Characterization of UGTs Active against SAHA and Association between SAHA Glucuronidation Activity Phenotype with UGT Genotype

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Abstract
Suberoylanilide hydroxamic acid (SAHA) is a histone deacetylase inhibitor used in the treatment of cutaneous T-cell lymphoma and in clinical trials for treatment of multiple other cancers. A major mode of SAHA metabolism is by glucuronidation via the UDP-glucuronosyltransferase (UGT) family of enzymes. To characterize the UGTs active against SAHA, homogenates from HEK293 cell lines overexpressing UGT wild-type or variant UGT were used. The hepatic UGTs 2B17 and 1A9 and the extrahepatic UGTs 1A8 and 1A10 exhibited the highest overall activity against SAHA as determined by $V_{\text{max}}/K_m$ (16 ± 6.5, 7.1 ± 2.2, 33 ± 6.3, and 24 ± 2.4 nL min$^{-1}$μg UGT protein$^{-1}$, respectively), with UGT2B17 exhibiting the lowest $K_m$ (300 μmol/L) against SAHA of any UGT in vitro. Whereas the UGT1A8p.Ala173Gly variant exhibited a 3-fold ($P < 0.005$) decrease in glucuronidation activity against wild-type UGT1A8, the UGT1A8p.Cys277Tyr variant exhibited no detectable glucuronidation activity: a similar lack of detectable glucuronidation activity was observed for the UGT1A10p.Gly139Lys variant. To analyze the effects of the UGT2B17 gene deletion variant (UGT2B17*2) on SAHA glucuronidation phenotype, human liver microsomes (HLM) were analyzed for glucuronidation activity against SAHA and compared with UGT2B17 genotype. HLM from subjects homozygous for UGT2B17*2 exhibited a 43% ($P < 0.01$) decrease in glucuronidation activity and a 73% ($P < 0.002$) increase in $K_m$ compared with HLMs from subjects homozygous for the wild-type UGT2B17*1 allele. Overall, these results suggest that several UGTs play an important role in the metabolism of SAHA and that UGT2B17-null individuals could potentially exhibit altered SAHA clearance rates with differences in overall response.

Introduction
Histone deacetylases (HDAC) are a family of enzymes that have been identified as a promising target to reverse aberrant epigenetic states associated with cancer via regulation of levels of histone and nonhistone protein acetylation and gene expression (1). Several classes of HDAC inhibitors have been developed to target HDACs, with hydroxamic acid–derived compounds found to be effective and potent pan-HDAC isoform inhibitors (2). The Food and Drug Administration–approved hydroxamic acid HDAC inhibitor, suberoylanilide hydroxamic acid (SAHA; Zolinza; Merck), is currently prescribed to treat cutaneous T-cell lymphoma and is also being tested in several phase I to III clinical trials for the treatment of a variety of other cancers including breast, lung, and colon (3, 4).

Although SAHA is commonly administered at a conventional oral dose of 400 mg daily, the dose may be reduced to 300 mg daily or 300 mg 5 days a week in certain patients due to increased toxicity including diarrhea, fatigue, nausea, and anorexia (3, 5). Pharmacokinetic studies have identified two inactive metabolites in patients treated with SAHA, SAHA-glucuronide and 4-anilino-4-oxobutanoic acid (Fig. 1; refs. 6, 7). In serum from patients treated with SAHA, SAHA-glucuronide and 4-anilino-4-oxobutanoic acid were on average 3- to 4-fold and 10- to 13-fold higher, respectively, than that of the parent compound (5). Because the apparent terminal half-life of SAHA-O-glucuronide was shown to be similar (~1.8 hours) to that of SAHA itself but much longer (~6–9 hours) for 4-anilino-4-oxobutanoic acid (7), the overall contribution of glucuronidation to SAHA metabolism is significant.

The UDP-glucuronosyltransferase (UGT) superfamily of enzymes catalyze the glucuronidation of a variety of endogenous compounds such as bilirubin and steroid hormones, as well as xenobiotics such as drugs and environmental carcinogens (8–10). Based on structural and amino acid sequence homology, UGTs are classified into several families and subfamilies (11). The UGT2B family members are derived from independent genes located on chromosome 4. The entire UGT1A family is derived from a single gene locus on chromosome 2, coding for 9 functional proteins that differ only in their amino-terminus as a result of alternate splicing of independent exon 1 regions to a shared carboxy terminus encoded by exons 2 to 5 (8, 12). These independent exon 1A regions are responsible for the wide range of substrate specificity shown by the UGT1A family of enzymes, whereas the common region coded by exons 2 to 5 is involved in UDP glucuronic acid binding (10). The specific enzymes responsible for the glucuronidation of SAHA have as yet to be identified.

Polymorphisms in drug metabolizing enzymes have been shown to alter drug efficiency and/or toxicity leading to interindividual differences in drug response (13, 14). Polymorphisms have been identified for many of the UGT genes and several studies have examined their potential role in risk for several cancer types (15–17). Specifically, the UGT2B17 gene deletion polymorphism has been shown to be associated with decreased carcinogen detoxification and increased risk for lung adenocarcinoma (18). UGTs also have a role in modifying response to chemotherapeutic
agents (19). For example, the UGT1A1*28 allele was associated with decreased glucuronidation activity in liver microsomes against SN-38, the major metabolite of irinotecan (20), and irinotecan-treated patients homozygous for the UGT1A1*28 allele exhibit higher levels of its active metabolite (SN-38; ref. 21) and exhibit significant toxicity (19). Similarly, the UGT2B7p.His268Tyr variant was recently associated with decreased liver microsomal glucuronidation activity against major active tamoxifen metabolites, which may be linked to altered patient response to tamoxifen (22); in some cases, however, the UGT2B7p.His268Tyr variant was shown to have no effect or exhibit increased activity against certain substrates (e.g., morphine; ref. 23). As glucuronidation is an important mode of SAHA metabolism in vivo, it is possible that variant UGTs may contribute to differences in SAHA toxicity and potentially in overall patient response to SAHA. The goals of the present study were to fully characterize the human UGT(s) responsible for the glucuronidation of SAHA and to determine whether genetic variations in the major SAHA-glucuronidating enzymes potentially contribute to altered metabolism of SAHA.

**Materials and Methods**

**Chemicals and materials.** SAHA was synthesized in the Organic Synthesis Core at Penn State University College of Medicine. Alamethicin, β-glucuronidase, and bovine serum albumin were purchased from Sigma-Aldrich. DMEM, Dulbecco’s PBS (minus calcium chloride and magnesium chloride), fetal bovine serum, penicillin-streptomycin, geneticin (G418), the Platinum Pfx DNA polymerase, and the pcDNA3.1/V5-His-TOPO mammalian expression vector were all obtained from Invitrogen. The Hotstar PCR kit, the RNeasy Mini and Midi kits, and the QIAEX II gel extraction kit were all purchased from Qiagen. The BCA protein assay kit was purchased from Pierce. All restriction enzymes were purchased from New England Biolabs. PCR primers were purchased from IDT. All other chemicals were purchased from Fisher Scientific unless specified otherwise.

**Tissues.** The normal human liver tissue specimens used for these studies have been described previously (24). Colon tissue was obtained from the Penn State College of Medicine Tissue Bank. Human liver microsomes (HLM) were prepared through differential centrifugation as previously described (25) and stored (10–20 mg microsomal protein/mL) at −80 °C. Microsomal protein concentrations were measured using the BCA assay.

Colon homogenate was prepared as described below for cell line homogenates.

**UGT overexpressing cell lines and cell homogenate preparation.** Four new UGT-overexpressing cell lines were generated for the experiments outlined in this study. UGT1A5 cDNA was amplified from the UGT1A5 pENTR223.1 vector (Open Biosystems) using primers UGT1A5S (sense, 5′-TGGATGCGACAGCTCAGGTCTC-3′) and UGT1A5AS (antisense, 5′-TTCTCAATGGGTCTGTGGATTTG-3′), corresponding to nucleotides −4 to +22 and +1584 to +1608, respectively, relative to the UGT1A5 translation start site. The PCR product encompassing the UGT1A5 coding region (1612 bp) was subcloned into the pcDNA3.1/V5-His-TOPO mammalian expression vector, and confirmation of insert orientation and sequence was performed using 2 vector primers and 2 internal UGT1A5 primers (5′-CAGACCCCTTTCACCTGCG-3′ and 5′-AGCCACAT-TAATGCTTTTG-3′, corresponding to nucleotides +452 to +472 and +876 to +896, respectively, relative to the UGT1A5 translation start site) to be previously described (26). The cloned UGT1A5 insert was compared with the sequence described in Genbank and was confirmed to be 100% homologous to the wild-type UGT1A5 sequence.

Site-directed mutagenesis using the QuikChange site-directed mutagenesis kit (Stratagene) was performed for the UGT1A7*2 and UGT1A7*4 alleles [encoding the UGT1A7p.(Asn129Lys) + (Arg131Lys) and UGT1A7p.Trp208Arg variants, respectively] using a previously synthesized wild-type UGT1A7 clone (27). The UGT1A7*2 allele [encoding the UGT1A7p.(Asn129Lys) + (Arg131Lys) + (Trp208Arg) variant] was made using the newly synthesized UGT1A7*2 clone as template. Primer set UGT1A7-129/131S (sense, 5′-GCAAGGATTTGTTAATGCGGAAAATGTAGAATATCTTAAGG-3′) and UGT1A7-129/131AS (antisense, 5′-CCCTTATAAGTCTACTAATTTTCTCG-GTCATTAAAAACTCCTGCG-3′), corresponding to nucleotides +371 to +422 relative to the UGT1A7 translation start site, were used to generate constructs that encode for the amino acid changes at UGT1A7 codons 129 (Asn→Lys) and 131 (Arg→Lys). Primer set UGT1A7-208S (5′-CAAGTGGTGCATGATGTTGCCTCTCTCTCTCTAAGGCTAGATG-3′) and UGT1A7-208AS (5′-CAAGTGGTGCATGATGTTGCCTCTCTCTCTCTAAGGCTAGATG-3′), corresponding to nucleotides +607 to +632 relative to the UGT1A7 translation start site, were used to generate constructs that encode for the amino acid change at codon 208 (Trp→Arg). The italicized base for each primer indicates the bp change. Site-directed mutagenesis PCR amplification and construct confirmation were performed as previously described (26) with newly generated UGT-overexpressing constructs compared with sequences described in GenBank—all were confirmed to be 100% homologous to their respective allele.

Each construct was used to generate individual UGT-overexpressing human embryonic kidney fibroblast HEK293 cell lines by standard...
independent experiments were performed for rate determination assays with all assays within each experiment performed in triplicate; two performed for kinetic analysis of UGT-overexpressing cell homogenates, glucuronidation activity. Three independent experiments were always untransfected HEK293 cell homogenate protein as a negative control for using HLM as a positive control for glucuronidation activity and to reaction as the reference. SAHA-glucuronide was confirmed by sensitivity and SAHA-glucuronide peaks using the known amount of SAHA to each unconjugated SAHA after calculating the area under the curve for the SAHA acetonitrile; a linear gradient to 72% buffer B over 3 min was performed. and 94.4% buffer A [10 mmol/L ammonium acetate (pH 5.0) and 10% acetonitrile]; a linear gradient to 72% buffer B over 3 min was performed. Reactionswerecentrifugedat13,000g for 10 min at 4 °C, and supernatants were collected and then diluted 5-fold using water/acetonitrile (1:1). Glucuronidation assays. Glucuronidation activities of HLM or homogenates from human UGT-overexpressing cell lines or human colon against SAHA were determined after an initial incubation of colon homogenate (200 μg protein), cell line homogenate (400 μg protein for an initial screen for activity or 40 μg protein for kinetic analysis), or HLM (20 μg protein) with alanethinic (50 μg/mg protein) for 15 min in an ice bath similar to that described previously (24, 27, 30). Incubations (40 μL for cell homogenate and 20 μL for HLM and colon homogenate) were subsequently performed at 37 °C in 50 mmol/L Tris buffer (pH 7.5), 10 mmol/L MgCl₂, 4 mmol/L UDPGA, and 65 μmol/L to 8 mmol/L of substrate. Screening assays for glucuronidation activity in UGT-overexpressing cell lines were performed using a 1-h incubation, and reactions were terminated by the addition of the same volume as the initial reaction of cold acetonitrile. Reactions were centrifuged at 13,000 g for 10 min at 4 °C, and supernatants were collected and then diluted 5-fold using water/acetonitrile (1:1). Glucuronidation assays (1–10 μL) were analyzed for SAHA glucuronidation using a Waters ACQUITY UPLC System as previously described (26) on a gradient (9, 26, 28, 29). All UGT-overexpressing cell lines were grown in DMEM to 80% confluence as described above before preparation of cell homogenates by resuspending pelleted cells in TBS [25 mmol/L Tris base, 138 mmol/L NaCl, and 2.7 mmol/L KCl (pH 7.4)] and subjecting them to three rounds of freeze-thaw before gentle homogenization. Cells were stored at −80 °C in 100-μL aliquots. Total homogenate protein concentrations were measured using the BCA protein assay.

Western blot analysis. UGT protein levels were determined by Western blot analysis for all UGT-overexpressing cell lines examined in this study as previously described (26). For UGT1A1-overexpressing cells, the UGT1A antibody from Gentest was used and a UGT1A standard of known concentration (Gentest) was used for normalization; for UGT2B-overexpressing cells, a previously described UGT2B-specific antibody was used and a UGT2B7 standard of known concentration (Gentest) was used for normalization (26). Relative UGT protein levels were expressed as the mean of three independent experiments, and all activity assays were normalized relative to UGT expression in the respective UGT-overexpressing cell line.

Glucuronidation assays. Glucuronidation activities of HLM or homogenates from human UGT-overexpressing cell lines or human colon against SAHA, cell lines overexpressing wild-type UGTs were examined. Real-time PCRs were performed in a volume of 10 μL containing equal amounts of cDNA (20 ng) from each liver specimen. PPIA was used as the normalizing “housekeeping” gene for expression because this gene was shown to exhibit the least variability of any housekeeping gene tested using the TaqMan hsaeri.endogenous control plate (Applied Biosystems) using total RNA from a series of six of the tested liver specimens described above.4 PCRs were carried out in 384-well thin-well PCR plates covered with optically clear sealing film (Applied Biosystems). Amplification, detection, and data analysis were performed using the ABI 7900HT sequence detection system and SDS 2.2.2 software using standard settings provided by ABI (Applied Biosystems). Results were expressed using the comparative threshold method following the recommendations of the manufacturer (Applied Biosystems). The threshold cycle number (CT) value for UGT2B17 was normalized against PPIA and calculated as ΔCT = CTUGT2B17 − CT_PPIA. Relative UGT2B17 mRNA expression was expressed as fold of UGT2B17 versus reference: F = 2−ΔΔCT. HLM genotyping for UGT2B17 has been previously described (18).

Statistical analysis. Michaelis-Menten kinetic constants were determined using Prism Version 5 software (GraphPad Software). The Student’s t test (two-sided) was used for comparing rates and kinetic values of glucuronidation. Student’s t test was used to compare the serum and urine of patients treated with SAHA, it has yet to be determined which UGT enzymes are responsible for this activity (6, 7, 33). To identify the UGTs responsible for the glucuronidation of SAHA, cell lines overexpressing wild-type UGTs were examined. As shown, in glucuronidation assays with UGT1A7-overexpressing cell homogenate (Fig. 2A), homogenate prepared from colon tissue (B), or with HLM (C), the unconjugated SAHA peak was observed at a retention time of 2.85 minutes and a postulated glucuronide peak was observed with a retention time of 2.59 minutes. The postulated glucuronide peak was sensitive to treatment with β-glucuronidase (D), and similar to that observed previously for

4 Unpublished results.

Results

Characterization of the UGTs responsible for SAHA glucuronidation. Although the SAHA glucuronidase has been identified in the serum and urine of patients treated with SAHA, it has yet to be determined which UGT enzymes are responsible for this activity (6, 7, 33). To identify the UGTs responsible for the glucuronidation of SAHA, cell lines overexpressing wild-type UGTs were examined. As shown, in glucuronidation assays with UGT1A7-overexpressing cell homogenate (Fig. 2A), homogenate prepared from colon tissue (B), or with HLM (C), the unconjugated SAHA peak was observed at a retention time of 2.85 minutes and a postulated glucuronide peak was observed with a retention time of 2.59 minutes. The postulated glucuronide peak was sensitive to treatment with β-glucuronidase (D), and similar to that observed previously for

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other compounds (34), this glucuronide peak was not alkali-sensitive (data not shown), suggesting that this glucuronide was an O-glucuronide of SAHA. The mass spectrum for the SAHA-O-glucuronide observed at 2.59 minutes [with protonated molecules (M+H)+ of 441] showed a clear daughter ion at m/z 265 corresponding to the (M+H)+ of SAHA (Fig. 2E), a pattern that was identical to the previously published ion spectra for SAHA-glucuronide (35).

To screen for activity against SAHA, 400 µg of UGT-overexpressing cell homogenate was used in in vitro glucuronidation activity assays. Of the UGTs tested, UGTs 1A3, 1A7, 1A8, 1A9, 1A10, and 2B17 exhibited high levels of glucuronidation against SAHA. Although UGTs 1A1, 1A4, 1A6, and 2B7 exhibited detectable levels of glucuronidation against SAHA, their K_Ms were all above 8 mmol/L (accurate K_Ms could not be measured). No detectable glucuronidation activity against SAHA was observed in our in vitro glucuronidation assays for UGTs 1A5, 2B4, 2B10, 2B11, and 2B15. All of the peaks identified by UPLC for UGTs active against SAHA exhibited the same retention time (2.59 minutes; data not shown) as that observed for UGT1A7 or HLM (see Fig. 2).

Kinetic analysis was performed for those UGTs (1A3, 1A7, 1A8, 1A9, 1A10, and 2B17) for whom accurate kinetic data could be calculated. The kinetic plots for this screening are illustrated in Fig. 3. As shown in Table 1, UGTs 2B17, 1A8, and 1A10 were considerably more active against SAHA compared with any other UGT family member as determined by V_max/K_M. UGT2B17 exhibited the lowest K_M (300 µmol/L) of all the UGTs screened, with the UGT exhibiting the closest K_M being 3-fold higher (UGT1A10) than that observed for UGT2B17. UGT2B17 exhibited a 2.3- and 9.4-fold higher level of glucuronidation activity compared with the other 2 active hepatic UGTs (1A9 and 1A3, respectively) as determined by V_max/K_M.

In vitro characterization of effects on SAHA glucuronidation by missense polymorphic variants of active UGTs. To address potential interindividual differences in glucuronidation rates against SAHA, kinetic analysis of missense variants of the most active UGTs, 1A7, 1A8, and 1A10, were performed. UGT1A7 has 3 common (>2% prevalence in Caucasians, African Americans, or Asians) amino acid-changing polymorphisms that confer four known variant alleles: wild-type UGT1A7*1, UGT1A7*2, UGT1A7*3, and UGT1A7*4 (36). UGT1A8 has two known variant alleles, UGT1A8*2 and UGT1A8*3, which contain amino acid changes encoding UGT1A8p.Ala173Gly and UGT1A8p.Cys277Tyr, respectively (37). UGT1A10 has a variant allele, UGT1A10*2, that contains an amino acid change encoding UGT1A10p.Gly139Lys (38). There are no known common missense variants for UGT2B17.

As shown in Table 2, the UGT1A8p.Ala173Gly variant exhibited a 3-fold (P < 0.005) decrease in glucuronidation activity compared with the UGT1A8 wild-type; no detectable glucuronidation activity was observed for the UGT1A8p.Cys277Tyr variant using up to 8 mmol/L SAHA. Similarly, no glucuronidation activity against SAHA was observed for the UGT1A10p.Gly139Lys variant. However,
both the UGT1A8p.Cys277Tyr and UGT1A10p.Gly139Lys variants did exhibit detectable levels of activity against 4-methylumbelliferone (data not shown), indicating that the UGT1A8- and UGT1A10-variant cell homogenates used in these glucuronidation assays were active. No significant difference in glucuronidation activity was observed against SAHA for any of the UGT1A7 variants.

**UGT2B17 genotype and characterization of SAHA glucuronidation in HLM.** Data from recent studies have shown the

### Table 1. Kinetic analysis of SAHA-glucuronide formation using UGT-overexpressing cell homogenates

<table>
<thead>
<tr>
<th>UGT</th>
<th>$K_M$ (mmol/L)</th>
<th>$V_{max}$ (pmol·min$^{-1}$·µg$^{-1}$)$^*$</th>
<th>$V_{max}/K_M$ (nL·min$^{-1}$·µg$^{-1}$)$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGT1A3</td>
<td>3.4 ± 0.8</td>
<td>6.0 ± 1.8</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>UGT1A7</td>
<td>2.7 ± 0.6</td>
<td>10 ± 0.4</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>UGT1A8</td>
<td>1.9 ± 0.1</td>
<td>62 ± 7.6</td>
<td>33 ± 6.3</td>
</tr>
<tr>
<td>UGT1A9</td>
<td>1.6 ± 0.5</td>
<td>11 ± 1.3</td>
<td>7.1 ± 2.2</td>
</tr>
<tr>
<td>UGT1A10</td>
<td>1.0 ± 0.1</td>
<td>24 ± 2.7</td>
<td>24 ± 2.4</td>
</tr>
<tr>
<td>UGT2B17</td>
<td>0.3 ± 0.1</td>
<td>3.7 ± 0.7</td>
<td>16 ± 6.5</td>
</tr>
</tbody>
</table>

**NOTE:** All reactions were performed using 40 µg of UGT-overexpressing cell homogenate and incubated for 1 h at 37°C. Kinetic data are reported as mean ± SD for three independent experiments.

$^*$ $V_{max}$ values are adjusted per µg of the corresponding UGT protein as determined by Western blot analysis.

**Figure 3.** Representative concentration curves for SAHA-glucuronide formation. Representative concentration curves for homogenates from wild-type UGT-overexpressing cell lines and HLM. SAHA-glucuronide formation assays were performed for 1 h at 37°C using 40 µg total cell homogenate protein or 20 µg HLM total protein.
presence of a prevalent polymorphic deletion of the entire UGT2B17 gene (39, 40) that was associated with reduced glucuronidation activity against tobacco carcinogens in assays of HLM (32) and in the levels of glucuronlated tobacco carcinogens in the urine of smokers (18). To examine the effect of the UGT2B17 whole-gene deletion on SAHA glucuronidation activity in human liver, HLMs were prepared from normal liver tissue from 100 independent subjects, which were screened for SAHA glucuronidation activities using 200 μmol/L SAHA (the apparent KM for SAHA-glucuronidation is from UGT2B17). In addition, the KM is significantly increased (75%; P = 0.0018) in HLM from UGT2B17 (*2/*2) subjects compared with HLM from UGT2B17 (*1/*1) subjects. This is consistent with the higher level of activity observed for UGT2B17 relative to the other hepatic SAHA-glucuronidating enzymes UGT1A9 and UGT1A3. The increase in KM from 1.2 to 2.1 mmol/L in HLMs from subjects homozygous for the wild-type UGT2B17 (*2/*2) deletion genotype is also clearly consistent with the apparent KM observed in vivo for UGTs 2B17, 1A9, and 1A3, and are consistent with the fact that all three UGTs are expressed in liver and are contributing to SAHA glucuronidation. Interestingly, the KM values obtained in vitro for the UGT-overexpressing cell lines (outlined in Table 1) are highly consistent with the KM values obtained in HLM from subjects with intact UGT2B17 versus HLM from subjects deleted for UGT2B17, indicating a high degree of integrity in the HEK293 cell line system for in vitro analysis of glucuronidation kinetics for individual UGTs. The fact that 45% of overall glucuronidation activity is still observed in HLM from subjects homozygous for the wild-type UGT2B17 (*2/*2) deletion genotype is also consistent with the pattern observed in vivo for UGTs 2B17, 1A9, and 1A3, and are consistent with the fact that all three UGTs are expressed in liver and are contributing to SAHA glucuronidation.

The extrahepatic enzymes UGT1A8 and 1A1 also exhibited high levels of activity against SAHA in vivo, suggesting that they too may play an important role in SAHA glucuronidation in vivo. This effect could potentially be most important in terms of target tissues where these enzymes are expressed and for which SAHA is being used as a chemotherapeutic target including lung, breast, colon, small intestine, and tissues of the aerodigestive tract (17, 29, 41, 42). As colon is a high expresser of extrahepatic UGTs (41, 43), the significant levels of glucuronidation activity against

Discussion

Pharmacokinetic studies have identified two inactive metabolites in patients treated with SAHA, SAHA-glucuronide and 4-anilino-4-oxobutanoic acid (Fig. 1; refs. 6, 7). Although the specific enzymes responsible for the formation of 4-anilino-4-oxobutanoic acid has not as yet been investigated, results from the present analysis show that UGT2B17 is a major hepatic enzyme involved in the glucuronidation of SAHA. The apparent KM exhibited by UGT2B17 against SAHA was 5- and 11-fold lower than that observed for the other active hepatic UGTs, 1A9 and 1A3, respectively. Based on a comparison of the levels of SAHA-glucuronidation formation in HLM from UGT2B17-deleted subjects [excluding the UGT2B17 (*2/*2) genotype] versus HLM from subjects wild-type for UGT2B17, ~45% of hepatic SAHA glucuronidation is from UGT2B17. In addition, the KM is significantly increased (75%; P = 0.0018) in HLM from UGT2B17 (*2/*2) subjects compared with HLM from UGT2B17 (*1/*1) subjects. This is consistent with the higher level of activity observed for UGT2B17 relative to the other hepatic SAHA-glucuronidating enzymes UGT1A9 and UGT1A3. The increase in KM from 1.2 to 2.1 mmol/L in HLMs from subjects homozygous for the wild-type UGT2B17 (*2/*2) deletion genotype is also clearly consistent with the apparent KM observed in vitro for UGTs 2B17, 1A9, and 1A3, and are consistent with the fact that all three UGTs are expressed in liver and are contributing to SAHA glucuronidation. Interestingly, the KM values obtained in vitro for the UGT-overexpressing cell lines (outlined in Table 1) are highly consistent with the KM values obtained in HLM from subjects with intact UGT2B17 versus HLM from subjects deleted for UGT2B17, indicating a high degree of integrity in the HEK293 cell line system for in vitro analysis of glucuronidation kinetics for individual UGTs. The fact that 45% of overall glucuronidation activity is still observed in HLM from UGT2B17-deleted subjects are consistent with a role for UGTs 1A9 and, potentially, 1A3, being important in hepatic SAHA glucuronidation.

The extrahepatic enzymes UGT1A8 and 1A1 also exhibited high levels of activity against SAHA in vivo, suggesting that they too may play an important role in SAHA glucuronidation in vivo. This effect could potentially be most important in terms of target tissues where these enzymes are expressed and for which SAHA is being used as a chemotherapeutic target including lung, breast, colon, small intestine, and tissues of the aerodigestive tract (17, 29, 41, 42). As colon is a high expresser of extrahepatic UGTs (41, 43), the significant levels of glucuronidation activity against

Table 2. Kinetic analysis of SAHA-glucuronide formation by UGT1A variants

<table>
<thead>
<tr>
<th>UGT allele</th>
<th>Amino acid change</th>
<th>KM (mmol/L)</th>
<th>Vmax (μmol·min⁻¹·μg⁻¹)</th>
<th>Vmax/KM (nL·min⁻¹·μg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGT1A7*1</td>
<td></td>
<td>2.7 ± 0.6</td>
<td>10 ± 0.4</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>UGT1A7*2</td>
<td>(Asn129Lys)+Arg131Lys</td>
<td>2.5 ± 0.3</td>
<td>12 ± 2.5</td>
<td>5.0 ± 1.6</td>
</tr>
<tr>
<td>UGT1A7*3</td>
<td>(Asn129Lys)+Arg131Lys+Trp208Arg</td>
<td>2.3 ± 0.3</td>
<td>15 ± 4.0</td>
<td>6.7 ± 2.0</td>
</tr>
<tr>
<td>UGT1A7*4</td>
<td>Trp208Arg</td>
<td>2.2 ± 0.5</td>
<td>12 ± 4.4</td>
<td>5.4 ± 1.9</td>
</tr>
<tr>
<td>UGT1A8*1</td>
<td></td>
<td>1.9 ± 0.1</td>
<td>62 ± 7.6</td>
<td>33 ± 6.3</td>
</tr>
<tr>
<td>UGT1A8*2</td>
<td>Ala173Gly</td>
<td>3.0 ± 0.7</td>
<td>34 ± 2.6</td>
<td>12 ± 2.2</td>
</tr>
<tr>
<td>UGT1A8*3</td>
<td>Cys277Tyr</td>
<td>No detectable activity</td>
<td>24 ± 2.7</td>
<td>24 ± 2.4</td>
</tr>
<tr>
<td>UGT1A10*1</td>
<td></td>
<td>1.0 ± 0.1</td>
<td></td>
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<tr>
<td>UGT1A10*2</td>
<td>Gly193Lys</td>
<td>No detectable activity</td>
<td></td>
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</table>

Note: All reactions were performed using 40 μg of UGT-overexpressing cell homogenate and incubated for 1 h at 37°C. Kinetic data are reported as mean ± SD for three independent experiments.

*Vmax values are adjusted per μg of the corresponding UGT protein as determined by Western blot analysis.

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SAHA exhibited by colon homogenate in this study is consistent with a potential role for UGTs 1A8 and/or 1A10 in SAHA glucuronidation in extrahepatic tissues. This suggests that functional single nucleotide polymorphisms in these enzymes may potentially be important in interindividual variability in target tissue SAHA glucuronidation and in SAHA absorption within the colon/intestinal tract.

Variants of UGTs have previously been shown to alter drug response and toxicity (13, 44). The UGT1A1*28 allele, which is associated with decreased UGT1A1 expression (45), has been linked to decreased glucuronidation of SN-38, the major active metabolite of Irinotecan, in HLM and in the levels of urinary SN-38-glucuronide in patients treated with Irinotecan (19, 20, 46, 47). These decreases in excretion have been linked to increased Irinotecan toxicity (19, 46, 48), and testing for the UGT1A1*28 allele is a FDA-approved genetic screening test for patients who may be considered for treatment with this agent (49). Similarly, UGT2B10 is the major N-glucuronidating enzyme of nicotine, and the UGT2B10*2 allele, which is associated with inactivation of UGT2B10 due to a Asp>Tyr amino acid change at codon 67, was shown to be linked to a null activity phenotype against nicotine in HLM (50).

Variation in patient response to SAHA has been clinically observed (3, 5, 51). Recent studies have indicated that resistance to HDAC inhibitors such as SAHA may be multifactorial (52), and that a pharmacogenetic mechanism may be responsible for the differences in overall response to SAHA treatment (33, 52). Results from the present study showed significant alterations in SAHA glucuronidation associated with variants in UGTs active against SAHA. Although active against other substrates, the UGT1A8p.Cys277Tyr and UGT1A10p.Gly139Lys variants were shown to be inactive against SAHA in vitro experiments using homogenates from cell lines overexpressing these variants. Although the prevalence of their corresponding alleles are relatively low in the population (~3% in Caucasians; refs. 37, 38), their presence could potentially have high penetrance in terms of target tissue metabolism of SAHA. The UGT1A8p.Ala173Gly variant was associated with decreased glucuronidation activity against SAHA in vitro compared with wild-type UGT1A8; although less penetrant than the UGT1A8p.Cys277Tyr and UGT1A10p.Gly139Lys variants, it is more common (~28% prevalence in Caucasians; ref. 37) and could affect larger segments of the population.

Perhaps most important is the significant decrease in SAHA-glucuronide formation observed in HLM with the UGT2B17-null genotype. The 45% decrease in SAHA-glucuronide formation observed in HLM from subjects homozygous for the UGT2B17*2 allele against SN-38, the major metabolite of Irinotecan (48). Irinotecan-treated patients show significant toxicity, a pattern that contributed to this genotype being a FDA-approved genetic test for Irinotecan treatment (19). Therefore, the similar alteration in glucuronidation activity against SAHA observed in HLM from subjects with the UGT2B17-null genotype suggests that a similarly significant effect on overall levels of circulating SAHA and subsequent toxicity or overall patient response could be observed in UGT2B17-null patients treated with SAHA.

UGT2B17 exhibits high levels of activity against endogenous compounds including androgens as well as many xenobiotics including various types of compounds including carcinogens,

Figure 4. HLM glucuronidation activity and UGT2B17 expression stratified by UGT2B17 genotype. A. SAHA-glucuronide formation versus UGT2B17 genotype in HLM. Glucuronidation activity assays were performed using 200 μmol/L SAHA, and SAHA metabolites were separated by UPLC as described in the Materials and Methods. Real-time PCR was performed using genomic DNA from the same liver specimens for which HLMs were also prepared and used to determine UGT2B17*1/*1, *1/*2, and *2/*2 genotypes. Comparative analysis was performed using ULM from subjects with the UGT2B17*1/*1 genotype as the reference, with the P value shown for HLM from subjects with the UGT2B17*2/*2 genotype; columns, mean; bars, SE. B. UGT2B17 expression versus UGT2B17 genotype in human liver. UGT2B17 expression was determined relative to PPIA as the housekeeping gene by real-time PCR as described in the Materials and Methods. Comparative analysis was performed using the UGT2B17*1/*1 genotype group as the reference, with the P value shown for the UGT2B17*2/*2 genotype group; columns, mean; bars, SE. C. K_m for HLMs versus UGT2B17 genotype. Glucuronidation activity assays and kinetic analyses were performed for the 13 HLM samples that exhibited the UGT2B17*1/*1 genotype, and for 13 randomly chosen HLM from subjects with the UGT2B17*2/*2 genotype. Glucuronidation activity assays and kinetic analyses were performed using 65 to 8,000 μmol/L SAHA, and SAHA metabolites were separated by UPLC as described in the Materials and Methods.
cumarins, anthraquinones, flavonoids, nonsteroidal anti-inflammatory drugs, monoterpenoids, and phenols (53). The UGT2B7 gene deletion could potentially have a significant clinical effect on the metabolism of these as well as other UGT2B7 substrates. For example, urine from smokers homozygous for the UGT2B7*2 allele exhibit a significant reduction in the ratio of NNAL-glucuronide/NNAL, a pattern that was linked to risk for lung adenocarcinoma (18). The UGT2B7 deletion variant has also been associated with altered levels of glucuronides of androstanediol, testosterone, estradiol, and dihydrotestosterone in human serum compared with serum from UGT2B7 (1*/1) or (1*/0) subjects (54, 55). These data are consistent with a clinical effect by the UGT2B7 deletion and a potential effect on SAHA metabolism in vivo. It should be emphasized that characterization of the pathway that produces 4-anilino-4-oxobutanolic acid must be similarly performed to fully evaluate the UGT2B7 deletion on overall SAHA metabolism.

No difference in SAHA-glucuronide formation was observed in HLM from subjects with either one or two intact copies of the UGT2B7 gene. This corresponded with the fact that no difference in UGT2B7 expression was observed in the same liver specimens as determined by real-time PCR. Studies are under way to examine the mechanisms underlying this pattern of UGT2B7 expression.

Together, the data presented in this report suggest that the presence of genetic variation in active UGTs, including UGT2B7, are associated with alterations in SAHA metabolism. Studies are currently on going to determine whether these differences are potentially associated with observed differences in overall SAHA toxicity or patient response to SAHA.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Characterization of UGTs Active against SAHA and Association between SAHA Glucuronidation Activity Phenotype with UGT Genotype

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