Metabolism of the c-Fos/Activator Protein-1 Inhibitor T-5224 by Multiple Human UDP-Glucuronosyltransferase Isoforms

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ABSTRACT:
We developed 3-[5-[4-(cyclopentyloxy)-2-hydroxybenzoyl]-2-[(3-hydroxy-1,2-benzisoxazol-6-yl)methoxy]phenyl] propionic acid (T-5224) as a novel inhibitor of the c-Fos/activator protein-1 for rheumatoid arthritis therapy. We predicted the metabolism of T-5224 in humans by using human liver microsomes (HLM), human intestinal microsomes (HIM), recombinant human cytochrome P450s (P450s), and UDP-glucuronosyltransferases (UGTs). T-5224 was converted to its acyl O-glucuronide (G2) by UGT1A1 and UGT1A3 and to its hydroxyl O-glucuronide (G3) by several UGTs, but it was not metabolized by the P450s. A comparison of the intrinsic clearances (CLint) between HLM and HIM suggested that the glucuronidation of T-5224 occurs predominantly in the liver. UGT1A1 showed a higher kcat/Km value than UGT1A3 for G2 formation, but a lower kcat/Km value than UGT1A3 for G3 formation. A high correlation was observed between G2 formation activity and UGT1A1-specific activity (β-estradiol 3-glucuronidation) in seven individual HLM. A high correlation was also observed between G2 formation activity and UGT1A1 content in the HLM. These results strongly suggest that UGT1A1 is responsible for G2 formation in human liver. In contrast, no such correlation was observed with G3 formation, suggesting that multiple UGT isoforms, including UGT1A1 and UGT1A3, are involved in G3 formation. G2 is also observed in rat and monkey liver microsomes as a major metabolite of T-5224, suggesting that G2 is not a human-specific metabolite. In this study, we obtained useful information on the metabolism of T-5224 for its clinical use.
Molecular structures of two major T-5224 glucuronides and revealed the UGT isoforms responsible for its glucuronidation.

Materials and Methods

Materials. T-5224 (Fig. 1) was synthesized at Toyama Chemical Co., Ltd. (Tokyo, Japan). 14C-labeled T-5224 was synthesized at Daichii Pure Chemicals Co., Ltd. (Ibaraki, Japan). UDP-glucuronic acid (UDPGA) was purchased from Nacalai Tesque Inc. (Kyoto, Japan). Alamethicin and β-estradiol were purchased from Sigma-Aldrich (St. Louis, MO). Two lots of pooled HLM (from donors were purchased from Tissue Transformation Technologies (Edison, NJ)). Microsomes from seven individual human livers, including allelic variants, were prepared from BD Biosciences (San Diego, CA). The following lot numbers were purchased: HH629 (UGT1A1*28*28), HG43, HG18, and HH650 (UGT1A1*1*1); HH855 (UGT1A1*1*28); HH741; and HH13, Recombinant human UGTs (UGT1A1, UGT1A3, UGT1A4, UGT1A6, UGT1A7, UGT1A8, UGT1A9, UGT1A10, UGT2B4, UGT2B7, UGT2B15, and UGT2B17) and recombinant human P450s (CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2D6, CYP2E1, and CYP3A4) were purchased from Sigma-Aldrich (St. Louis, MO) and from Calbiochem (San Diego, CA). All other chemicals and solvents were of analytical or highest commercially available grade.

Metabolism of T-5224 by Recombinant Human P450 Isoforms. The incubation mixture for the P450 reaction (500 μl total volume) contained 100 mM Tris-HCl buffer (pH 7.5) or 100 mM potassium phosphate buffer (pH 7.4) (for CYP2A6 and CYP2C9*1), 50 pmol/ml amounts of each of the recombinant human P450s (CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C19, CYP2D6, CYP2E1, and CYP3A4), 50 μmol/ml of each of the recombinant human P450s (CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C19, CYP2D6, CYP2E1, and CYP3A4), and 2 μM of [14C]T-5224. [14C]T-5224 was dissolved in dimethyl sulfoxide (DMSO) with a final concentration of 0.5 μM in the incubation mixtures. After incubation for 30 min at 37°C, the reaction was terminated by the addition of 1.5 ml of acetonitrile-methanol (1:1, v/v). The supernatant obtained by centrifugation (14,000 g at 4°C) was subjected to high-performance liquid chromatography (HPLC) analysis using the CAPCELL PAK C18-MG analytical column (4.6 × 150 mm, 3 μm; Shiseido, Tokyo, Japan) at 40°C, and the radiopeak of the metabolite were detected. The mobile phase A was 5% (v/v) acetonitrile, the mobile phase B was 80% (v/v) acetonitrile, and the flow rate was 1 ml/min.

Enzymatic Synthesis and Extraction of the T-5224 Glucuronides. To synthesize the T-5224 glucuronides enzymatically, recombinant human UGT1A1 was expressed in yeast cells (Ishikuro et al., 2004). First, human UGT1A1 cDNA was isolated by reverse transcription-polymerase chain reaction (PCR) from a total RNA fraction prepared from human liver using the PCR primer set described as forward primer, CCCAAAGCTTAAAAATGGCTGTGGAGTCCCAGGGC and reverse primer, CCCAAGCTTCTAATGGCTGTGGAGTCCCAGGGC. For insertion of UGT1A1 cDNA into the pGYR expression vector, both primers contained HindIII sites. The resulting PCR fragment was digested with HindIII and inserted into the HindIII site of the vector pGYR, which contained a 2-μm DNA ori, a Leu2 gene as a marker, a Saccharomyces cerevisiae NADPH-P450 reductase gene, pUC ampr, a glyceraldehyde-3-phosphate dehydrogenase promoter, and a terminator derived from Zygosaccharomyces rouxii. The resulting plasmid, pGYR-hUGT1A1, was introduced into S. cerevisiae AH22 cells as described previously (Oeda et al., 1985). The recombinant yeast cells expressing UGT1A1 were cultivated in a synthetic, minimal medium containing 2% (v/v) d-glucose and 0.67% (w/v) yeast nitrogen base without amino acids, supplemented with histidine (20 mg/l). The microsomal fractions were prepared as described previously (Oeda et al., 1985). The protein concentrations of the microsomes were determined with bichromic acid protein assay reagent (Nacalai Tesque) using bovine serum albumin as a standard.

The reaction mixture (200 ml) contained 50 mM Tris-HCl buffer (pH 7.5), 8 mM MgCl₂, 600 mg of yeast microsomes, 20 μM T-5224, and 4 mM UDPGA. After incubation at 37°C for 24 h, the reaction was terminated by the addition of acetonitrile (100 ml). After removal of the protein by centrifugation at 14,000 g for 20 min at 4°C, the supernatant was evaporated under reduced pressure at room temperature to obtain the aqueous solvent containing the hydrophilic components. The aqueous solvent was transferred to solid-phase extraction cartridges (Oasis HLB, 60 mg/3 ml; Waters, Milford, MA), which were previously rinsed with 3 ml of methanol and water. Each cartridge was washed with water (3 ml) and eluted twice with methanol (3 ml), and, finally, 120 ml of eluate was recovered. DMSO (200 μl) was added to the eluate, which was concentrated to approximately 2 ml by evaporation under reduced pressure at 40°C. The resulting residue was injected onto a Develosil ODS-HG column (20 × 250 mm, 5 μm; Nomura Chemical, Aichi, Japan) at room temperature. The mobile phases A and B were the same as described above, and the following linear gradient was used: 0 to 100% B for 40 min and hold at 0% B for 10 min. The flow rate was 1 ml/min. Each fraction containing G2 (approximately 20 ml) or G3 (approximately 40 ml) was automatically collected with the fraction collector (FRC-10A; Shimadzu, Kyoto, Japan). DMSO (100 μl) was added to each fraction, and the organic...
solvent was evaporated under reduced pressure at room temperature to obtain the aqueous solutions containing G2 or G3. The aqueous solutions were transferred to solid-phase extraction cartridges (Oasis MAX, 500 mg/6 ml; Waters) that were previously rinsed with 3 ml of methanol and water. The cartridges were washed with 4 ml of water and methanol and eluted twice with 5 ml of methanol containing 5% (v/v) formic acid. The eluates were evaporated to dryness under reduced pressure at room temperature to obtain G2 and G3, which were used for mass spectrometric analysis.

Identification of T-5224 Glucuronides by High-Performance Liquid Chromatography/Hybrid Fourier Transform Mass Spectrometry. The T-5224 glucuronides were analyzed using a HPLC/hybrid Fourier transform mass spectrometry system (LTQ Orbitrap XL; Thermo Fisher Scientific, Waltham, MA). The HPLC conditions were the same as described above except for the flow rate. The HPLC system was operated in an isocratic mode with a flow rate of 0.5 ml/min, and the mobile phases A (50%) and B (50%) were mixed in a liquid chromatography pump. The LTQ Orbitrap was operated in negative-ion mode, and the settings were as follows: spray voltage 3.0 kV, resolution 30,000, and full mass spectrometry mass range m/z 150 to 1200. Glucuronides were analyzed in high-energy collision dissociation (HCD) mode with normalized collision energies of 30, 40, 50, and 60%.

Alkaline Hydrolysis of the T-5224 Glucuronides. The T-5224 glucuronides, G2 and G3, were each incubated with NaOH (0.17 M) for 2 h at room temperature. The reactions were terminated by neutralization with HCl, and the products were analyzed by HPLC.

Kinetic Analyses. Kinetic studies were performed using the pooled HLM, pooled HIM, and recombinant human UGTs (UGT1A1, UGT1A3, and UGT1A8). For determining the kinetic parameters, T-5224 concentrations (1–50 μM) were used for analysis. The incubation times were 10 min except for the HIM (20 min), which had lower T-5224 concentrations (less than 5 μM), and the recombinant human UGTs (60 min). Kinetic parameters were estimated from the fitted curves using the KaleidaGraph computer program (Synergy Software, Reading, PA), which was designed for nonlinear regression analysis. The following equations were applied for substrate inhibition kinetics (eq. 1):

\[
V = \frac{V_{\text{max}} \times S}{K_m + S + \frac{S}{K_{si}}}
\]

where \(V\) is the rate of reaction, \(V_{\text{max}}\) is the maximum velocity, \(K_m\) is the Michaelis constant, \(S\) is the substrate concentration, and \(K_{si}\) is the constant describing the substrate inhibition interaction (Houston and Kenworthy, 2000). A turnover number (\(k_{\text{cat}}\)) was calculated as (eq. 2)

\[
k_{\text{cat}} = \frac{V_{\text{min}}}{E_0}
\]

where \(E_0\) is the UGT concentration. To estimate the in vitro intrinsic clearance (CL_{int}), eq. 3 was used:

\[
\text{CL}_{\text{int}} = \frac{V_{\text{max}}}{K_m} \times \frac{\text{milligram of microsomal protein}}{\text{gram of tissue}} \times \frac{\text{gram of tissue}}{\text{kilogram of body weight}}
\]

FIG. 2. HPLC profiles of T-5224 and its glucuronides. T-5224 (10 μM) was incubated at 37°C with UDP-glucuronic acid for 10 min in pooled human liver microsomes (A) and intestinal microsomes (B).
As reported by Soars et al. (2002), the CL_{int} values for T-5224 glucuronidation were calculated for the HLM (45 mg of microsomal protein/g of liver and 20 g of liver/kg b.wt.) and the HIM (3 mg of microsomal protein/g intestine and 30 g of intestine/kg b.wt.).

**Effects of UDPGA Concentrations on T-5224 Glucuronidation.** To estimate the K_{m} value for UDPGA in T-5224 glucuronidation, a constant T-5224 concentration (10 μM) was incubated with different UDPGA concentrations. The components of the incubation mixture were the same as described above. After preincubation at 37°C for 5 min, the reactions were initiated by addition of UDPGA at final concentrations of 0, 0.1, 0.2, 0.4, 1, 2, or 4 mM. After incubation at 37°C for 10 min, the reactions were terminated by the addition of acetonitrile (100 μl). The subsequent analyses were the same as described above. Equation 4 was applied for Michaelis-Menten kinetics:

\[
V = \frac{V_{\text{max}} \times S}{K_{m} + S}
\]

**Inhibition Analysis of T-5224 Glucuronidation Activity in Human Liver Microsomes and Recombinant Human UGT1A1.** β-Estradiol (Senafi et al., 1994) is a typical substrate for UGT1A1. The inhibitory effects of β-estradiol on T-5224 glucuronidation were investigated with the pooled HLM and recombinant human UGT1A1. The reaction mixtures contained T-5224 (10 μM), UDPGA (2 mM), β-estradiol (0–500 μM), and the same components as described above. β-Estradiol was dissolved in DMSO; therefore, the reaction mixture contained 2% (v/v) of DMSO. After incubation at 37°C for 10 min (HLM) or 60 min (UGT1A1), the reactions were terminated by the addition of acetonitrile (100 μl). The subsequent analyses were the same as described above.

**Immunoblot Analyses.** Polyclonal antibodies against each UGT isoform-specific peptide and a C-terminal peptide common to all human UGT1A or UGT2B isoforms have been developed in our laboratory (Kasai et al., 2004; Ikushiro et al., 2006) and were used for the detection of the UGTs. To obtain clear UGT bands on the immunoblots, microsomes were treated with endoglycosidase H (recombinant UGT) or N-glycosidase F (HLM except for detecting UGT1A1) (New England Biolabs) according to the manufacturer’s protocol and subjected to SDS-polyacrylamide gel electrophoresis as described previously (Ikushiro et al., 1995). The proteins in the gel were blotted to nitrocellulose membranes using a semidyblotting method. The membranes were blocked with 1.5% (w/v) bovine serum albumin or PVDF Blocking Reagent Can Get Signal (Toyobo Engineering, Osaka, Japan) at room temperature. The membranes were incubated overnight with diluted primary antibodies (1:2000 or 1:4000 dilution with Can Get Signal Solution 1; Toyobo Engineering) at room temperature. They were then incubated with a diluted anti-primary antibody (1:2000 or 1:4000 dilution with Can Get Signal solution 2; Toyobo Engineering) of alkaline phosphatase-conjugated goat anti-rabbit IgG (Cell Signaling Technology, Danvers, MA) at room temperature for 2 to 5 h. Immunodetection was performed by adding a nitro blue tetrazolium chloride-5-bromo-4-chloro-3-indolylphosphatase p-toluidine salt solution (1-Step NBT/BCIP; Thermo Fisher Scientific). The band intensities were quantified using a densitometric scanner and image software (ImageJ, version 1.38; National Institutes of Health, Bethesda, MD). The UGT isoform contents expressed in recombinant UGT microsomes were quantified using anti-UGT1A or anti-UGT2B antibodies. The recombinant UGT1A1 and UGT2B4

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**Fig. 3.** T-5224 glucuronidation activity in each recombinant human UGT isoform. T-5224 was incubated at 5 μM (A) or 50 μM (B) for 60 min at 37°C with UDP-glucuronic acid, and the HPLC profiles of the recombinant human UGT1A1, UGT1A3, and UGT1A8 are shown (C). The incubations were performed in duplicate, and the glucuronidation activities (VE_{a}) were calculated with the UGT content obtained by immunoblot analyses. Glucuronides were not detected in UGT1A4, UGT1A9, UGT2B4, UGT2B7, UGT2B15, UGT2B17, and Mock.
microsomes, with UGT contents known to be 1.6 and 0.6 nmol/mg protein, respectively, were used as standards (Kasai et al., 2004).

**Correlation Analyses.** The correlations between T-5224 and β-estradiol glucuronidation activity and between T-5224 glucuronidation activity and the expression levels of UGTs were determined in seven individual HLM. The Pearson product moment method was used to judge the correlations. \( p < 0.05 \) was considered statistically significant.

**Results**

**T-5224 Glucuronide Formation in Human Liver and Intestinal Microsomes.** After incubation of T-5224 with microsomes in the presence of UDPGA, two major peaks containing the glucuronides G2 and G3 were observed on HPLC chromatograms in the pooled HLM and HIM. A small peak containing glucuronide G1 was observed in the pooled HLM (Fig. 2). Because the amounts of G1 formed were very low, we focused on G2 and G3 in the further studies. In pooled HLM and HIM, both G2 and G3 increased linearly with increasing microsomal protein concentrations (0.1, 0.25, 0.5, and 1.0 mg/ml) or incubation times (5, 10, 20, and 30 min) (data not shown).

**Metabolism of T-5224 by Recombinant Human P450s and UGTs.** None of the P450 isoforms metabolized T-5224 (Supplemental Fig. s1), but multiple UGT isoforms showed significant T-5224 glucuronidation. Two major glucuronides, G2 and G3, were formed in the recombinant human UGTs with 5 or 50 μM T-5224 (Fig. 3, A and B). Quantitative immunoblot analyses were performed, assuming that the reactivities of anti-UGT1A and anti-UGT2B antibodies for each UGT
subfamily were similar among each isoform. The protein contents of each UGT in the microsomes were as follows: UGT1A1, UGT1A3, UGT1A4, UGT1A6, UGT1A7, UGT1A8, UGT1A9, and UGT1A10 were 2.6, 1.4, 2.3, 2.1, 1.7, 1.6, 1.7, and 3.1 nmol/mg protein, respectively, and UGT2B4, UGT2B7, UGT2B15, and UGT2B17 were 0.14, 0.75, 0.14, and 0.63 nmol/mg protein, respectively (Supplemental Fig. s2A). From these immunoblot analyses, T-5224 glucuronidation activities per UGT molecule (V/E₀) were estimated for G2 and G3. G2 formation was only catalyzed by UGT1A1 and UGT1A3. On the other hand, G3 formation was catalyzed by multiple UGT isoforms, and UGT1A1, UGT1A3, and UGT1A8 showed the highest activities among the other isoforms. Therefore, we focused on UGT1A1, UGT1A3, and UGT1A8 for the kinetic analyses. Two major glucuronide peaks (G2 and G3) and no G1 peak were observed on HPLC chromatograms in recombinant human UGT1A1, UGT1A3, and UGT1A8 (Fig. 3C). Both G2 and G3 formations increased linearly with increasing microsomal protein concentration (0.05, 0.1, and 0.2 mg/ml) or incubation time (10, 20, and 60 min) (data not shown).

Mass Spectrometric Analysis of the T-5224 Glucuronides. The Orbitrap electrospray mass spectra of the four peaks typically formed by the incubation of T-5224 with HLM in the presence of UDPGA had [M – H]⁻ ions at m/z 868.23083 (G1, C₄₁H₄₂O₂₃N), m/z 692.19830 (G2, C₃₅H₃₄O₁₄N), m/z 692.19818 (G3, C₃₅H₃₄O₁₄N), and m/z 516.16595 (T-5224, C₂₉H₂₆O₈N) with mass accuracy between 0.85 and 0.30 ppm (Fig. 4). These results suggest the possibility that...
G1 is a diglucuronide of T-5224, whereas G2 and G3 are monoglucuronides of T-5224. Purified G2 and G3 were analyzed in HCD mode. With varied normalized collision energies (30–60%), G2 and G3 showed precursor ions at m/z 692 and product ions at m/z 516 for the aglycon, m/z 369 for the cleaved aglycon, and m/z 175 for the derivative of the glucuronic acid moiety (Fig. 5, A and B). The product ion at m/z 193 for the deprotonated glucuronic acid was only produced from G2, suggesting the possibility that G2 is an acyl O-glucuronide (Fig. 5A).

**Alkaline Hydrolysis of the T-5224 Glucuronides.** After incubation of the purified G2 and G3 with NaOH, 79 and 40% of G2 and G3, respectively, were hydrolyzed to form T-5224, suggesting that G2 is more unstable than G3. These results, together with the mass spectrometric analyses, strongly suggest that G2 is an acyl O-glucuronide and that G3 is either a hydroxyl O-glucuronide or N-glucuronide of T-5224.

**Kinetics of T-5224 Glucuronidation in Human Liver and Intestinal Microsomes and Recombinant Human UGTs.** Kinetic analyses of T-5224 glucuronidation were performed in pooled HLM, pooled HIM, and recombinant human UGTs (UGT1A1, UGT1A3, and UGT1A8). The data points were fitted to the substrate inhibition equation (Fig. 6) to yield the kinetic parameters (Tables 1 and 2). To calculate $k_{in}$ values, the UGT contents ($E_u$) obtained from the immunoblot analyses were used: UGT1A1, UGT1A3, and UGT1A8 were 1.5, 1.0, and 1.9 nmol/mg protein, respectively (Supplemental Fig. S2B). The pooled HIM showed a $V_{max}/K_m$ value comparable to that for the pooled HLM for G2 formation (HIM, 40.9 μM · min⁻¹ · mg protein⁻¹; HLM, 44.0 μM · min⁻¹ · mg protein⁻¹) and a higher $V_{max}/K_m$ value than that for the pooled HLM for G3 formation (HIM, 34.6 μM · min⁻¹ · mg protein⁻¹; HLM, 19.5 μM · min⁻¹ · mg protein⁻¹). However, the pooled HIM showed much lower $V_{max}/K_m$ values (G2, 3.68 μM · min⁻¹ · kg⁻¹; G3, 3.12 μM · min⁻¹ · kg⁻¹) than the pooled HLM (G2, 39.6 μM · min⁻¹ · kg⁻¹; G3, 17.5 μM · min⁻¹ · kg⁻¹) (Table 1). In the pooled HLM and recombinant human UGT1A1, the $V_{max}/K_m$ and $k_{in}/K_m$ values for G2 (HLM, 44.0 μM · min⁻¹ · mg protein⁻¹; UGT1A1, 903 M⁻¹ · s⁻¹) were higher than those for G3 (HLM, 19.5 μM · min⁻¹ · mg protein⁻¹; UGT1A1, 284 M⁻¹ · s⁻¹). In contrast, in recombinant human UGT1A3, the $k_{in}/K_m$ value for G3 (774 M⁻¹ · s⁻¹) was higher than that for G2 (252 M⁻¹ · s⁻¹). Recombinant human UGT1A3 showed a higher $k_{in}/K_m$ value than UGT1A1 for G3. Recombinant human UGT1A8 only catalyzed the formation of G3, with a $k_{in}/K_m$ value (303 M⁻¹ · s⁻¹) similar to that of UGT1A1 (Table 2).

**Inhibitory Analyses of T-5224 Glucuronidation Activity in Human Liver Microsomes and Recombinant Human UGT1A1.** β-Estradiol, which is an UGT1A1-specific substrate, inhibited G2 formation in both pooled HLM and recombinant human UGT1A1 with IC₅₀ values of 39 and 24.9 μM, respectively. However, β-estradiol showed weak or no inhibition of G3 formation in pooled HLM and recombinant human UGT1A1 (Fig. 7).

**Correlations of the Glucuronidation Activity between T-5224 and β-Estradiol or UGT-Isoform Expression.** Among seven individual HLM, including homozygotes or heterozygotes of the UGT1A1*28 allele, the interindividual difference in the formation activity of G2 [3.6-fold; coefficient of variation (CV) = 52%] was...
higher than that of G3 (2.1-fold; CV = 24%) (Fig. 8A). In addition, G2 formation activity was significantly correlated with the β-estradiol 3-glucuronidation (UGT1A1) activity ($r = 0.939$, $p < 0.005$), whereas the G3 formation activity was not significantly correlated with it ($r = 0.568$) (Fig. 8, B and C). Western blot analyses revealed interindividual variabilities in UGT expression among the seven HLM with it ($r$). The levels of loading controls (calnexin and NADH-cytochrome b$_5$ reductase) did not vary among individuals (data not shown). Therefore, correlations were analyzed between the glucuronidation activities and the expression level of UGT1A1 or UGT1A3. A high correlation was observed between UGT1A1 level and G2 formation activity ($r = 0.985$, $p < 0.00005$) (Fig. 9B) but not with G3 formation activity (Fig. 9C). High correlations were also not observed between expression levels and glucuronidation activity in UGT1A3 (data not shown). The liver microsomes from a homozygous UGT1A1*28*28 carrier (HH629) showed the lowest G2 and G3 formation activities among the seven HLM.

**Discussion**

A February 2008 U.S. Food and Drug Administration guidance (http://www.fda.gov/default.htm) strongly recommended human metabolic evaluations for new drugs. Additional safety assessments may also be needed for human-specific and putative toxic metabolites, such as acylglucuronides. However, with phase II (conjugated) metabolites, which are generally more water-soluble and pharmacologically inactive, the need for further evaluations can be eliminated. Thus, characterizing the metabolism of new drugs in humans is required.

Our animal studies revealed that the major T-5224 metabolites were glucuronides. In addition, glucuronide metabolites were major metabolites in human urine (data not shown). A comprehensive study is needed to clarify the clear elimination pathway of T-5224 including sulfonation and glucuronidation. To begin with, we focused glucuronidation and characterized T-5224 glucuronidation using HLM, HIM, and recombinant human UGTs. We also estimated the contribution of each human UGT isoform to T-5224 glucuronidation and verified whether the glucuronide was an acylglucuronide.

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### Kinetic parameters of T-5224 glucuronidation for G2 and G3 in recombinant human UGT isoforms

<table>
<thead>
<tr>
<th>Glucuronide</th>
<th>UGT Isoform</th>
<th>$V_{\text{max}}$ (pmol min$^{-1}$ mg protein$^{-1}$)</th>
<th>$K_m$ (µM)</th>
<th>$K_i$ (µM)</th>
<th>$V_{\text{max}}/K_m$ (pmol min$^{-1}$ mg protein$^{-1}$)</th>
<th>$k_{\text{cat}}$ (s$^{-1}$)</th>
<th>$k_{\text{cat}}/K_m$ (M$^{-1}$ s$^{-1}$)</th>
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<tr>
<td>G2</td>
<td>1A1</td>
<td>664 ± 410</td>
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<td>2.71 ± 2.64</td>
<td>13.5 ± 5.0</td>
<td>15.5</td>
<td>1.82 × 10$^{-3}$</td>
<td>252</td>
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<tr>
<td>G3</td>
<td>1A1</td>
<td>146 ± 73</td>
<td>5.56 ± 3.85</td>
<td>4.67 ± 3.12</td>
<td>26.2</td>
<td>1.38 × 10$^{-3}$</td>
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</tr>
<tr>
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<td>2.55 ± 1.67</td>
<td>47.5</td>
<td>1.84 × 10$^{-3}$</td>
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As shown in Fig. 1, T-5224 is possibly conjugated at four positions: 1) carboxyl group, 2) OH group in a benzisoxazole, 3) NH group in a benzisoxazole, and 4) phenolic OH group. The mass spectrometric analyses of G2 and G3 using hybrid Fourier transform mass spectrometry showed different fragmentation patterns between G2 and G3 and different collision energies (30–60%). The fragment $m/z$ 193 was produced only from G2. Fenselau and Johnson (1980) and Niemeier et al. (1991) reported that the O bond to the aromatic ring is not readily broken in the mass spectrometric analysis of phenols or phenol derivatives. The $m/z$ 193 ion is considered to be the deprotonated glucuronic acid ion produced by cleaving the carboxyl group C–O bond, as reported by Jaggii et al. (2002) and Plumb et al. (2007) on the acyl $O$-glucuronides of desmethylpropranolol and ibuprofen. Given the mass spectrometric analysis and the fact that G2 is alkali-labile, this strongly suggests that G2 is the acyl $O$-glucuronide of T-5224. G2 was also observed as a major T-5224 metabolite in rat and monkey liver microsomes (Supplemental Fig. s3), suggesting that G2 is not a human-specific metabolite. Therefore, animal studies could be important in the safety assessment of the T-5224 acyl $O$-glucuronide in humans. In addition, the amount of covalent binding of T-5224 and its metabolites (oxidation and conjugation products) in human liver S9 fractions and microsomes was much less than that of the positive controls diclofenac and acetaminophen (data not shown). G3, another metabolite, showed no $m/z$ 193 ion with any collision energy, indicating that G3 is the hydroxyl $O$-glucuronide or $N$-glucuronide of T-5224. A metabolite profiling study using NMR and rat and monkey matrices showed that the glucuronide corresponding to G3 at the same retention time on the HPLC chromatogram was the hydroxyl $O$-glucuronide of desmethylpropranolol and ibuprofen.

The kinetic profiles for G2 and G3 exhibited the substrate inhibitions for pooled HLM, pooled HIM, and recombinant human UGTs. Each value represents the mean ± S.D. ($n = 3$).
UGT1A1, UGT1A3, and UGT1A8. However, both $K_m$ and $K_{si}$ values for G2 ($K_m = 4.93 \mu M; K_{si} = 13.2 \mu M$) and G3 ($K_m = 15.7 \mu M; K_{si} = 27.0 \mu M$) were much higher in the pooled HLM than in vivo ED$_{50}$ for T-5224 corresponding to a $C_{max}$ of 0.03 to 0.5 $\mu M$ (Aikawa et al., 2008). Based on these results, eq. 1 could be simplified to eq. 5:

$$V = \frac{V_{max} \times S}{K_m}$$  

(5)

Therefore, the physiologically, essential kinetic parameters are $V_{max}/K_m$ and $k_{cat}/K_m$ (Tables 1 and 2).

UGT1A1, UGT1A3, and UGT1A8 appear to be essential for T-5224 metabolism (Fig. 3). Of these UGT isoforms, UGT1A8 is expressed in the human intestines but not in the human liver (Cheng et al., 1998; Fisher et al., 2001), and UGT1A1 and UGT1A3 are expressed in both the human liver and intestine (Strassburg et al., 1998; Fisher et al., 2001). The $k_{cat}/K_m$ value of UGT1A8 for G3 was comparable to that of UGT1A1 (Table 2). This may indicate a large contribution of intestinal UGT1A8 to G3 formation. When drugs are administered orally, intestinal UGT and P450s have major roles in the first-pass metabolism (Fisher et al., 2001; Cubitt et al., 2009). However, the Cl$_{int}$ values estimated for G2 and G3 in the intestine were much lower than those in the liver (Table 1), which suggests that the contribution of intestinal UGTs to T-5224 metabolism is negligible, and hepatic UGTs have important roles in this metabolism. Thus, we focused on UGT1A1 and UGT1A3 in the further analyses.

Recombinant human UGT1A1 showed a higher $k_{cat}/K_m$ value for G2 (903 M$^{-1}$ s$^{-1}$) than for G3 (284 M$^{-1}$ s$^{-1}$). The UGT1A1 $k_{cat}/K_m$ value for G2 was significantly higher than that of UGT1A3 (252 M$^{-1}$ s$^{-1}$). A typical UGT1A1 substrate, $\beta$-estradiol, significantly inhibited G2 formation (Fig. 7). A high correlation was observed between G2 formation and $\beta$-estradiol 3-glucuronidation activities (Fig. 8B). These results strongly suggest that UGT1A1 is responsible for G2 formation. A high correlation between the UGT1A1 expression level and G2 formation activity confirmed this in the human liver (Fig. 9B).

Although recombinant UGT1A3 showed a much higher $k_{cat}/K_m$ value than UGT1A1, no correlation was observed between G3 formation and the UGT1A3 expression level in the HLM; however, a weak correlation was observed between G3 formation and the UGT1A1 expression level in the HLM (Fig. 9C). In addition, a weak correlation was observed between G3 formation and $\beta$-estradiol 3-glucuronidation activity (Fig. 8C), which suggests a considerable contribution of UGT1A1 to the G3 formation in the human liver. Based on these results, the contribution of UGT1A1 appears to be larger than that of UGT1A3 for the G3 formation in the human liver. To our surprise, $\beta$-estradiol did not inhibit recombinant UGT1A1-dependent G3 formation, but it inhibited G2 formation (Fig. 7B). This may be due to an interaction between the T-5224 and $\beta$-estradiol in the UGT1A1 active site. UGT1A1-dependent glucuronidation of $\beta$-estradiol is reported to demonstrate homotropic activation kinetics in the presence of UGT1A1 substrates and other compounds (Williams et al., 2002). In another case, Zhou et al. (2010b) suggested that UGT1A4 has multiple aglycon binding sites and found that the high-affinity UGT1A4 substrate, tamoxifen, activates and/or inhibits the formation of other UGT1A4 substrates (dihydrotestosterone and trans-androsterone). On the basis of these findings, it is possible to assume that $\beta$-estradiol could bind to a substrate-binding pocket of UGT1A1 with T-5224 and inhibit the binding of T-5224 to catalyze the formation of G2 but not G3.

To date, several reports have shown the relative expression of UGT mRNAs in the human liver (Congiu et al., 2002; Izukawa et al., 2009).
and in multiple human tissues (Nishimura and Naito, 2006; Zhang et al., 2007; Nakamura et al., 2008; Ohno and Nakajin, 2009). In a more recent report from Court (2010), the relative abundance of UGT mRNAs in the human liver was summarized as the following: “highest,” UGT2B4; “high to medium,” UGT1A4, UGT2B7, and UGT2B15; “medium to low,” UGT1A1, UGT1A3, UGT1A6, UGT1A9, and UGT2B10; and “trace level or not detected,” UGT1A7 and UGT1A10. Incidentally, Ritter et al. (1999) found that the UGT1A1 mRNA levels were correlated with the UGT1A1 protein levels, and the UGT1A1 protein levels were correlated with human hepatic UGT1A1 activity. On the basis of these reports and our findings with recombinant UGT isoforms, UGT1A6, which was detected in all seven individual HLM, might make a small contribution to G3 formation in the human liver (Figs. 3 and 9); however, UGT1A7 and UGT1A10 contributions appear to be negligible. The human UGT superfamily comprises 19 isoforms. We have not evaluated the contribution of UGT1A5, UGT2B10, UGT2B11, UGT2B28, UGT2A1, UGT2A2, and UGT2A3 to T-5224 glucuronidation. The contribution of UGT1A5 and UGT2B28 to whole glucuronidation is likely to be small by the report of Court (2010). UGT2B10 is reported to catalyze the N-glucuronidation with quaternary amines such as tricyclic antidepressants (Zhou et al., 2010a). It is unlikely that UGT2B10 contributes to T-5224 metabolism because we could not confirm N-glucuronide of T-5224. The contribution of the other isoforms such as UGT2A might be small but cannot be neglected.

Including the homozygous UGT1A1*28 allele, the interindividual variability for G2 formation, which is mainly catalyzed by UGT1A1, was higher (52% CV) than that for G3 formation (24% CV), which is catalyzed by multiple UGT isoforms. These results indicate that G2 formation may be a T-5224 metabolism variation factor in humans. It should be noted that the magnitude of UGT-based drug interactions is generally smaller than that of the P450-mediated drug interactions (Lin and Wong, 2002; Williams et al., 2004). The variabilities in the oral area under the curve of 7-ethyl-10-hydroxycamptothecin (SN-38), the active metabolite of irinotecan, which is further conjugated by UGT1A1 and UGT1A9 (Iyer et al., 1998; Gagné et al., 2002), and its glucuronide were reported to be 3-fold in nine patients with lung cancer, including those with the homozygous UGT1A1*28 allele (Ando et al., 1998). Furthermore, Ramchandani et al. (2007) reported that the variability in the SN-38 area under the curve was approximately 10% (CV) in 82 patients including those homozygous for the UGT1A1*28 allele. Considering that T-5224 has multiple glucuronidation pathways shared by multiple UGT isoforms, T-5224 most likely will not cause a drug interaction via glucuronidation. However, we must monitor the pharmacokinetic outcomes of T-5224 when it is coadministered with typical UGT inhibitors or inducers (Kiang et al., 2005).

In conclusion, our study found the following: 1) T-5224 is metabolized to form two major isomeric glucuronides, and one of them is an acyl O-glucuronide, which was also detected in rats and monkeys as a major metabolite; 2) UGT1A1 and UGT1A3 have central roles in the glucuronidation of T-5224, and UGT1A1 is responsible for the formation of the acyl O-glucuronide; and 3) interindividual differences in the glucuronidation of T-5224 were not very large, even with...
a homozygous UGT1A1*28 allele. Therefore, in vitro T-5224 metabolism studies provide useful information to study the safety of T-5224 in humans.

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Authorship Contributions

Participated in research design: Uchihashi, Onoda, Hayakawa, Ikushiro, and Sakaki.

Conducted experiments: Uchihashi and Fukumoto.

Contributed new reagents or analytic tools: Ikushiro.

Performed data analysis: Uchihashi and Fukumoto.

Wrote or contributed to the writing of the manuscript: Uchihashi, Onoda, Hayakawa, Ikushiro, and Sakaki.

References


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Supplemental Data

Metabolism of the c-Fos/activator protein-1 inhibitor T-5224 by multiple human UGT isoforms
Shinsuke Uchihashi, Hiroyuki Fukumoto, Makoto Onoda, Hiroyoshi Hayakawa, Shin-ichi Ikushiro, Toshiyuki Sakaki

DRUG METABOLISM AND DISPOSITION

\[ \text{Fig. s1} \quad \text{Ratio of T-5224 metabolites generated by recombinant human cytochrome P450.} \quad ^{14}\text{C-T-5224 (2 \mu M) was incubated for 30 min at 37}\quad ^{\circ}\text{C and radioactive peak of metabolites were detected. Mock 1; control for CYP1A2 and CYP2D6*1. Mock 2; control for CYP2B6, CYP2C8, CYP2C19, CYP2E1 and CYP3A4. Mock 3; control for 2A6 and 2C9*1.} \]
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DRUG METABOLISM AND DISPOSITION

Fig. s2  UGT contents in recombinant human UGT microsomes used in screening study (A), and kinetics study and inhibition study (B). UGT contents were estimated by quantitative immunoblot analysis using anti-UGT1A or anti-UGT2B antibodies. Known-concentration UGT1A1
Supplemental Data

or UGT2B4 was used as standards. Values are represented as mean ± standard error (n = 3 to 6).
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DRUG METABOLISM AND DISPOSITION

**Fig. s3** HPLC profiles of T-5224 and its glucuronides in liver microsomes from human, rat and monkey. T-5224 (10 μM) was incubated at 37°C with UDP-glucuronic acid for 10 min in pooled liver microsomes.
Supplemental Data

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DRUG METABOLISM AND DISPOSITION
Fig. s4 ¹H-NMR spectrum of T-5224 (A) and hydroxyl-glucuronide isolated from monkey bile (B).