIATIONS: MK-0822, N-1-{(1-cyanocyclopropyl)-4-fluoro-N-(1S)-2,2,2-trifluoro-1-[4′-(methylsulfonyl)biphenyl-4-yl]ethyl}-L-leucinamide; HPLC, high-performance liquid chromatography; LC, liquid chromatography; MS/MS, tandem mass spectrometry; AUC, area under the plasma concentration versus time curve; MS, mass spectrometry; RAD, radioactivity detector; CNS, central nervous system.
found in the supplemental data). To make the hydroxymethylsulfone derivative of odanacatib, the sodium sulfinate salt of the synthetic standard of M4 was reacted with aqueous formaldehyde (37%), and the product, hydroxymethylsulfone odanacatib, was then purified by preparative HPLC using an acidic mobile phase and was isolated as the trifluoroacetic acid salt. Stock solutions of the salt were prepared in methanol for studies conducted with this derivative of odanacatib. [14C]Odanacatib (specific activity of 146.9 Ci/mg) was synthesized with 14C distributed over the six carbons within the phenyl ring bearing the methylsulfonyl functional group (Fig. 1). All other materials were of HPLC or analytical grade.

Pharmacokinetic and Mass Balance Studies. All animal studies were performed using protocols approved by the Merck Institutional Animal Care and Use Committee. Studies were conducted in male Sprague-Dawley rats (n = 4 per route of administration) and male rhesus monkeys (n = 4; intravenously first and then orally after a 1-week washout period), which were given an intravenous (1 mg/kg) or oral (5 mg/kg) dose of [14C]odanacatib. The intravenous dose was dissolved in dimethyl sulfoxide at concentrations of 2.5 mg/ml (for rats) and 10 mg/ml (for monkeys), and the oral dose was dissolved in PEG400 (2.5 mg/ml) and suspended in Imwitor-Tween 80 (1:1) [5 mg/ml] for dosing rats and monkeys, respectively. The average amount of radioactivity administered to each animal was 155.4 ± 9.1 μCi/kg (rat) and 8.2 ± 0.6 μCi/kg (monkey). Animals were fasted overnight before dosing. In rats, jugular cannulas were surgically implanted and were used for both administration of the intravenous dose and collection of blood. In monkeys, the intravenous dose was administered via either the cephalic or saphenous vein and blood collection was via cannulas implanted in either the iliocaval or femoral artery. Beagle dogs (n = 2) were also given an intravenous (2 mg/kg) and oral (1 mg/kg) dose of nonlabeled odanacatib in a non-crossover fashion. The intravenous dosing solution was formulated in 60% PEG200 in water (2 mg/ml), and the drug was suspended in 10% PEG200 in methyl cellulose for oral dosing (0.2 mg/ml). An additional group of rats (10 mg/kg, n = 2) and dogs (5 mg/kg, n = 2) was dosed orally using 0.5% methyl cellulose in water as the vehicle. Plasma was prepared by centrifugation immediately after collection of blood samples. Plasma samples were then stored at −20°C until analysis. Urine (rat and monkey) was collected on dry ice, and urine and feces (rat and monkey) samples were stored at −20°C.
Quantitative analysis of odanacatib in plasma. The concentration of odanacatib in rat and monkey plasma was determined by LC-MS/MS in the positive ion mode using the TurbolonSpray interface. Odanacatib and the internal standard (MK1) were isolated from plasma (50 μl) by liquid-liquid extraction using methyl tert-butyl ether. The extract was evaporated (37°C) to dryness, and the residue was reconstituted with 40:60 acetonitrile-water containing 0.1% formic acid (100 μl) and 5-μl aliquots were injected into the LC-MS/MS system. Analysis was performed on a Scie Xi 4000 mass spectrometer interfaced to a 200 series pump (PerkinElmer Life and Analytical Sciences, Waltham, MA). The column used was a Prodigy ODS3 (2 × 50 mm, 5 μm; Phenomenex, Torrance, CA); the mobile phase consisted of 0.1% formic acid in water and 0.1% formic acid in acetonitrile. Quantitation was based on selected reaction monitoring of the following precursor/product ion pairs: m/z 526.1 → 313.2 (odanacatib); and m/z 482.2 → 313.2 (MK1). The lower limit of quantitation was 4 and 0.4 nM in rat and monkey plasma, respectively. The assay was linear over the concentration range of 0.4 to 950 nM, and the extraction efficiency was 52 to 64% for both odanacatib and the internal standard. A slightly different method was used for quantitation of odanacatib in dog plasma. An aliquot of plasma (100 μl) containing the internal standard (MK2) was treated with acetonitrile (200 μl) and centrifuged. The supernatant (25 μl) was injected into the LC-MS/MS system and analyzed by positive ion electrospray ionization MS/MS. The lower limit of quantitation was 19 nM.

Calculation of pharmacokinetic parameters. Pharmacokinetic parameters were calculated by established noncompartmental methods. The area under the plasma concentration versus time curve (AUC) was determined using Watson by comparing each animal’s intravenous and oral AUC. The dog data were intravenous AUC. In the case of monkeys, the bioavailability was calculated by comparing the individual oral AUC with the mean intravenous AUC. In the case of monkeys, the bioavailability was calculated by comparing each animal’s intravenous and oral AUC. The dog data were obtained using the mean intravenous and oral AUCs.

Tissue Distribution Study in Rats. The tissue distribution of radioactivity was determined after a single oral dose of [14C]odanacatib to male Long-Evans rats (n = 6) [conducted at Aptuit, Inc., Kansas City, MO]. The drug was formulated as a solution in PEG400 at a concentration of 150 μCi/5 mg/2 ml/kg animal. Animals (one animal per time point) were sacrificed at 2, 6, 24, 72, 168, and 672 h postdose. Blood was collected, plasma was isolated at specified time points (cardiac puncture immediately before sacrifice), and the carcasses were frozen for autoradiographic analysis. The distribution of radioactivity was determined by quantitative whole-body autoradiography with storage phosphor imaging plates (radioluminography; thickness of tissue slice was 40 μm). Concentrations of drug-derived radioactivity were determined in blood, plasma, tissues, and bodily fluids to evaluate tissue distribution and elimination of odanacatib-derived radioactivity. Whole blood and plasma were analyzed for total radioactivity by oxidation and/or liquid scintillation counting. The lower limit of quantitation for quantitative whole-body autoradiography was determined to be 0.96 nCi/g (0.030 μg Equ/g).

Excretion and Metabolism Studies. The in vivo metabolism of odanacatib was evaluated in bile duct-cannulated rats (n = 3), rhesus monkeys (n = 2), and dogs (n = 2), which were administered an intravenous dose of [14C]odanacatib to male Long-Evans rats (n = 6) [conducted at Aptuit, Inc., Kansas City, MO]. The drug was formulated as a solution in PEG400 at a concentration of 150 μCi/5 mg/2 ml/kg animal. Animals (one animal per time point) were sacrificed at 2, 6, 24, 72, 168, and 672 h postdose. Blood was collected, plasma was isolated at specified time points (cardiac puncture immediately before sacrifice), and the carcasses were frozen for autoradiographic analysis. The distribution of radioactivity was determined by quantitative whole-body autoradiography with storage phosphor imaging plates (radioluminography; thickness of tissue slice was 40 μm). Concentrations of drug-derived radioactivity were determined in blood, plasma, tissues, and bodily fluids to evaluate tissue distribution and elimination of odanacatib-derived radioactivity. Whole blood and plasma were analyzed for total radioactivity by oxidation and/or liquid scintillation counting. The lower limit of quantitation for quantitative whole-body autoradiography was determined to be 0.96 nCi/g (0.030 μg Equ/g).

TABLE 1
Pharmacokinetic parameters of odanacatib after oral administration

<table>
<thead>
<tr>
<th>Species</th>
<th>Dose</th>
<th>Cmax (μM)</th>
<th>tmax (h)</th>
<th>AUC0→∞ (μM·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat</td>
<td>5</td>
<td>2.2 ± 0.4</td>
<td>1.8 ± 1.5</td>
<td>36 ± 10</td>
</tr>
<tr>
<td>Dog</td>
<td>1</td>
<td>3.6</td>
<td>8</td>
<td>318 ± 122</td>
</tr>
<tr>
<td>Monkey</td>
<td>5</td>
<td>0.3 ± 0.1</td>
<td>6.0 ± 2.3</td>
<td>4.8 ± 1.8</td>
</tr>
</tbody>
</table>

TABLE 3
Recovery of radioactivity (% of radioactive dose) in urine and feces after oral (5 mg/kg) and intravenous (1 mg/kg) administration of [14C]odanacatib to rats and monkeys

<table>
<thead>
<tr>
<th>Route</th>
<th>Urine</th>
<th>Feces</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral</td>
<td>2.9 ± 0.3</td>
<td>88 ± 9.2</td>
<td>91 ± 9.2</td>
</tr>
<tr>
<td>Intravenous</td>
<td>3.7 ± 1.6</td>
<td>94 ± 1.8</td>
<td>98 ± 3.2</td>
</tr>
<tr>
<td>Monkey</td>
<td>5.8 ± 2.9</td>
<td>87 ± 6.0</td>
<td>93 ± 3.9</td>
</tr>
<tr>
<td>Intravenous</td>
<td>11 ± 3.0</td>
<td>81 ± 12</td>
<td>93 ± 12</td>
</tr>
</tbody>
</table>

96 h (rat and monkey) and 168 h (dog). The urine, bile, and feces samples were stored at −20°C until analysis.

Preparation of Samples for HPLC-MS/Radiochromatography. Aliquots of urine sample were centrifuged to remove particulate matter and analyzed directly without further purification by HPLC-MS/MS in conjunction with an on-line radioactivity detector (RAD). Aliquots of bile were diluted 1:1 with water, centrifuged, and analyzed by HPLC-MS/MS-RAD directly. For plasma samples, protein was precipitated with 2 volumes of acetonitrile. The samples were then vortex-mixed and centrifuged, and the supernatant was dried to near dryness on a TurboVap evaporator at 37°C. The residue was reconstituted in 80:20 mobile phase A/B and then analyzed by HPLC-MS/MS-RAD. Feces extracts were prepared by weighing approximately 1 g of aqueous feces homogenate into a vial followed by the addition of acetonitrile (3.0 ml) (recovery of radioactivity was >85%). The mixture was vortex-mixed and centrifuged, and the resulting supernatant was dried to near dryness on a TurboVap evaporator at 37°C. The residue was dissolved in 250 μl of 80:20 mobile phase A/B, and the sample was reconstituted to sediment any undissolved solid before HPLC-MS/MS-RAD analysis.

Radioactivity Measurement. Sample preparation. Weighed aliquots of bile and urine samples were directly counted in Ultima Gold by liquid scintillation counting. Likewise, aliquots of plasma were counted directly in Ultima Gold. To each feces sample, approximately 3 volumes of water/weight of feces was added, and the samples were homogenized using a Omni homogenizer. The total weight of the homogenate was recorded, and approximate 0.5-g aliquots were weighed into combustion cones and dried overnight in a laboratory hood. The samples were then combusted using a Packard model 307 oxidizer (PerkinElmer Life and Analytical Sciences).

Liquid scintillation counting. Samples were counted by liquid scintillation counting on a Packard TriCarb 2900 TR liquid scintillation counter (PerkinElmer Life and Analytical Sciences) using the transformed spectral index of the external standard as the quench-indicating parameter with automatic efficiency correction. For samples other than oxidized feces, an Ultima Gold quench curve was used, whereas for oxidized feces samples a toluene quench curve was applied.

LC-MS/MS Radiochromatographic Analysis. HPLC analysis was conducted on a HP1100 gradient system (Hewlett Packard, Palo Alto, CA) interfaced to a TSK Quantum mass spectrometer (Thermo Fisher Scientific, Waltham, MA). Separation was achieved on a Zorbax Rx C18 column (4.6 mm × 25 cm, 5 μm) using a mobile phase consisting of 10 mM aqueous ammonium acetate (solvent A) and 100% acetonitrile (solvent B) at a constant flow rate of 1.0 ml/min. The gradient was as follows: 0–5 min, 20% B; 5–10 min, 50% B; and 10–15 min, 100% B. Mass spectral analyses were

TABLE 2
Pharmacokinetic parameters of odanacatib after oral administration

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</tbody>
</table>

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TABLE 4

<table>
<thead>
<tr>
<th>Time</th>
<th>Bile</th>
<th>Feces</th>
<th>Urine</th>
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</thead>
<tbody>
<tr>
<td>0–24 h</td>
<td>41 ± 3.4</td>
<td>9.1 ± 1.7</td>
<td>7.0 ± 1.8</td>
</tr>
<tr>
<td>24–48 h</td>
<td>17 ± 1.7</td>
<td>11 ± 3.3</td>
<td>2.1 ± 1.3</td>
</tr>
<tr>
<td>48–72 h</td>
<td>5.3 ± 1.6</td>
<td>4.9 ± 3.9</td>
<td>0.9 ± 0.9</td>
</tr>
<tr>
<td>72–96 h</td>
<td>NS</td>
<td>2.0 ± 1.3</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>63 ± 2.8</td>
<td>27 ± 7.0</td>
<td>10 ± 3.7</td>
</tr>
</tbody>
</table>

% dose

- Bile: 5.6; N.S.; 0.7
- Feces: 4.9; 6.6; 0.5
- Urine: 5.9; 8.7; 0.6

TABLE 5

<table>
<thead>
<tr>
<th>Metabolite</th>
<th>MH⁺</th>
<th>MS/MS Fragments</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>508⁺ &gt; 299</td>
<td></td>
</tr>
<tr>
<td>M-2</td>
<td>556 &gt; 538, 518, 428, 313</td>
<td></td>
</tr>
<tr>
<td>M-3</td>
<td>718 &gt; 542, 460, 432, 313</td>
<td></td>
</tr>
<tr>
<td>M-4</td>
<td>512 &gt; 494, 492, 436, 385, 299, 177</td>
<td></td>
</tr>
<tr>
<td>M-5</td>
<td>528 &gt; 508, 452, 315, 177</td>
<td></td>
</tr>
<tr>
<td>M-6</td>
<td>687 &gt; 667, 611, 338</td>
<td></td>
</tr>
<tr>
<td>M-7</td>
<td>540 &gt; 520, 430, 313</td>
<td></td>
</tr>
<tr>
<td>M-8</td>
<td>526 &gt; 506, 450, 416, 313, 177</td>
<td></td>
</tr>
</tbody>
</table>

- MS/MS spectra are available in the supplemental data.
- 508⁺ is not the MH⁺ ion, but (MH⁺H₂O)⁺.
ocular, central nervous system (CNS), and reproductive tissues, tissue/plasma concentration ratios were greater than 1 in most tissues with measurable concentrations of radioactivity throughout the time course examined. High concentrations of radioactivity were associated with the alimentary canal contents, liver, adrenal glands, and harderian glands. Concentrations of radioactivity in the CNS were low (3% of plasma). The bone/plasma concentration ratios were 0.09, 0.11, and 0.06 at 2, 6, and 24 h postdose, respectively. By 168 h, elimination was essentially complete, indicating that odanacatib-related radioactivity is not selectively retained by melanin-containing tissues.

**Metabolite Profiles.** The identities of M4, M5, and M8 (the synthetic standard of M8 was a diastereomeric mixture not separable by the HPLC method used) were established by comparing the HPLC retention times and MS/MS spectra of the metabolites observed in bile, feces, and urine with those obtained from authentic standards. The structures of the other metabolites were proposed on the basis of full-scan MS and product ion spectra (Table 5 and supplemental data).

Rats. The fraction of the radioactive dose accounted for by metabolites (59.5%) and the parent compound (19%) is shown in Table 6; on the basis of this information, the contribution of metabolism and excretion of intact parent to the clearance of an intravenous dose of odanacatib was estimated to be 76 and 24%, respectively. A representative radiochromatogram obtained from rat bile is shown in Fig. 2, and the fraction of the dose accounted for by metabolites is shown in Table 6. The major metabolites in rats were M4 (sulfonic acid), M5 (sulfonic acid), M8 [hydroxylated (methyl) metabolite], and M6 (cyclized cysteinylglycine adduct of odanacatib) (Fig. 1). When a sample of the synthetic hydroxymethylsulfone derivative of odanacatib was dissolved in phosphate buffer (pH 7.4), it was shown to decompose to M4 (Fig. 3), indicating that the hydroxymethylsulfone derivative is the precursor of this metabolite. This decomposition of hydroxymethylsulfone odanacatib upon dissolving in pH 7.4 buffer was instantaneous; on the other hand, hydroxymethylsulfone odanacatib was very stable under acidic (0.1% formic acid) conditions (Fig. 4). Other metabolites identified were M1-A and M1-B (MH+ = 526), M2-A and M2-B (MH+ = 556), M3 [the glucuronide of M8, β-glucuronidase hydrolysis of M3 gave rise to M8 (data not shown)], and M7 (presumably related to the aldehyde derivative of M8). M1-A and M1-B appear to be isomeric metabolites related to the oxygenated derivatives of M4. The forms of these metabolites detected were the dehydrated derivatives (m/z 508). It was shown by manipulating the source temperature that these metabolites underwent MS source fragmentation to the dehydrated products (data not shown). M2-A and M2-B are likely to be the carboxylic acid derivatives of M8. It appears that the HPLC method was able to separate the diastereomers of M1 and M2 (unlike those of M8).

The concentrations of radioactivity and parent compound were determined in plasma of rats after an intravenous dose, and selected plasma samples were profiled by HPLC-MS/radiochromatography. The plasma concentration versus time plots of odanacatib and radioactivity (Fig. 5) indicate that radioactivity and the parent compound decline in parallel. Representative radiochromatograms obtained from rat plasma (Fig. 6) show that the parent compound is the only radioactive peak detected. Consistent with this result, the AUC ratio of parent compound to radioactivity was 98%.

**Monkeys.** In monkeys, odanacatib underwent extensive metabolism because only trace levels of the parent compound were...
detected in bile, urine, and feces (Fig. 2; Table 6). The major metabolites in monkeys were the hydroxylated species $M_8$ and its glucuronide $M_3$ (Fig. 2; Table 6). $M_1$ and $M_7$ also were formed and represented 5.4 and 0.6% of the dose, respectively. In addition, several trace-level metabolites were detected (Table 6). The plasma concentration versus time profiles of odanacatib and radioactivity are shown in Fig. 7. The AUC ratio of parent compound to radioactivity was 54%; however, the parent compound was the only identifiable peak in radiochromatograms obtained from plasma (Fig. 8).

**Dogs.** Because of the slow elimination of the drug in dogs, the fraction of the dose that was profiled was smaller compared with that of rats and monkeys. The metabolites identified in bile and feces were $M_4$, $M_5$, and $M_6$ (Fig. 2; Table 6). No metabolites related to the methyl hydroxylation pathway were detectable in dog excreta. The parent compound was also a significant component of the biliary and fecal radioactivity.

**Discussion**

The pharmacokinetics of odanacatib was evaluated in rats, dogs, and monkeys after both intravenous and oral administration. Odanacatib proved to be a low-clearance compound in rats and monkeys (5–20% of hepatic blood flow) and exhibited an extremely low clearance in dogs (<1% of hepatic blood flow). Consistent with the unusually low systemic clearance, the plasma elimination half-life in dogs was long (64 h) (Table 1) despite the modest volume of distribution (0.7 l/kg). The oral bioavailability of odanacatib was limited by the low aqueous solubility of the compound and was, thus, highly dependent on the vehicle used. It also appears that bioavailability is species-dependent: the compound showed complete absorption in the dog when dosed in a nonaqueous vehicle. Using nonaqueous vehicles, the bioavailability was 43, 100, and 18% in rats, dogs, and monkeys, respectively. The bioavailability was only 6% (dog) and 8% (rat) when the dose was suspended in an aqueous vehicle.

In a rat tissue distribution study, odanacatib-related radioactivity was shown to undergo extensive tissue distribution, including to the bone; CNS, to which there was little drug distribution, was a notable exception. At the final sampling time of 28 days postdose, elimination was essentially complete, indicating that odanacatib-related radioactivity is not selectively retained by any tissue. This result contrasts sharply with the tissue distribution behavior of the bisphosphonate
class of antiresorptive osteoporosis drugs, which show long bone residence in animals (half-life of 200-1000 days) and humans (half-life of 10 years) (Lin et al., 1991; Usui et al., 1995; Khan et al., 1997).

Odanacatib displayed good mass balance (>90%) after either intravenous or oral administration in rats and monkeys. After both routes of administration the majority of drug-related material was recovered in the feces (rat, 88–94%; monkey, 81–87%). The source of most of the fecal radioactivity after intravenous administration was confirmed to be biliary secretion, indicating that the biliary route is an important mode of excretion of the radioactive dose. Renal excretion was a relatively minor pathway (<12% of dose) in all species. The appearance of a significant fraction of the dose in the feces (27, 15, and 14% in rats, dogs, and monkeys, respectively) after intravenous administration to bile duct-cannulated animals indicates that intestinal secretion plays an important role in the elimination of odanacatib and/or its metabolites. Because odanacatib is a good P-glycoprotein substrate in rats, mice, and humans (M. Yamazaki, unpublished observations), it is possible that odanacatib (most of the radioactivity in rat feces was composed of...
Odanacatib is subject to P-glycoprotein-mediated efflux into the intestinal lumen. In monkeys, odanacatib was almost completely eliminated by metabolism; metabolism also played a major role in the clearance of odanacatib in rats, although excretion of unchanged parent compound was significant (~20% of the dose). In dogs, on the basis of the limited data, both metabolism and excretion of the parent compound appear to be important. Odanacatib displayed species-dependent biotransformation, with a different major metabolite in each species. Thus, in monkeys odanacatib is cleared principally via the methyl hydroxylation pathway, whereas methyl sulfone demethylation is not a significant pathway. On the other hand, the major metabolites in rats result from methyl sulfone demethylation. The hydroxylated metabolite M8 or its derivatives were not detectable in dogs, and glutathione conjugation appeared to be a prominent pathway. Although it was difficult to determine an in vitro intrinsic clearance for any species because of the low turnover in in vitro systems, the absence of the methyl hydroxylation pathway, a major pathway in rats and monkeys, is likely to contribute to the unusually long plasma half-life of odanacatib in dogs.

The major pathway in rats (formation of M4 and M5) probably involves oxidative demethylation of the methyl sulfone moiety of odanacatib. With use of a synthetic standard it was shown that the hydroxymethylsulfone derivative of odanacatib was the precursor of the sulfonic acid M4. The hydroxymethylsulfone was completely unstable at physiological pH but was very stable under acidic conditions. Although the methyl sulfone moiety is a structural feature of many drugs (e.g., Chauret et al., 2001; Dean et al., 2007; Karanam et al., 2007), to date there is no report with respect to this kind of biotransformation, and, thus, this represents a novel oxidative metabolism not presented previously in the literature. The cyclic cysteinylglycine conjugate M6 was detected as metabolite of odanacatib in all three species. This metabolite is presumably formed via reversible addition of glutathione to the nitrile group of odanacatib followed by γ-glutamyltranspeptidase-mediated removal of the glutamyl residue. The free N terminus of cysteinylglycine would then allow rearrangement to the stable cyclic form. The synthetic preparation of analogous 5-membered ring 2-thiazolines via condensation of cysteine and other β-mercapto amino acids with nitriles in aqueous carbonate buffer has been described previously (Krimmer et al., 1987).

In summary, the studies described in this article have collectively resulted in a good understanding of the metabolism and pharmacokinetic properties of odanacatib in a number of preclinical species. Odanacatib exhibited reasonable (albeit vehicle-dependent) oral bioavailability, low clearance, and long plasma half-life (especially in dogs). The compound is eliminated largely via oxidative metabolism (methyl hydroxylation and methyl sulfone demethylation), although there is excretion of a significant amount of intact parent in rats and dogs. Finally, the disposition and metabolism of odanacatib in rats, dogs, and monkeys, species that have been used in the safety evaluation of the compound, were representative of what was observed in humans (K. Kassahun, unpublished data).

Acknowledgments

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Authorship Contributions

Participated in research design: Kassahun, Black, Nicoll-Griffith, Chauret, Day, and Koepflinger.
Conducted experiments: McIntosh, Chauret, Day, and Koepflinger.
Contributed new reagents or analytic tools: Chauret.
Performed data analysis: Kassahun, McIntosh, Chauret, Day, and Koepflinger.
Wrote or contributed to the writing of the manuscript: Kassahun, Black, Nicoll-Griffith, Chauret, Rosenberg, and Koepflinger.

References


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Synthetic standards for M4 and M5 were prepared as described in Scheme 1. Ethyl 3-[(4-bromophenyl)thio]propionate 1 was converted to the corresponding boronate ester using the conditions of Giroux et al. Further coupling with arylbromide 3 provided the functionalized biaryl 4. Oxidation of the sulphide to the corresponding sulfone, followed by treatment with base to cleave the propionate group generated the sulfinic acid M4. Subsequent oxidation to the sulfonic acid provides M5.

A synthetic standard of the M8 metabolite was prepared as described in Scheme 2. Odanacatib was treated with BF3 etherate resulting in elimination of the tertiary fluoride to provide the isobutylene derivative 6. Dihydroxylation with osmium tetroxide provide 7 which was selectively acylated to provide 8. Treatment with DAST re-installed the tertiary fluoride atom. Subsequent cleavage of the acetate provided the desired hydroxyfluoroleucine derivative M8 as a 1.5:1 mixture of diastereomers by 1H NMR.

Scheme 1

Reagents and conditions: (a) bis(pinacolato)diboron, Pd2Cl2dppf, KOAc, DMF; (b) Pd2Cl2dppf, Na2CO3, DMF; (c) Na2WO4·2H2O, nBu4NHSO4, 30% H2O2, EtOAc; (d) NaOEt, THF/EtOH; (e) 30% H2O2, EtOH.
Scheme 2

Reagents and conditions: (a) BF₃·OEt₂, CHCl₃; (b) OsO₄, NMO, Acetone/H₂O; (c) Ac₂O, Et₃N, DMAP, CH₂Cl₂; (d) DAST, CH₂Cl₂; (e) K₂CO₃, MeOH.

1 André Giroux, Yongxin Han, Petpiboon Prasit Tetrahedron Lett. 1997, 38, 3841-3844.
ODANACATIB PARENT DRUG

030902A03 #1427  RT: 36.50  AV: 1  NL: 2.79E6
F: + c Full ms2 526.00@-15.00  [ 150.00-600.00]
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-1
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-2

030903B01 #646 RT: 16.51 AV: 1 NL: 5.22E5
F: + c Full ms2 556.00@-15.00 [ 150.00-600.00]
METABOLITE M-3

030903B01 #637-663  RT: 16.33-16.95  AV: 9  NL: 6.93E4
F: + c Full ms2 718.00@-15.00 [150.00-800.00]
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

HYDROXYMETHYL SULFONE-ODANACATIB
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-4

030903B01 #807-823 RT: 20.64-21.05 AV: 9 NL: 1.33E5
F: + c Full ms2 512.00@-15.00 [ 150.00-600.00]
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-5

030902A03 #827-839  RT: 21.18-21.43  AV: 6  NL: 5.10E4
F: + c Full ms2 528.00@-15.00 [150.00-600.00]
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-6

030903B07 #954  RT: 24.40  AV: 1  NL: 1.11E7
F: + c Full ms2 687.00@25.00 [ 150.00-700.00]
SUPPLEMENTAL DATA - MS/MS SPECTRA OF ODANACATIB METABOLITES

METABOLITE M-7

030902A03 #1207-1226  RT: 30.88-31.34  AV: 7  NL: 9.98E4
F: + c Full ms2 540.00@-15.00 [ 150.00-600.00]
METABOLITE M-8

030902A03 #1139-1165 RT: 29.16-29.78 AV: 9 NL: 1.39E7
F: + c Full ms2 542.00@-15.00 [150.00-600.00]