Sorafenib Is an Inhibitor of UGT1A1 but Is Metabolized by UGT1A9: Implications of Genetic Variants on Pharmacokinetics and Hyperbilirubinemia

Cody J. Peer1, Tristan M. Sissung1, AeRang Kim2, Lokesh Jain1, Sukyung Woo1, Erin R. Gardner1, C. Tyler Kirkland2, Sarah M. Troutman3, Bevin C. English3, Emily D. Richardson3, Joel Federspiel1, David Venzon4, and William D. Figg1,3

Introduction

Sorafenib tosylate inhibits VEGF receptors and several tyrosine kinases and thus is considered an antiangiogenic agent with dual multikinase activity (1). Although sorafenib is currently approved for the treatment of renal cell and unresectable hepatocellular carcinomas, it may also have activity in other solid tumors, which led to the initiation of several sorafenib-based clinical trials (2–5). There is wide variation in the response and toxicity between patients following sorafenib treatment that seems to be, at least in part, related to cumulative drug exposure (3). For this reason, studies investigating the sources of interindividual variation in sorafenib exposure are needed.

In humans, the majority (77%) of the sorafenib dose is of elimination require glucuronidation catalyzed by UGT1A9 (7, 8), although it remains unclear if other uridine

Abstract

Purpose: Several case reports suggest sorafenib exposure and sorafenib-induced hyperbilirubinemia may be related to a (TA)3/k7 repeat polymorphism in UGT1A1*28 (UGT, uridine glucuronosyl transferase). We hypothesized that sorafenib inhibits UGT1A1 and individuals carrying UGT1A1*28 and/or UGT1A9 variants experience greater sorafenib exposure and greater increase in sorafenib-induced plasma bilirubin concentration.

Experimental Design: Inhibition of UGT1A1-mediated bilirubin glucuronidation by sorafenib was assessed in vitro. UGT1A1*1 and UGT1A9*3 genotypes were ascertained with fragment analysis or direct sequencing in 120 cancer patients receiving sorafenib on five different clinical trials. Total bilirubin measurements were collected in prostate cancer patients before receiving sorafenib (n = 41) and 19 to 30 days following treatment and were compared with UGT1A1*28 genotype.

Results: Sorafenib exhibited mixed-mode inhibition of UGT1A1-mediated bilirubin glucuronidation (IC50 = 18 μmol/L; Ki = 11.7 μmol/L) in vitro. Five patients carrying UGT1A1*28*/28 (n = 4) or UGT1A9*3/*3 (n = 1) genotypes had first dose, dose-normalized areas under the sorafenib plasma concentration versus time curve (AUC) that were in the 93rd percentile, whereas three patients carrying UGT1A1*28*/28 had AUCs in the bottom quartile of all genotyped patients. The Drug Metabolizing Enzymes and Transporters genotyping platform was applied to DNA obtained from six patients, which revealed the ABCC2-24C>T genotype cosegregated with sorafenib AUC phenotype. Sorafenib exposure was related to plasma bilirubin increases in patients carrying 1 or 2 copies of UGT1A1*28 alleles (n = 12 and n = 5; R2 = 0.38 and R2 = 0.77; P = 0.032 and P = 0.051, respectively). UGT1A1*28 carriers showed two distinct phenotypes that could be explained by ABCC2-24C>T genotype and are more likely to experience plasma bilirubin increases following sorafenib if they had high sorafenib exposure.

Conclusions: This pilot study indicates that genotype status of UGT1A1, UGT1A9, and ABCC2 and serum bilirubin concentration increases reflect abnormally high AUC in patients treated with sorafenib. Clin Cancer Res; 18(7); 2099–107. ©2012 AACR.

Introduction

Sorafenib tosylate inhibits VEGF receptors and several tyrosine kinases and thus is considered an antiangiogenic

Authors’ Affiliations: 1Clinical Pharmacology Program, 2Pharmacology and Experimental Therapeutics Section, 3Molecular Pharmacology Section, 4Biostatistics and Data Management Branch, 5Medical Oncology Branch, and 6HIV/AIDS Malignancy Branch, National Cancer Institute, Bethesda, Maryland.

C.J. Peer and T.M. Sissung contributed equally to the work.

Corresponding Author: William D. Figg, Medical Oncology Branch, CCR, NCI/NIH, 9000 Rockville Pike, Building 10, Room 5A01, Bethesda, MD 20892. Phone: 301-402-3622; Fax: 301-402-8606; E-mail: wf13e@nih.gov
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We investigated UGT1A-mediated (UGT, uridine glucuronosyl transferase) sorafenib glucuronidation in vitro and inhibition of UGT1A1 bilirubin conjugation by sorafenib, and ascertained whether patients carrying UGT1A1*28 treated with sorafenib had increased sorafenib exposure or increased risk of developing hyperbilirubinemia. We also investigated genetic variation in genes encoding sorafenib-metabolizing enzymes (UGT1A9, CYP3A4/5) and the glucuronide transporter, ABCC2. In vitro data show that sorafenib inhibits UGT1A1. Patients carrying UGT1A1*28 had abnormally low exposure to sorafenib if they also carried the −24C>T variant in ABCC2, but had abnormally high exposure to sorafenib if they were wild-type for ABCC2. Patients carrying UGT1A1*28/28 also had greater increases in total bilirubin if sorafenib exposure was high. The clinical data suggest that sorafenib can cause hyperbilirubinemia in patients with Gilbert’s syndrome, which can lead to abnormally high or low sorafenib exposure. Therefore, serum bilirubin concentration increases reflect high area under the curve in patients harboring UGT1A1*28.

Materials and Methods

Materials

The following chemicals were purchased from their respective suppliers: sorafenib tosylate (CTEP, c/o Bayer Schering Pharma); Human CYP3A4 supersones containing CYP450 oxidoreductase and NADPH generating system, 0.5 mmol/L potassium phosphate, pH 7.4, 100 mmol/L Tris buffer, pH 7.4, Human UGT1A1 and UGT1A9 Supersones and UGT Reaction Mix (BD Biosciences), methanol and acetonitrile (Optima grade, Fisher Scientific), formic acid and acetic acid (Sigma-Aldrich). β-glucuronidase was purchased from Roche (Roche Diagnostics). All water used was deionized and purified with a Millipore system.
bibilirubin glucuronidation was also studied. Details are discussed in Supplementary Methods.

Patients and treatment

Patients (n = 120) from 5 clinical trials involving sorafenib treatment were used for subsequent pharmacogenetic analysis, consisting of 2 phase I trials and 3 phase II trials. The phase I trials were BAY-BEV (200 mg twice daily sorafenib with bevacizumab; n = 27; ref. 3), and BAY-KS (200 mg qd or 200–400 mg twice daily sorafenib with ritonavir in Kaposi’s sarcoma; n = 8; unpublished data). AUC data from patients on the BAY-KS trial who received ritonavir were not available; thus potential AUC-influencing drug–drug interactions between ritonavir and sorafenib were not accounted for in future analyses. The phase II trials were BAY-CRPC (400 mg twice daily sorafenib in castration resistant prostate cancer; n = 46; refs. 2, 4), BAY-NSCLC (400 mg twice daily sorafenib in non–small cell lung cancer; n = 22) (20, 21), and BAY-CRC (400 mg twice daily sorafenib with cetuximab in colorectal cancer; n = 17; unpublished data). Written informed consent was obtained from all patients before enrollment on the trials and genotyping was approved by the Institutional Review Board of the National Cancer Institute. All inclusion/exclusion criteria were met with patients administered different doses. Linear pharmacokinetics were not assumed from first-dose AUC values, rather individual patient exposures were correlated to physiologic changes [i.e., HFSR, progression-free survival (PFS), and plasma bilirubin concentration].

Statistical considerations

Hardy–Weinberg equilibrium was tested by the $\chi^2$ test. Genetic linkage statistics were obtained with Haploview (Broad Institute). Comparisons of genotype versus demographic, preclinical measures, and pharmacokinetics were conducted with nonparametric statistical tests including the Wilcoxon rank-sum test or Kruskal Wallis ANOVA. Kruskal–Wallis ANOVA was also used to compare sorafenib AUC with the clinical grade of HFSRs. The Fisher Exact Test was conducted with nonparametric statistical tests including the Wilcoxon rank-sum test or Kruskal Wallis ANOVA. Kruskal–Wallis ANOVA was also used to compare sorafenib AUC and was also used in comparisons between AUC and the bilirubin change from baseline in the different genotype groupings. Cox model analysis was conducted to compare genotypes versus PFS. Statistical significance was assigned if $P < 0.05$ as this study was conducted in an exploratory mode for potential confirmation in independent data.

Results

Case report

The patient was a 12-year-old boy who enrolled on a phase I trial of sorafenib for children with neurofibromatosis type 1 and inoperable plexiform neurofibromas (23). Before treatment, he had a total elevated bilirubin of 2.0 mg/dL with a direct of 0.3 mg/dL, normal serum alanine aminotransferase and aspartate aminotransferase, and was clinically diagnosed with Gilbert's syndrome. This was later confirmed with genetic testing as he was found to be homozygous for the A(TA)$_2$TAA allele of the UGT1A1 gene (i.e., UGT1A1*28/*28). The protocol required a bilirubin concentration within normal limits for study entry, except for patients with Gilbert’s syndrome. He was treated with a dose of 115 mg/m$^2$ twice daily [approximately 50% of the adult maximum tolerated dose (MTD) based on an average adult body surface area of 1.8 m$^2$].

The patient had day 1 pharmacokinetics conducted, and his $\text{AUC}_{0-24h}$ was noted to be 81 µg/h/mL, which is greater than the average $\text{AUC}_{0-24h}$ of 28 ± 17 µg/h/mL observed in children treated at the MTD of 200 mg/m$^2$ on the refractory solid tumor phase I trial (24). The patient came off-treatment after 9 days due to dose limiting grade 3 tumor pain. The protocol was subsequently amended to exclude patients with known Gilbert’s syndrome from trial participation.

On the basis of this case observation and the published case reports that sorafenib induced hyperbilirubinemia in a small number of patients who carry a UGT1A1*28 allele (14, 15), we hypothesized that genetic variation in UGT1A1 was a potential source of alterations in sorafenib exposure and sorafenib-induced hyperbilirubinemia. Moreover, because UGT1A9 is known to primarily glucuronidate sorafenib (8), we hypothesized that UGT1A9 alleles might also contribute to both endpoints; thus, we studied sorafenib and sorafenib-N-oxide glucuronidation by UGT1A1 and UGT1A9 in vitro (Supplementary Methods and Results), and ascertained UGT1A1 and UGT1A9 genotypes in patients treated with sorafenib for comparison with pharmacokinetics and sorafenib-induced hyperbilirubinemia endpoints. Patient characteristics are reported in Table 1.

In vitro sorafenib glucuronidation

Sorafenib glucuronidation by UGT1A9 was confirmed via in vitro metabolism experiments with recombinant UGT1A9 via liquid chromatography-mass spectrometry, whereas a similar experiment with UGT1A1 did not metabolize sorafenib (see Supplementary Results). This is in agreement with literature (7, 8). On the basis of exploratory studies, neither UGT1A1 nor UGT1A9 glucuronidated the CYP3A4-mediated sorafenib-N-oxide (M-2; data not shown). On the basis of previous reports (14, 15, 17), we hypothesized that UGT1A1 could bind sorafenib and that this binding event could inhibit bilirubin glucuronidation. Increasing amounts of sorafenib were added to an in vitro
UGT1A1-catalyzed bilirubin glucuronidation enzyme activity assay to determine the extent and mechanism of inhibition by sorafenib. Bilirubin concentrations used were based on literature reports of its \( K_m \) for UGT1A1-mediated glucuronidation, ranging between 0.2 and 26 \( \mu \)mol/L (25–28). Graphical modeling suggested sorafenib best fits a mixed-mode (mixed-type) inhibitor of UGT1A1 (model correlation \( r = 0.96 \), which shows properties of both a competitive and noncompetitive inhibitor (Supplementary Results). Based on model correlations (noncompetitive \( r = 0.93 \); competitive \( r = 0.88 \)), it was suggested that although sorafenib is a mixed-type inhibitor, it exhibits more non-competitive-type inhibitor characteristics than competitive.

A bilirubin \( K_m \) of 5.9 \( \mu \)mol/L and an inhibitor constant \( (K_i) \) of 11.8 \( \mu \)mol/L were determined empirically through the mixed-type model. The IC\( _{50} \) of sorafenib for UGT1A1-mediated bilirubin glucuronidation was determined to be 18 \( \mu \)mol/L following a separate experiment (see Supplementary Methods). These values were slightly higher than the literature values obtained by studying the mixed-type sorafenib-mediated inhibition of SN38 glucuronidation by UGT1A1, in which \( K_i \) was found to be 2.7 \( \mu \)mol/L (17). The most likely reason for this discrepancy is that UGT1A1 is different substrates used in the experiment (SN38 vs. bilirubin). Because sorafenib shows a competitive inhibition factor (model correlation 0.88), the substrate likely has an affect on inhibitor \( K_i \).

**Table 1. Patient demographics and baseline characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values n (%) or median (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>120 (100.0)</td>
</tr>
<tr>
<td>Male</td>
<td>86 (71.7)</td>
</tr>
<tr>
<td>Female</td>
<td>34 (28.3)</td>
</tr>
<tr>
<td>Age</td>
<td>63.2 (60.9–65.4)</td>
</tr>
<tr>
<td>Race</td>
<td></td>
</tr>
<tr>
<td>Caucasian</td>
<td>99 (82.5)</td>
</tr>
<tr>
<td>African American</td>
<td>11 (9.2)</td>
</tr>
<tr>
<td>Hispanic</td>
<td>4 (3.3)</td>
</tr>
<tr>
<td>Asian</td>
<td>5 (4.2)</td>
</tr>
<tr>
<td>Unknown</td>
<td>1 (0.8)</td>
</tr>
<tr>
<td>BSA (m(^2))</td>
<td>2.0 (1.9–2.0)</td>
</tr>
<tr>
<td>Study/disease</td>
<td></td>
</tr>
<tr>
<td>BAY-BEV/solid tumors</td>
<td>27 (22.5)</td>
</tr>
<tr>
<td>BAY-KS/Kaposi’s sarcoma</td>
<td>8 (6.7)</td>
</tr>
<tr>
<td>BAY-CRPC/prostate</td>
<td>46 (38.3)</td>
</tr>
<tr>
<td>BAY-NSCLC/lung</td>
<td>22 (18.3)</td>
</tr>
<tr>
<td>BAY-CRC/cancer rectum</td>
<td>17 (14.2)</td>
</tr>
<tr>
<td>Albumin (g/dL)</td>
<td>3.6 (3.5–3.7)</td>
</tr>
<tr>
<td>Alkaline phosphatase (U/L)</td>
<td>81.0 (74.0–89.0)</td>
</tr>
<tr>
<td>Total bilirubin (mg/dL)</td>
<td>0.6 (0.6–0.7)</td>
</tr>
<tr>
<td>SGOT (U/L)</td>
<td>26 (24–28)</td>
</tr>
<tr>
<td>CrCl (mL/min)</td>
<td>90.9 (84.8–97.7)</td>
</tr>
<tr>
<td>CrCl (&lt;60 mL/min)</td>
<td>17 (14.2)</td>
</tr>
</tbody>
</table>

Genotype versus sorafenib exposure

On the basis of the case report presented above, data indicating that sorafenib is glucuronidated by UGT1A9 (Supplementary Results), and the sorafenib-mediated inhibition of bilirubin glucuronidation through UGT1A1 (Supplementary Results), we next hypothesized that genetic variants in UGT1A1 and UGT1A9 would affect sorafenib pharmacokinetics and bilirubin metabolism in patients with solid tumors who received sorafenib.

We excluded patients with low CrCl (<60 mL/min) and a single patient with abnormally high SGOT (90 U/L) given the importance of hepatic and renal function in sorafenib pharmacokinetics (Supplementary Results). Carriers of \( UGT1A1^*28/28 \) tended to be younger and have higher median total bilirubin. Patients with wild-type CYP3A4 and CYP3A5 allelics had lower median SGOT and median CrCl than variant allele carriers, respectively. A more detailed summary can be found in the Supplementary Results section. None of the above associations are likely to have altered the results presented in later sections.

Initial analysis of UGT1A1 A(TA)\(^n\)TAA and UGT1A9*3 genotypes versus day 1 dose-normalized sorafenib AUC\(_{12h}\) revealed 5 patients carrying \( UGT1A1^*28/28 \) (\( n = 4 \)) and \( UGT1A9^*3/3 \) (\( n = 1 \)) have higher AUCs than those patients corresponding to any other genotypes with normal CrCl and SGOT (i.e., all > 93\( ^{rd} \) percentile; range = 109.9–198.6 ng/h/mL/mg), and 1 patient carrying \( UGT1A1^*28/28 \) had an AUC in the 76th percentile (AUC = 72.5 ng/h/mL/mg). Interestingly, of the 3 remaining patients carrying \( UGT1A1^*28/28 \), 2 had the lowest AUCs (i.e., less than 3rd percentile; range = 2.7–6.3 ng/h/mL/mg) while one had an AUC in the 21st percentile (AUC = 18.0 ng/h/mL/mg). For this reason, \( UGT1A1^*28 \) status was considered to confer different phenotypes: those having an abnormally high exposure, those having exposures matching the rest of the cohort, and those having low exposure (Fig. 1). Analysis of \( UGT1A1 \) and \( UGT1A9 \) genotypes versus sorafenib AUC in the different genotype groupings did not lead to a statistically significant result due to the wide variability in phenotype in the \( UGT1A1^*28/28 \) genotype grouping (\( P = 0.32 \); Kruskal-Wallis ANOVA; Fig. 1); however, there were strongly significant differences in the odds of having AUCs greater than 93rd percentile (i.e., \( \geq 107 \) ng/h/mL/mg) and also carrying \( UGT1A1^*28/28 \) (\( n = 4 \)) or \( UGT1A9^*3/3 \) (\( n = 1 \); OR [95% CI] = 179.7 (8.5–3787)); \( P < 0.0001 \); Fisher exact test). In addition, there was a strongly significant difference in the odds of carrying \( UGT1A1^*28/28 \) and also having AUCs of 3\( ^{rd} \) or less percentile [OR (95% CI) = 57.3 (2.5–1326); \( P = 0.0084 \); Fisher exact test], further justifying consideration of \( UGT1A1^*28 \) alleles as conferring different phenotypes. Although \( UGT1A9 \) IVS\(-1^B\) (399C>T) and \(-118dT\(_{3\text{G}}\)) in linkage disequilibrium with \( UGT1A1 \) A(TA)\(_n\)TAA (Supplementary Results), these polymorphisms were not associated with alterations in AUC (\( P \geq 0.39 \); data not shown). Neither CYP3A4*1B (\( P = 0.42 \)) nor CYP3A5*3C (\( P = 0.52 \)) status was associated with increased sorafenib exposure. Therefore, \( UGT1A1^*28 \) and possibly...
DMET analysis revealed that only the AUCs (ng/mL) of the UGT1A1 (TA)nTAA genotypes (AUC = 17.3 and 20.2 ng/mL/mg) while the single UGT1A9 3/3 carrier also carried UGT1A1 (TA)nTAA (AUC = 153.3 ng/mL/mg, as indicated by *). UGT1A-impaired implies patients with deficient UGT1A1 or UGT1A9 metabolism based on genomics. Excluded patients (n = 38) are described in the Supplementary Results section and n = 82 individuals were included in this analysis. Of these, AUC data for n = 8 patients participating on BAY-KS were not available; thus potential drug–drug interactions between ritonavir and sorafenib were not accounted for. There was no association between UGT1A1 and UGT1A9 genotype status when compared with sorafenib AUC (P = 0.20; Kruskal–Wallis ANOVA).

The UGT1A9*3 single-nucleotide polymorphism (SNP) seemed to be the major predictive alleles associated with phenotype.

To further study the apparently different phenotypes for patients carrying only UGT1A1*28 alleles (n = 8), we genotyped 1,936 polymorphisms in 225 genes involved in clinical pharmacology with the Drug Metabolizing Enzymes and Transporters (DMET) Plus panel (Coriell Institute). DMET genotyping was only successful (≥90% call rate) in a total of 6 patients with the following AUCs (ng/mL/mg): 2.7, 6.3, 18.0, 109.9, 116.2, and 139.6. DMET analysis revealed that only the ABCC2 -24C>T SNP cosegregated with sorafenib metabolism phenotype. After sequencing the ABCC2 -24C>T SNP in all patients carrying UGT1A1*28/28, it was determined that the patient with the lowest observed AUC (i.e., 2.7 ng/mL/mg) was double variant, whereas patients with the next lowest AUCs (6.3, 18.0, and 72.5 ng/mL/mg) were heterozygous followed by those with the highest AUCs (109.9, 116.2, and 139.6) who carried homozygous wild-type alleles. A single patient with AUC = 198.6 ng/mL/mg was not ascertainable as ABCC2 genotyping by direct sequencing was not successful. Upon sequencing the whole population for ABCC2 -24C>T, it was determined that individuals carrying only variant alleles in this SNP tended to have lower median AUC (29.8 versus 40.5 ng/mL/mg) than individuals carrying 1 or 2 copies of wild-type allele, but this was not statistically significant (P = 0.21). Therefore, the ABCC2 -24C>T SNP only seems to modify AUC phenotype in those carrying only UGT1A1*28 alleles.

Genotype versus bilirubin change following sorafenib

Because previous case-report data indicated that sorafenib might induce bilirubin changes in patients based on UGT1A1 allele status (14, 15), we hypothesized that sorafenib exposure would correspond to greater increases in post-sorafenib bilirubin concentration in those patients with low functioning UGT1A1 alleles (i.e., UGT1A1*28). Analysis of bilirubin versus genotype was only conducted in men with prostate cancer receiving sorafenib as comprehensive bilirubin data were not obtained in other trials. The median change in bilirubin plasma concentration was 0 mg/dL (range = −0.3 to 0.5 mg/dL; n = 45). A total of 3 patients with normal CrCl developed hyperbilirubinemia (i.e., bilirubin concentration ≥1.0 mg/dL) following sorafenib (UGT1A1 (TA)nTAA (TA)n = 1, (TA)n/TTA): n = 2), and 2 patients that presented with hyperbilirubinemia before the sorafenib dose had a further rise in bilirubin concentration following sorafenib (UGT1A1 (TA)n/TTA; n = 1, (TA)n/TTA): n = 1; the latter patient had a 0.4 mg/dL increase). UGT1A1 (TA)n/TTA status was not related to change in bilirubin from baseline (P = 0.39; Fig. 2A). However, regression analysis indicated that sorafenib exposure was related to bilirubin serum concentration in patients with normal CrCl (R² = 0.29; P = 0.005; Fig. 2B). When regression analyses were stratified on the basis of UGT1A1 (TA)n/TTA genotype status, this analysis revealed that sorafenib exposure was not related to bilirubin increases in patients carrying either UGT1A1 (TA)n/TTA or (TA)n/TTA, or UGT1A1 (TA)n/TTA genotypes (R² = 0.43 and 0.030 respectively; P = 0.35 and 0.51; respectively; Fig. 2C and D). However, only 4 individuals carried a copy of UGT1A1 (TA)n, and there is an apparent (albeit nonsignificant) proportional increase in both AUC and sorafenib-induced bilirubin changes consistent with the rather high R² for this genotype grouping. When the data were stratified by UGT1A1 (TA)n/TTA and UGT1A1 (TA)n/TTA genotypes, a significant (or marginally nonsignificant) relationship was observed in both cases with a relatively high correlation (R² = 0.38 and 0.77 respectively; P = 0.032 0.051, respectively; Fig. 2E and F). For patients with the UGT1A1 (TA)n/TTA genotype, the data indicate that bilirubin increased by 0.1 mg/dL for every 25.7 (ng/mL/mg) unit increase in sorafenib AUC. Carriers of UGT1A1 (TA)n/TTA had a similar relationship between bilirubin and AUC (i.e., a 30.9 ng/mL/mg unit increase in AUC corresponded to a 0.1 mg/dL increase in bilirubin). These data are consistent with previous case reports in which UGT1A1 (TA)n/TTA carriers developed jaundice following sorafenib treatment and are also consistent with our results that sorafenib is a mixed inhibitor of UGT1A1.
Genotype versus PFS and toxicity

The CYP3A4*1B allele was weakly associated with PFS according to a Cox model analysis accounting for the multiple clinical trials in which the present patient cohort was ascertained (data not shown). Those patients carrying variant alleles at CYP3A4*1B (n = 19) tended to have shorter PFS than those patients carrying homozygous wild-type alleles (n = 99; P = 0.034). None of the other alleles studied herein were related to PFS (P > 0.05); however, the small numbers of variants within each trial led to wide CIs for the individual HR estimates and the present results with respect to PFS should be interpreted with caution.

Consistent with previous literature (22), the incidence of HFSR was associated with increases in sorafenib AUC (P = 0.0054; Fig. 3). However, all patients who had AUC more than 100 ng/mL/h/mg (n = 7) developed HFSR regardless of genotype (P = 0.0085): thus, although UGT1A1 genotypes were not associated with HFSR in this study (due to heterogeneity of phenotype and low allele frequency), it is likely that UGT1A1*28/*28 and UGT1A9*3 carriers are subject to increased incidence of HFSR as they likely have higher exposure to sorafenib, and this should be confirmed by future studies.

Discussion

The case report presented here involved a child with Gilbert’s syndrome (UGT1A1*28/*28) who upon receiving sorafenib for treatment of a neurofibroma had higher than expected sorafenib exposure. On the basis of this and previously published observations (14–17), we hypothesized and assessed whether UGT1A1 genotype was associated with sorafenib systemic exposure and serum bilirubin concentrations in patients treated with sorafenib. We confirmed previous hypotheses and findings (14–17) that sorafenib is an inhibitor of, but is not metabolized by, UGT1A1; rather, UGT1A9 is involved in sorafenib glucuronidation, which also confirms another report (8). It is
unclear as to the exact reason for the approximately 4- to 10-fold difference in $K_i$ values, however there is one plausible reason. Both this study and literature described sorafenib as a mixed-type inhibitor of UGT1A1, and although sorafenib shows more noncompetitive characteristics (based on higher model correlation), there is a competitive inhibitor portion to the $K_i$ calculation that is potentially altered based on the substrate used. The UGT1A1 substrate used in the literature was SN38, whereas bilirubin was used in this study, and the affinity of that substrate may affect the $K_i$ of sorafenib SN38 has a $K_m$ of 11 $\mu$mol/L for UGT1A1 (29), whereas bilirubin has a reported $K_m$ range of 0.2 to 26 $\mu$mol/L (25–28) due to the numerous stereoisomers present. Furthermore, the $K_i$ of 11 $\mu$mol/L and IC$_{50}$ of 18 $\mu$mol/L are clinically relevant plasma concentrations following 400 mg twice daily dosing, which typically result in maximum plasma concentrations between 11 and 21 $\mu$mol/L after a cycle lasting either 7 or 28 days (30). Although sorafenib is more than 99% plasma protein bound, there is a high enough intrahepatic sorafenib concentration in patients to inhibit the UGT1A1-mediated bilirubin glucuronidation. From our data, patients carrying at least one allele of UGT1A1*28 and having sorafenib AUC more than 60 ng·h/mL or 130 nmol·h/L, were related to increases in serum bilirubin following sorafenib treatment (Fig. 2E and F). This provides clinical evidence that intrahepatic sorafenib concentrations can be achieved in high enough levels to inhibit UGT1A1.

These results suggest that patients carrying only UGT1A1*28, and possibly UGT1A9*3, alleles are at an increased risk of elevated sorafenib concentrations, as well as a greater incidence of HFSR. However, there remained a group of patients carrying UGT1A1*28/*28 and ABC2 -24C>T that had abnormally low sorafenib AUC, thereby complicating this analysis. Nonetheless, sorafenib AUC was well correlated with change in bilirubin concentrations in patients carrying at least a single UGT1A1*28 allele; conversely, it was not correlated with AUC in patients who carried only wild-type genotypes at this site.

The mechanism underlying the observation that individuals carrying UGT1A1*28/*28 also have high AUC, a phenotype that seems to be modified by ABC2 -24C>T, is currently unclear. We tested the hypothesis that UGT1A1*28 alleles were merely in linkage disequilibrium with UGT1A9 alleles [i.e., UGT1A9*-3, UGT1A9 IVS+1 (399C>T), and -118T(-910)] that were truly responsible for the observed differences in AUC. Although linkage was observed, the current UGT1A9 alleles did not explain the association between UGT1A1*28/*28 and AUC. We also tested whether or not ABC2 -24C>T was itself related to AUC regardless of UGT1A1 genotype; this also revealed no apparent association outside of those patients carrying UGT1A1*28/*28. Only parent sorafenib pharmacokinetics were analyzed, however, no bias was expected through analysis of metabolites, because it has previously been shown that altering one metabolic pathway of sorafenib does not alter parent drug pharmacokinetics (6).

These results show that UGT1A1 binds sorafenib; others showed that sorafenib binds to ABC2 and inhibits transport of other substrates but is not transported by ABC2 (31). Elimination of sorafenib glucuronides through ABC2 may also be involved, however it is unclear whether sorafenib glucuronides are actually transported by ABC2. One previous report has also shown that the liver contains binding sites for drugs that act as "sinks" to slowly dissociate bound drug that is subsequently metabolized by liver enzymes (32). It is therefore possible that given the extensive enterohepatic circulation of sorafenib (10, 11), individuals expressing relatively high levels of liver UGT1A1 (i.e., those not carrying UGT1A1*28) and possibly other proteins that bind sorafenib have a greater propensity to extrude sorafenib from the serum and hold sorafenib in the liver where it can be metabolized more extensively before hepatobiliary elimination. This may explain the significantly higher sorafenib AUCs of individuals who have reduced expression of UGT1A1 due to genetic polymorphisms. Still, our hypothesis does not explain why individuals carrying both UGT1A1*28 and ABC2 -24C>T variants have some of the lowest AUCs. As both proteins are involved in bilirubin elimination (19), we expected that patients carrying both UGT1A1*28 and ABC2 -24C>T would have less ability to glucuronidate and eliminate bilirubin due to decreased sorafenib-mediated UGT1A1 inhibition; however, this was not the case in this patient cohort (data not shown). Therefore, the fact that both proteins regulate bilirubin concentrations that could in turn influence binding of sorafenib to UGT1A1 in the liver is not likely to be the cause of ABC2 -24C>T modifying the sorafenib exposure phenotype of patients carrying UGT1A1*28/*28.

Although our data did not point to a specific mechanism underlying associations between UGT1A1*28/*28 and AUC, we observed a clear relationship between sorafenib exposure and bilirubin concentration. We showed that sorafenib inhibits bilirubin glucuronidation as a mixed inhibitor in vitro. Based on this observation and the aforementioned case reports, we assessed whether or not sorafenib inhibited bilirubin glucuronidation in patients and
whether or not this depended on UGT1A1 A(TA)$_2$TAA status. The results indicated that sorafenib exposure was not correlated with total bilirubin concentration in patients that do not carry UGT1A1*28; however, there was an increasingly strong correlation between sorafenib AUC and total bilirubin in patients carrying a single copy or 2 copies of UGT1A1*28. Therefore, hyperbilirubinemia seems to be a marker of high sorafenib exposure in patients expressing low levels of UGT1A1 and care should be taken in monitoring patients carrying UGT1A1*28 that are known to have high sorafenib exposure. Nonetheless, none of the genes studied in this investigation were related to the PFS of the various sorafenib studies with the exception of the weak association with the CYP3A4*1B allele. The results of the present Cox model should be interpreted with caution.

To our knowledge, this pilot study represents the first exploration of sorafenib AUC in patients based on UGT1A1 and UGT1A9 genotype status and suggests that future studies should focus on the UGT1A1 A(TA)$_2$TAA and UGT1A9*3 alleles and bilirubin increases in relation to sorafenib exposure, and HFSR.

Disclosure of Potential Conflicts of Interest
The content of this publication does not necessarily reflect the views or policies of the Department of Health and Human Services, nor does mention of trade names, commercial products, or organization imply endorsement by the U.S. Government. No potential conflicts of interest were disclosed.

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