

Optimized Methods for Targeted Peptide-Based Quantification of Human Uridine 5'-Diphosphate-Glucuronosyltransferases in Biological Specimens Using Liquid Chromatography-Tandem Mass Spectrometry

Yuichiro Sato, Masanori Nagata, Kazuhiro Tetsuka, Kouichi Tamura, Aiji Miyashita, Akio Kawamura, and Takashi Usui

Drug Metabolism Research Laboratories, Astellas Pharma Inc., Yodogawa-ku, Osaka, Japan (Y.S., M.N., A.M., A.K., T.U.); Astellas Research Institute of America LLC., Skokie, Illinois (K.Te., K.Ta.)

Received November 28, 2013; accepted March 4, 2014

ABSTRACT

The aim of this study was to optimize methods for quantifying 13 uridine 5'-diphosphate-glucuronosyltransferase (UGT) isoforms (UGT1A1, 1A3, 1A4, 1A6, 1A7, 1A8, 1A9, 1A10, 2B4, 2B7, 2B10, 2B15, and 2B17) in human liver, intestinal, and kidney microsomes, and in recombinant human UGT-expressing insect cell membranes (rhUGTs) by targeted peptide-based quantification using liquid chromatography-tandem mass spectrometry. Production of targeted peptides was compared by combining three denaturing agents (urea, sodium deoxycholate, and octyl glucoside) and three denaturing temperatures (37°C, 60°C, and 95°C) followed by tryptic digestion for 2–20 hours. Denaturing conditions and digestion times yielding high production efficiency varied markedly among

isoforms and specimens, indicating the importance of specific optimization. Each UGT isoform was quantified using the methods found to be optimal. The expression of 10 (1A1, 1A3, 1A4, 1A6, 1A9, 2B4, 2B7, 2B10, 2B15, and 2B17), 6 (1A1, 1A3, 1A4, 1A10, 2B7, and 2B17), and 3 (1A6, 1A9, and 2B7) isoforms was detected in human liver, intestinal, and kidney microsomes, respectively, and levels were reproducible using multiple protocols. All isoforms were quantified in rhUGTs. Determining the levels of UGTs in human tissue specimens and those in rhUGTs is important for estimating the contribution of glucuronidation to body clearance based on in vitro-in vivo extrapolation.

Introduction

Uridine 5'-diphosphate-glucuronosyltransferases (UGTs) catalyze glucuronidation, the transfer of glucuronic acid from uridine 5'-diphosphate glucuronic acid to substrates (Dutton, 1980). In addition to cytochrome P450 (P450)-mediated oxidation, glucuronidation is an important biotransformation for various xenobiotics as well as endogenous compounds (Tukey and Strassburg, 2000; Wells et al., 2004). Glucuronidation accounts for approximately 35% of phase II drug metabolism (Evans and Relling, 1999) and represents the primary clearance pathway for 10% of the 200 most prescribed drugs (Williams et al., 2004). Evaluation of the contribution of glucuronidation to body clearance is therefore an important issue in drug development.

The contribution of metabolic pathways to drug metabolism in vivo can be estimated from the activity of enzymes determined in vitro (Iwatsubo et al., 1997a,b). In principle, in vitro metabolic activity (activity per enzyme molecule) determined using a recombinant enzyme is multiplied by the amount of enzyme in human tissues to calculate the in vivo metabolic rate. To extrapolate in vitro glucuronidation activities,

information must be acquired regarding the amounts of UGTs expressed in recombinant systems as well as in human tissues.

Although immunochemical approaches such as western blotting or enzyme-linked immunosorbent assays are standard methods for protein quantification, preparing UGT isoform-specific antibodies is generally difficult because of their high degree of sequence similarity (Milne et al., 2011). An alternative approach is targeted peptide-based protein quantification using liquid chromatography-tandem mass spectrometry (LC-MS/MS) (Gerber et al., 2003). In this approach, the protein of interest is enzymatically digested after denaturation, and the proteotypic peptide fragment is quantified using LC-MS/MS. Typically, a peptide of the same sequence labeled with stable isotopes is used as the internal standard (IS). Major advantages of LC-MS/MS-based quantification include its specificity, large quantification range ($>10^3$), and ability to analyze multiple analytes simultaneously.

The results of studies on LC-MS/MS-based UGT quantification in human tissue specimens are not always consistent (Fallon et al., 2008; Harbourt et al., 2012; Ohtsuki et al., 2012; Sato et al., 2012b; Schaefer et al., 2012). This may be explained by differences in the proteotypic peptides used as the calibrants or experimental procedures, such as denaturation and proteolytic digestion. Certain studies indicate that the accuracy of targeted peptide-based protein quantification varies according to the method used as well as the protein, and that optimizing

This study was supported by Astellas Pharma Inc. and Astellas Research Institute of America, LLC.

dx.doi.org/10.1124/dmd.113.056291.

□ This article has supplemental material available at dmd.aspetjournals.org.

ABBREVIATIONS: HIM, human intestinal microsomes; HKM, human kidney microsomes; HLM, human liver microsomes; IS, internal standard; LC-MS/MS, liquid chromatography-tandem mass spectrometry; OG, octyl glucoside; PAR, peak area ratio; P450, cytochrome P450; rhUGTs, recombinant human UGT-expressing insect cell membranes; SDC, sodium deoxycholate; UGT, uridine 5'-diphosphate-glucuronosyltransferase.

proteolysis is important. For example, Proc et al. (2010) compared 14 methods for tryptic digestion of human plasma proteins using various denaturing agents and found that sodium dodecyl sulfate and sodium deoxycholate (SDC) facilitated the generation of digested peptides. Balogh et al. (2012) investigated targeted peptide-based quantification of organic anion-transporting polypeptide in human liver membranes using various denaturing methods and found that the production of organic anion-transporting polypeptide-proteotypic peptides varied markedly among denaturing agents, and that the highest yields were obtained using SDC.

Here, we compared 36 methods for their ability to efficiently produce proteotypic peptides of 13 UGT isoforms using three denaturing agents, three denaturing temperatures, and four digestion times. Protein quantification in human tissue specimens and recombinant human UGT-expressing insect cell membranes (rhUGTs) was then performed utilizing methods that were optimized for each isoform and biologic specimen.

Materials and Methods

Chemicals and Reagents. Bovine serum albumin, urea, ammonium bicarbonate, and methyl methanethiol sulfonate were purchased from Wako Pure Chemicals (Osaka, Japan), and tris(2-carboxyethyl)phosphine was from Tokyo Chemical Industry (Tokyo, Japan). Sequencing-grade modified trypsin was purchased from Promega (Madison, WI). SDC, octyl glucoside (OG), unlabeled standard peptides (purity $\geq 95\%$), and AQUA peptides (peptides whose sequences were identical to the standard peptides and labeled at their C termini with ^{13}C and ^{15}N) were obtained from Sigma-Aldrich (St. Louis, MO). Human liver microsomes (HLM; 20 mg/ml), human intestinal microsomes (HIM; 10 mg/ml), and human kidney microsomes (HKM, 10 mg/ml) were obtained from XenoTech LLC (Lenexa, KS). Solutions of rhUGTs (5 mg/ml) were purchased from BD Biosciences (San Jose, CA). The protein concentrations of the biologic specimens were provided by the suppliers. All other chemicals and reagents used were commercially available with guaranteed purity. Appropriate containment and personal protective equipment were used for handling potentially biologically hazardous materials.

Equipment. An LC-MS/MS system comprising a Prominence high-performance liquid chromatography (Shimadzu, Kyoto, Japan) and QTRAP5500 (AB SCIEX, Foster City, CA) was used.

Denaturing and Digestion Methods. Samples were prepared in duplicate. A 2- μl aliquot of human tissue specimens (pooled HLM, HIM, or HKM) or a mixture of 13 rhUGT solutions was added to a 14- μl aliquot of 100 mM ammonium bicarbonate. A denaturing solution (2 μl) and 50 mM tris(2-carboxyethyl)phosphine (2 μl) were added and incubated to denature and reduce the proteins. Denaturing solutions were 10 M urea, 10% SDC, and 10% OG. Incubation conditions were 37°C for 1 hour, 60°C for 1 hour, and 95°C for 15 minutes. Methyl methanethiol sulfonate (2 μl , 200 mM, isopropanol solution) was added to the preparations at room temperature for 10 minutes to alkylate thiol residues. A 5- μl aliquot of trypsin aqueous solution (0.5 mg/ml) was added and incubated at 37°C for 2, 4, 8, and 20 hours. Tryptic digestion was terminated by adding a 4-fold volume of 2% formic acid. A 2- μl aliquot of an IS solution (mixture of 13 AQUA peptide solutions) was added and mixed. After filtration using centrifugal filters, a 12- μl aliquot of supernatant was injected into the LC-MS/MS system. LC was performed using a Synergi Fusion-RP 100A 100 \times 2.00 mm, 2.5- μm column (Phenomenex, Torrance, CA) at a flow rate of 0.5 ml/min. The LC mobile phases, 0.1% formic acid (A) and acetonitrile with 0.1% (v/v) formic acid (B), were delivered with a gradient program of 5%–16% B for 4 minutes, 16%–50% B for 9 minutes, 50%–100% B for 9.01 minutes, 100% B for 10 minutes, 100%–5% B for 10.01 minutes, and 5% B for 12 minutes. The sample rack and column temperatures were maintained at 10°C and 45°C, respectively. Analysis was performed in positive multiple reaction monitoring mode, and data were processed using the Analyst 1.5.2 software package (AB SCIEX). The peak area ratio (PAR) was calculated to determine the efficiency of denaturing and digestion methods for producing UGT-proteotypic peptides.

Quantification of UGTs in Biologic Specimens. Biologic specimens (HLM, HIM, HKM, and rhUGTs) were denatured under optimum conditions and then alkylated as described earlier. These samples were prepared in triplicate. After adding the IS solution, tryptic digestion was performed for 2, 4, and 8 hours.

For calibration, a reference standard solution of UGT-proteotypic peptides and IS solution were added to the bovine serum albumin solution (20 mg/ml) digested as described earlier. Quantification was performed based on the calibration curves. The lower limit of quantification was set as follows: 1 pmol/mg protein for HLM (3 pmol/mg protein for UGT2B17), 2 pmol/mg protein for HIM and HKM, and 50 pmol/mg protein for rhUGTs.

Results

LC-Multiple Reaction Monitoring. A high-throughput LC-multiple reaction monitoring method for simultaneous determination of 13 UGT-proteotypic peptides was developed. To select proteotypic peptides that could be digested efficiently, we preliminarily analyzed tryptic digests of rhUGTs using enhanced mass spectrometry scanning, and identified peptide fragments by ProteinPilot (AB SCIEX) according to a published method (data not shown) (Sato et al., 2012a). Proteotypic peptides identified with the highest confidence values here or reported to yield highly reproducible quantities by others were selected as analytes (Supplemental Table 1) (Fallon et al., 2008; Harbourt et al., 2012; Sato et al., 2012b; Fallon et al., 2013b). Each peptide sequence was confirmed as unique among all sequences in the database of the Universal Protein Resource Knowledge Base. All 13 analytes were determined in a single 12-minute run (Supplemental Fig. 1).

Characterization of Denaturing and Digestion Methods. The efficiencies of urea, SDC, and OG for generating high yields of proteotypic peptides of 13 UGT isoforms in four biologic specimens were compared by combining three denaturing temperatures (37°C, 60°C, and 95°C) and four tryptic digestion times (2, 4, 8, and 20 hours). The results of generating UGT2B7-proteotypic peptide in HLM are shown in Fig. 1. The highest PAR was achieved when the sample of HLM was denatured in the presence of SDC at 37°C for 1 hour followed by tryptic digestion for 4 hours. High yields of peptides ($\geq 75\%$ of the highest PAR) were also achieved using three other denaturing conditions as follows: SDC at 60°C for 1 hour, OG at 37°C for 1 hour, and OG at 60°C for 1 hour.

Similar experiments were performed using other isoforms and biologic specimens (Supplemental Fig. 2). Denaturing conditions that generated high yields of targeted peptides are summarized in Fig. 2. Proteotypic peptides of 10 isoforms (1A1, 1A3, 1A4, 1A6, 1A9, 2B4, 2B7, 2B10, 2B15, and 2B17) were detected in HLM. For each peptide, a PAR $\geq 75\%$ was achieved using multiple conditions, and denaturation with SDC or OG at 37°C generated high yields of these 10 peptides (Fig. 2A). In HIM, proteotypic peptides of six isoforms (1A1, 1A3, 1A4, 1A10, 2B7, and 2B17) were detected, and high yields of these peptides were generated when the sample of HIM was

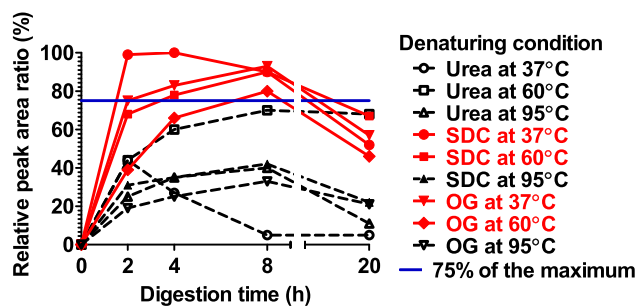


Fig. 1. Comparison of the efficiency of generating UGT2B7-proteotypic peptide in HLM. Pooled HLM were denatured at 37°C for 1 hour, 60°C for 1 hour, or 95°C for 15 minutes in the presence of 1 M urea, 1% SDC, or 1% OG followed by tryptic digestion. Digestion was terminated after 2, 4, 8, and 20 hours followed by addition of IS. The relative PAR was determined by defining the highest PAR as 100%. Denaturing conditions that yielded relative PARs $\geq 75\%$ of the maximum and the corresponding data are shown in red.

Isoform	Denaturing agents								
	Urea			SDC			OG		
	Denaturing temperature (°C)								
	37	60	95	37	60	95	37	60	95
1A1									
1A3									
1A4									
1A6									
1A9									
2B4									
2B7									
2B10									
2B15									
2B17									

Isoform	Denaturing agents								
	Urea			SDC			OG		
	Denaturing temperature (°C)								
	37	60	95	37	60	95	37	60	95
1A6									
1A9									
2B7									

Isoform	Denaturing agents								
	Urea			SDC			OG		
	Denaturing temperature (°C)								
	37	60	95	37	60	95	37	60	95
1A1									
1A3									
1A4									
1A6									
1A7									
1A8									
1A9									
1A10									
2B4									
2B7									
2B10									
2B15									
2B17									

Fig. 2. Optimum denaturing conditions for generating UGT-proteotypic peptides in HLM (A), HIM (B), HKM (C), and rhUGTs (D). Pooled HLM, HIM, HKM, and a mixture of 13 rhUGTs were denatured using nine conditions and incubated with trypsin for 2, 4, 8, and 20 hours. Denaturing conditions that yielded relative PARs $\geq 75\%$ of the maximum are highlighted.

denatured in the presence of SDC at 60°C (Fig. 2B). Proteotypic peptides of three isoforms (1A6, 1A9, and 2B7) were detected in HKM. UGT1A6- proteotypic peptide was efficiently produced when the sample of HKM was denatured with SDC or OG at 95°C. Specific peptides of the other two isoforms (UGT1A9 and 2B7) were produced at high yields when denatured with SDC or OG at 60°C (Fig. 2C). In rhUGTs, all 13 proteotypic peptides were produced in high yield when specimens were denatured with SDC at 37°C (Fig. 2D).

Quantification of UGTs in Biologic Specimens. Quantification methods of UGTs in HLM, HIM, HKM, and rhUGTs were optimized based on the results presented earlier. Denaturing conditions were as follows: HLM-SDC, 37°C, 1 hour; HIM-SDC, 60°C, 1 hour; HKM-SDC, 60°C, 1 hour and SDC, 95°C, 15 minute; and rhUGTs-SDC, 37°C, 1 hour. Samples were digested for 2, 4, and 8 hours to ensure that reactions reached a plateau. The quantities of targeted peptides were quantified according to calibration curves with correlation coefficients of ≥ 0.98 . The highest values from three time points were defined as the final result.

The results for quantifying UGT2B7 in 16 individual HLM are presented in Fig. 3, showing that the level of UGT2B7-proteotypic peptide plateaued with low intra-assay variability. Similar experiments were performed with the other isoforms and biologic specimens (Supplemental Figs. 3 and 4), and the protein levels are summarized in Table 1. The level of UGT2B7 in 16 individual HLM was highest (average 200 pmol/mg protein) among 10 isoforms, followed in order by 1A1, 2B4, 2B15, 1A4, 2B10, 1A9, 2B17, 1A6, and 1A3. The level of UGT2B17 was < 3 pmol/mg protein in 5 of 16 individual HLM. In six individual HIM, the level of UGT2B17 was highest (average 112 pmol/mg protein) among six isoforms, followed in order by 1A1, 1A10, 2B7, 1A3, and 1A4. In pooled HKM of four individuals, the levels of UGT1A6, 1A9, and 2B7 were 13.9, 171, and 95.3 pmol/mg protein, respectively. The levels of 13 UGTs in rhUGTs ranged from 292 to 4500 pmol/mg protein.

Discussion

Targeted peptide-based quantification of UGTs in human tissue specimens using LC-MS/MS has been reported (Fallon et al., 2008; Harbourt et al., 2012; Ohtsuki et al., 2012; Sato et al., 2012b; Schaefer et al., 2012). These studies used various denaturing and digestion methods but did not clearly state how the method was optimized. Here, we compared the efficiencies of urea, SDC, and OG for generating high yields of proteotypic peptides of 13 UGT isoforms in four biologic specimens. The efficiencies of proteolysis by trypsin in the presence of these denaturing agents are generally higher than those in the absence of the denaturant (Katayama et al., 2001, 2004; Zhang and Li, 2004; Zhou et al., 2006; Chen et al., 2007; Masuda et al., 2008; Proc et al., 2010; Balogh et al., 2012). As done by others, the best practice would be investigating multiple peptides per protein when available (Harbourt et al., 2012; Ohtsuki et al., 2012; Schaefer et al., 2012; Fallon et al., 2013b; Achour et al., 2014). However, the properties of each peptide might respond differently according to the denaturing conditions. Therefore, our approach was to ensure that the results were reliable by optimizing the denaturing method as well as using one peptide yielding a good outcome.

Urea is easily separated from the analyte using LC-MS/MS (Chen et al., 2007). SDC aids high-efficiency digestion of membrane proteins (Zhou et al., 2006; Masuda et al., 2008; Proc et al., 2010; Balogh et al., 2012), and OG increases the efficiency of tryptic digestion and does not interfere with MS analysis (Katayama et al., 2001, 2004; Zhang and Li, 2004). Because the denaturing temperature and tryptic digestion time vary among these studies, we tested three temperatures (37°C, 60°C, and 95°C) and four digestion times (2, 4, 8, and 20 hours).

The results of generating UGT2B7-proteotypic peptide in HLM varied markedly depending on the conditions. Interestingly, the amount of targeted peptide decreased after longer digestion (20 hours) for most conditions (Fig. 1). These results suggest that this UGT2B7-proteotypic

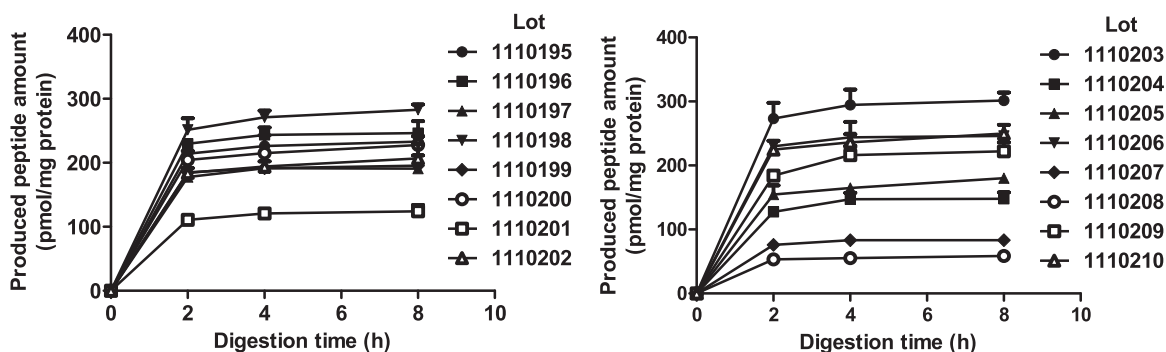


Fig. 3. Quantification of UGT2B7-proteotypic peptide in 16 individual HLM. HLM were denatured at 37°C for 1 hour in the presence of 1% SDC and incubated with trypsin for 2, 4, and 8 hours after addition of IS.

peptide may have been adsorbed or degraded during the reaction, and that the yields reflect its loss relative to production.

Proteotypic peptides of 10 isoforms (1A1, 1A3, 1A4, 1A6, 1A9, 2B4, 2B7, 2B10, 2B15, and 2B17) were detected in HLM, which was consistent with the results reported very recently by another study (Fallon et al., 2013b). In HIM, proteotypic peptides of six isoforms (1A1, 1A3, 1A4, 1A10, 2B7, and 2B17) were detected. Peptides of five of these isoforms (1A1, 1A3, 1A4, 2B7, and 2B17) were also detected in HLM, but denaturing conditions generating high yields of these peptides were not completely consistent between HLM and HIM (Fig. 2B). Proteotypic peptides of three isoforms (1A6, 1A9, and 2B7) were detected in HKM. Although these three peptides were also detected in HLM, efficient denaturing conditions in HLM did not necessarily generate high yields of these peptides in HKM (Fig. 2C). In rhUGTs, all 13 proteotypic peptides were detected. It is noteworthy that 10 peptides were produced at high yields using urea which was not efficient for generating any peptides in human microsomal samples (Fig. 2D). Results of the production efficiencies suggest that the effective denaturing conditions varied according to the nature of the biologic specimen, even for the same targeted peptide. Therefore,

to quantify UGTs, it is important to optimize conditions for a particular peptide and its source.

Quantification methods of UGTs in HLM, HIM, HKM, and rhUGTs were optimized based on the results of the production efficiency. The amount of targeted peptides did not consistently depend on digestion time, and the highest yields were obtained after incubation for 2–8 hours (Fig. 1; Supplemental Fig. 2). Thus, our strategy for quantification was to add IS solution before starting the tryptic digestion. This allowed normalizing of any loss of the targeted peptide caused by adsorption or degradation throughout proteolysis. Further, quantification was performed at 2, 4, and 8 hours after digestion to ensure that reactions reached a plateau. For most isoforms, high yields of targeted peptides were obtained with multiple denaturing conditions including those adopted, indicating that the levels determined by the adopted methods were reproducible using multiple protocols.

The level of UGT2B7 was the highest in HLM. Average levels in 16 individual HLM were comparable to the levels in pooled HLM of 50 individuals for all isoforms except UGT1A3 and 2B17, which showed large interindividual variability with coefficient of variation values of 99.9% and 112%, respectively. UGT2B17 was present in

TABLE 1.
Protein levels of UGT isoforms in biologic specimens

Isoform	HLM				HIM				HKM ^c	rhUGT
	Individual			Pool ^a	Individual			Pool ^b		
	Ave ^d	S.D.	%CV		Ave ^e	S.D.	%CV			
1A1	124	63.1	50.9	135	39.6	21.4	54.1	30.6	ND	3740
1A3	20.6	20.6	99.9	11.7	1.93 ^f	1.10	56.9	1.30	ND	1280
1A4	84.0	30.4	36.2	80.0	1.60 ^f	0.90	56.5	1.40	ND	826
1A6	22.6	12.7	55.9	26.4	ND	ND	ND	13.9	1980	1980
1A7	ND	ND	ND	ND	ND	ND	ND	ND	ND	1250
1A8	ND	ND	ND	ND	ND	ND	ND	ND	ND	4500
1A9	61.1	22.2	36.4	57.5	ND	ND	ND	ND	171	1900
1A10	ND	ND	ND	ND	17.9	6.95	38.7	13.1	ND	1960
2B4	102	47.6	46.9	98.8	ND	ND	ND	ND	ND	883
2B7	200	67.8	33.9	152	15.7	9.81	62.6	12.5	95.3	2720
2B10	69.3	31.7	45.7	49.5	ND	ND	ND	ND	ND	292
2B15	99.7	42.6	42.7	90.8	ND	ND	ND	ND	ND	878
2B17	54.3	60.8	112	25.5	112	36.6	32.7	72.8	ND	2860

Ave, average; ND, not determined because protein levels were below the lower limit of quantification (LLOQ; 1 pmol/mg protein for HLM, and 2 pmol/mg protein for HIM and HKM).

^aPooled microsomes of 50 individuals (31 males and 19 females).

^bPooled microsomes of 4 individuals (2 males and 2 females).

^cPooled microsomes of 18 individuals (11 males and 7 females).

^dAverage value of 16 individuals (9 males and 7 females). The levels of UGT1A6 and UGT2B17 were below the LLOQ in one and five samples, respectively. Values below the LLOQ were treated as zero for calculation.

^eAverage value of 6 individuals (6 males).

^fProtein levels in four individual samples were below the LLOQ and were extrapolated, because the analyte peak was detected clearly (the signal to noise ratio >5). The average was calculated using extrapolated values.

undetectable or minimally detectable levels in five individuals (approximately 30%), which is consistent with results published recently (Fallon et al., 2013b). We previously demonstrated that the levels of UGT1A1 and 2B7 correlate significantly with corresponding marker activities (estradiol 3 β -glucuronidation and morphine 3-O-glucuronidation) with coefficient of determination (r^2) values of 0.9434 and 0.5184, respectively (Sato et al., 2012b). Although the levels of UGT1A1 and 2B7 determined here were higher than those in our previous study using urea, the correlation between protein levels and marker activities was similar ($r^2 = 0.9256$ and $P < 0.0001$ for UGT1A1, $r^2 = 0.6408$ and $P = 0.0002$ for UGT2B7). These results suggest that relative protein levels can be investigated without optimizing the quantification method.

The level of UGT2B7 was also the highest in HIM. Average levels in six individual HIM were comparable to the levels in pooled HIM of 18 individuals. Five other isoforms (1A1, 1A3, 1A4, 1A10, and 2B17) were measurable, and levels of 1A3 and 1A4 were very low, which is similar to the results reported by another study (Fallon et al., 2013a). Low levels of UGT1A6, 1A7, 1A8, and 1A9 in HIM were reported by another study (<8.4 pmol/mg protein) (Harbourt et al., 2012). The difference between the results of that study and those presented here may be due to interindividual variability, because the number of specimens was low in both studies.

The level of UGT1A9 was the highest in HKM. UGT2B7 was also detected at a high level. Although the number of specimens was small, these results suggest that UGT1A9 is the major UGT isoform present in human kidney, and that UGT2B7 is highly expressed in all three tissues. Isoforms detected in HKM (1A6, 1A9, and 2B7) are consistent with the results reported by Fallon et al. (2013a). Detection of UGT1A1, 1A4, 1A7, 1A8, and 1A10 in pooled HKM was reported by Harbourt et al. (2012). Resolving this discrepancy will require further research.

In rhUGTs, although the total protein concentration of each membrane solution was equal (5 mg/ml), the levels of UGTs were markedly different among isoforms. As shown in a previous study using CYPs (Iwatsubo et al., 1997b), determining UGT levels in rhUGTs is useful for estimating the glucuronidation activity per UGT isoform. This value can be further multiplied by protein levels in human tissue specimens to assess the contribution of glucuronidation to body clearance based on in vitro–in vivo extrapolation.

In conclusion, optimum denaturing and digestion methods for targeted peptide–based quantification of UGTs in biologic specimens were established. Yields of targeted peptides varied greatly among methods. The expression of 10, 6, and 3 isoforms was detected in human liver, intestine, and kidney, respectively. The data were reproducible, because different protocols yielded similar results. This report demonstrates the quantities of 13 UGT isoforms in HLM, HIM, HKM, and rhUGTs, as determined by optimizing proteolysis conditions followed by analysis using LC-MS/MS.

Authorship Contributions

Participated in research design: Sato, Nagata, Tetsuka.

Conducted experiments: Sato.

Contributed new reagents or analytic tools: Sato, Nagata, Tetsuka.

Performed data analysis: Sato, Nagata.

Wrote or contributed to the writing of the manuscript: Sato, Nagata, Tetsuka, Tamura, Miyashita, Kawamura, Usui.

References

Achour B, Russell MR, Barber J, and Rostami-Hodjegan A (2014) Simultaneous quantification of the abundance of several cytochrome P450 and uridine 5'-diphospho-glucuronosyltransferase

- enzymes in human liver microsomes using multiplexed targeted proteomics. *Drug Metab Dispos* 42:500–510.
- Balogh LM, Kimoto E, Chupka J, Zhang H, and Lai Y (2012) Membrane protein quantification by peptide-based mass spectrometry approaches: studies on the organic anion-transporting polypeptide family. *J Proteomics Bioinform* 5:4:003.
- Chen EI, Cociorva D, Norris JL, and Yates JR, 3rd (2007) Optimization of mass spectrometry-compatible surfactants for shotgun proteomics. *J Proteome Res* 6:2529–2538.
- Dutton GJ (1980) *Glucuronidation of Drugs and Other Compounds*. CRC Press, Boca Raton, FL.
- Evans WE and Relling MV (1999) Pharmacogenomics: translating functional genomics into rational therapeutics. *Science* 286:487–491.
- Fallon JK, Harbourt DE, Maleki SH, Kessler FK, Ritter JK, and Smith PC (2008) Absolute quantification of human uridine-diphosphate glucuronosyl transferase (UGT) enzyme isoforms 1A1 and 1A6 by tandem LC-MS. *Drug Metab Lett* 2:210–222.
- Fallon JK, Neubert H, Goosen TC, and Smith PC (2013a) Targeted precise quantification of 12 human recombinant uridine-diphosphate glucuronosyl transferase 1A and 2B isoforms using nano-ultra-high-performance liquid chromatography/tandem mass spectrometry with selected reaction monitoring. *Drug Metab Dispos* 41:2076–2080.
- Fallon JK, Neubert H, Hyland R, Goosen TC, and Smith PC (2013b) Targeted quantitative proteomics for the analysis of 14 UGT1As and -2Bs in human liver using NanoUPLC-MS/MS with selected reaction monitoring. *J Proteome Res* 12:4402–4413.
- Gerber SA, Rush J, Stemman O, Kirschner MW, and Gygi SP (2003) Absolute quantification of proteins and phosphoproteins from cell lysates by tandem MS. *Proc Natl Acad Sci USA* 100:6940–6945.
- Harbourt DE, Fallon JK, Ito S, Baba T, Ritter JK, Glish GL, and Smith PC (2012) Quantification of human uridine-diphosphate glucuronosyl transferase 1A isoforms in liver, intestine, and kidney using nanobore liquid chromatography-tandem mass spectrometry. *Anal Chem* 84:98–105.
- Iwatsubo T, Hirota N, Ooie T, Suzuki H, Shimada N, Chiba K, Ishizaki T, Green CE, Tyson CA, and Sugiyama Y (1997a) Prediction of in vivo drug metabolism in the human liver from in vitro metabolism data. *Pharmacol Ther* 73:147–171.
- Iwatsubo T, Suzuki H, Shimada N, Chiba K, Ishizaki T, Green CE, Tyson CA, Yokoi T, Kamataki T, and Sugiyama Y (1997b) Prediction of in vivo hepatic metabolic clearance of YM796 from in vitro data by use of human liver microsomes and recombinant P-450 isozymes. *J Pharmacol Exp Ther* 282:909–919.
- Katayama H, Nagasu T, and Oda Y (2001) Improvement of in-gel digestion protocol for peptide mass fingerprinting by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry. *Rapid Commun Mass Spectrom* 15:1416–1421.
- Katayama H, Tabata T, Ishihama Y, Sato T, Oda Y, and Nagasu T (2004) Efficient in-gel digestion procedure using 5-cyclohexyl-1-pentyl-beta-D-maltoside as an additive for gel-based membrane proteomics. *Rapid Commun Mass Spectrom* 18:2388–2394.
- Masuda T, Tomita M, and Ishihama Y (2008) Phase transfer surfactant-aided trypsin digestion for membrane proteome analysis. *J Proteome Res* 7:731–740.
- Milne AM, Burchell B, and Coughtrie MW (2011) A novel method for the immunoquantification of UDP-glucuronosyltransferases in human tissue. *Drug Metab Dispos* 39:2258–2263.
- Ohtsuki S, Schaefer O, Kawakami H, Inoue T, Liehner S, Saito A, Ishiguro N, Kishimoto W, Ludwig-Schwelling E, and Ebner T, et al. (2012) Simultaneous absolute protein quantification of transporters, cytochromes P450, and UDP-glucuronosyltransferases as a novel approach for the characterization of individual human liver: comparison with mRNA levels and activities. *Drug Metab Dispos* 40:83–92.
- Proc JL, Kuzyk MA, Hardie DB, Yang J, Smith DS, Jackson AM, Parker CE, and Borchers CH (2010) A quantitative study of the effects of chaotropic agents, surfactants, and solvents on the digestion efficiency of human plasma proteins by trypsin. *J Proteome Res* 9:5422–5437.
- Sato Y, Miyashita A, Iwatsubo T, and Usui T (2012a) Simultaneous absolute protein quantification of carboxylesterases 1 and 2 in human liver tissue fractions using liquid chromatography-tandem mass spectrometry. *Drug Metab Dispos* 40:1389–1396.
- Sato Y, Nagata M, Kawamura A, Miyashita A, and Usui T (2012b) Protein quantification of UDP-glucuronosyltransferases 1A1 and 2B7 in human liver microsomes by LC-MS/MS and correlation with glucuronidation activities. *Xenobiotica* 42:823–829.
- Schaefer O, Ohtsuki S, Kawakami H, Inoue T, Liehner S, Saito A, Sakamoto A, Ishiguro N, Matsumaru T, and Terasaki T, et al. (2012) Absolute quantification and differential expression of drug transporters, cytochrome P450 enzymes, and UDP-glucuronosyltransferases in cultured primary human hepatocytes. *Drug Metab Dispos* 40:93–103.
- Tukey RH and Strassburg CP (2000) Human UDP-glucuronosyltransferases: metabolism, expression, and disease. *Annu Rev Pharmacol Toxicol* 40:581–616.
- Wells PG, Mackenzie PI, Chowdhury JR, Guillemette C, Gregory PA, Ishii Y, Hansen AJ, Kessler FK, Kim PM, and Chowdhury NR, et al. (2004) Glucuronidation and the UDP-glucuronosyltransferases in health and disease. *Drug Metab Dispos* 32:281–290.
- Williams JA, Hyland R, Jones BC, Smith DA, Hurst S, Goosen TC, Peterkin V, Koup JR, and Ball SE (2004) Drug-drug interactions for UDP-glucuronosyltransferase substrates: a pharmacokinetic explanation for typically observed low exposure (AUC_i/AUC) ratios. *Drug Metab Dispos* 32:1201–1208.
- Zhang N and Li L (2004) Effects of common surfactants on protein digestion and matrix-assisted laser desorption/ionization mass spectrometric analysis of the digested peptides using two-layer sample preparation. *Rapid Commun Mass Spectrom* 18:889–896.
- Zhou J, Zhou T, Cao R, Liu Z, Shen J, Chen P, Wang X, and Liang S (2006) Evaluation of the application of sodium deoxycholate to proteomic analysis of rat hippocampal plasma membrane. *J Proteome Res* 5:2547–2553.

Address correspondence to: Yuichiro Sato, Drug Metabolism Research Laboratories, Astellas Pharma Inc., 2-1-6 Kashima, Yodogawa-ku, Osaka 532-8514, Japan. E-mail: yuichiro.sato@astellas.com