Sorafenib Hepatobiliary Disposition: Mechanisms of Hepatic Uptake and Disposition of Generated Metabolites

Brandon Swift, Noelia Nebot, Jin K. Lee, Tianxiang Han, William R. Proctor, Dhiren R. Thakker, Dieter Lang, Martin Radtke, Mark J. Gnoth, Kim L.R. Brouwer

Division of Pharmacotherapy and Experimental Therapeutics (BS, NN, JKL, DRT, KLRB), Division of Molecular Pharmaceutics (TH, WRP), UNC Eshelman School of Pharmacy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Drug Metabolism and Pharmacokinetics, Bayer Schering Pharma AG, Wuppertal, Germany (DL, MR, MJG)
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Corresponding Author: Kim L. R. Brouwer UNC Eshelman School of Pharmacy, The University of North Carolina at Chapel Hill, 311 Pharmacy Lane, CB#7569, 3205 Kerr Hall, Chapel Hill, NC 27599-7569. Tel: (919)962-7030. Fax: (919)962-0644. E-mail: kbrouwer@unc.edu.

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 Abbreviation Used
organic anion transport (OAT); organic anion transporting polypeptide (OATP); organic cation transporter (OCT); Chinese hamster ovary (CHO); biliary excretion index (BEI); in vitro biliary clearance (Clbiliary); vascular endothelial growth factor receptor-1/-2/-3 (VEGFR-1/-2/-3); platelet derived growth factor receptor beta (PDGFR-β); cytochrome P450 3A4 (CYP3A4); uridine disphosphate-glucuronsyl-transferase (UGT1A9); area under the concentration-time profile (AUC); aspartate transaminase (AST); solute carrier (SLC); Na⁺-taurocholate co-transporting polypeptide (NTCP); Dulbecco’s modified Eagle’s medium (DMEM); tetraethylammonium (TEA); 1-methyl-4-phenylpyridinium (MPP⁺); 1,1-dimethyl-biguanide hydrochloride (metformin); fetal bovine serum (FBS); Hanks’ balanced salt solution (HBSS)
Abstract

Sorafenib is an orally active tyrosine kinase inhibitor used in the treatment of renal and hepatocellular carcinoma. This study was designed to establish whether transport proteins are involved in the hepatic uptake of sorafenib, and to determine the extent of biliary excretion of sorafenib/metabolites in human hepatocytes. Initial uptake was assessed in freshly isolated, suspended human hepatocytes in the presence of inhibitors and modulators. [14C]Sorafenib (1 µM) uptake at 4°C was reduced by ~61-63% of the uptake at 37°C, suggesting a high degree of passive diffusion. Hepatocyte uptake of [14C]sorafenib was not Na+-dependent or influenced by the organic anion transporter 2 (OAT2) inhibitor ketoprofen. However, initial [14C]sorafenib hepatocyte uptake was reduced by 46 and 30% compared to control values in the presence of the organic anion transporting polypeptide (OATP) inhibitor rifamycin SV, and the organic cation transporter (OCT) inhibitor decynium 22, respectively. [14C]Sorafenib (0.5 to 5 µM) uptake was significantly higher in hOCT1-transfected CHO cells compared to mock cells, and inhibited by the general OCT inhibitor, MPP+. OCT1-mediated uptake was saturable with a K_m of 3.80 ± 2.53 µM and V_max of 116 ± 42 pmol/mg/min. The biliary excretion index (BEI) and _in vitro_ biliary clearance (Cl_biliary) of sorafenib (1 µM) in sandwich-cultured human hepatocytes were low (~11% and 11 ml/min/kg, respectively). Results suggest that sorafenib uptake in human hepatocytes occurs via passive diffusion, and by OCT1 and a rifamycin-sensitive transporter. Sorafenib undergoes modest biliary excretion, predominantly as glucuronide conjugate(s).
Introduction

Sorafenib (Fig. 1), an orally active multikinase inhibitor, blocks tumor cell proliferation by targeting Raf/MEK/ERK, and exerts an antiangiogenic effect by targeting vascular endothelial growth factor receptor-1/-2/-3 (VEGFR-1/-2/-3), and platelet derived growth factor receptor beta (PDGFR-β) tyrosine kinases (Wilhelm et al., 2004). Sorafenib is approved for the treatment of renal and hepatocellular carcinomas, and has demonstrated activity towards other malignancies (Ratain et al., 2006; Miller et al., 2009).

Following oral administration of [14C]sorafenib to healthy volunteers, approximately 77% of a 100 mg oral dose was excreted in feces (51% as parent), and 19% of the dose was excreted in urine as glucuronidated metabolites; approximately 17% of circulating radioactivity in plasma was in the form of sorafenib N-oxide (Lathia et al., 2006). Sorafenib oxidative metabolism is mediated by cytochrome P450 3A4 (CYP3A4) yielding the N-oxide sorafenib metabolite. Sorafenib also undergoes glucuronidation by the uridine disphosphate-glucuronyl-transferase (UGT1A9) pathway (Fig 1; Lathia et al., 2006). Peak plasma concentrations of sorafenib occur within 2 to 3 hours after a single, oral dose (Strumberg et al., 2005); secondary peaks in the plasma concentration-time profile have been attributed to enterohepatic recirculation of sorafenib following cleavage of the glucuronide conjugate or reduction of the N-oxide in the gastrointestinal tract (Lathia et al., 2006). High inter-patient variability in the C_{max} and the area under the concentration-time profile (AUC) in human plasma of sorafenib and the primary metabolite, sorafenib N-oxide, have been reported following multiple oral doses of sorafenib (Strumberg et al., 2007; Miller et al., 2009). Variability in
pharmacokinetics can be caused by inter-individual differences in the metabolizing enzymes and/or the transport proteins, which also have been shown to be subject to polymorphisms. Understanding the mechanisms of hepatic uptake and the extent of biliary excretion of sorafenib is particularly important in patients with unresectable hepatocellular carcinoma, where the target site of sorafenib is the liver.

Transport proteins can play an important role in the clearance of drugs from hepatic sinusoidal blood, and the excretion of parent drug and/or metabolite(s) across the apical membrane into the bile canaliculus. The basolateral proteins that mediate uptake of endogenous and exogenous compounds into hepatocytes include members of the solute carrier (SLC) superfamily: Na\(^+\)-taurocholate co-transporting polypeptide (NTCP), organic anion transporters (OATs), organic cation transporters (OCTs), and organic anion transporting polypeptides (OATPs). NTCP, which is expressed exclusively in the liver, is Na\(^+\)-dependent and predominately accounts for uptake of bile acids (Ho et al., 2004). Recently, a few drugs such as rosuvastatin have been reported to be NTCP substrates (Ho et al., 2006). The OATPs exhibit broad and overlapping substrate specificity, and display an affinity for organic anions as well as some bulky cations and neutral steroids (Mikkaichi et al., 2004). In contrast to NTCP, the OATPs operate in a Na\(^+\)-independent manner, and have been shown to function as bidirectional carriers (Li et al., 2000; Briz et al., 2006; Mahagita et al., 2007). There are three human isoforms, OATP1B1, 1B3 and 2B1, that play a substantial role in hepatic uptake of many endogenous and exogenous compounds including bilirubin (Konig et al., 2000; Cui et al., 2001), fexofenadine (Cvetkovic et al., 1999) and many statins (Shitara and Sugiyama, 2006). OCTs are electrogenic uniporters that primarily mediate transport of
small cations, although transport of anions and uncharged compounds has been reported (Koepsell et al., 2003). The OATs constitute a family of proteins that mediate transport of negatively charged endogenous and exogenous compounds in exchange for dicarboxylate ions. OATs are predominantly expressed in the kidney, although OAT2 has higher expression on the sinusoidal membrane of hepatocytes compared to the basolateral membrane of proximal kidney tubules (Sun et al., 2001). Transporters located in the apical membrane involved in the removal of drug and/or metabolite(s) into the bile canaliculus include P-glycoprotein (P-gp), multidrug resistance-associated protein (MRP2), breast cancer resistance protein (BCRP) and the bile salt export pump (BSEP). Sorafenib is a weak substrate for P-gp, but the overall effect of this transporter on plasma concentrations is low based on in vivo results utilizing mdr1a/1b(-/-) knockout mice (Gnoth et al., 2010).

The objective of the present study was to identify whether transport proteins are involved in the hepatic uptake of sorafenib, and to determine the extent of biliary excretion of sorafenib and its metabolites in human hepatocytes. Initial uptake was assessed in freshly isolated human hepatocytes and in OCT1 transfected CHO cells. Sandwich-cultured human hepatocytes were utilized to determine the hepatobiliary disposition of sorafenib and metabolites.
Material and Methods

Materials Dulbecco’s modified Eagle’s medium (DMEM), F-12 Nutrient Mixture, MEM non-essential amino acids solution (100x), L-glutamine, penicillin G-streptomycin solution (100x), gentamicin, and penicillin G-streptomycin-amphotericin B solution (100x) were purchased from Invitrogen (Carlsbad, CA). Rifamycin SV, ketoprofen, dexamethasone, tetraethylammonium (TEA), 1,1-dimethyl-biguanide hydrochloride (metformin), fetal bovine serum (FBS), Triton X-100, HEPES, D-glucose, dexamethasone, trypsin-EDTA solution (1x), and Hanks’ balanced salt solution (HBSS) modified with (H-1387) or without (H-4891) calcium chloride were obtained from Sigma-Aldrich (St. Louis, MO). Sorafenib tosylate (purity 99.7%), [14C] sorafenib (3.09 MBq/mg, radiochemical purity 99.2%), the internal standard [2H3, 15N] sorafenib tosylate, and decynium 22 were provided by Bayer HealthCare AG (Wuppertal, Germany). [14C]TEA (55 mCi/mmol) was purchased from American Radiolabeled Chemicals (St. Louis, MO). [14C]Biguanide (metformin, 110 μCi/mmoll) was purchased from Moraveck Biochemicals (Brea, CA). ITS+™ (insulin/transferrin/selenium) culture supplement was purchased from BD Biosciences Discovery Labware (Bedford, MA). Bicinchoninic acid (BCA) protein assay reagents and BSA for the protein assay standard were purchased from Pierce Chemical Co. (Rockford, IL). Ultima Gold™ XR scintillation cocktail, was purchased from Perkin Elmer Life Sciences (Boston, MA). All other chemicals and reagents were of analytical grade and available from commercial sources.

Suspension Hepatocyte Isolation and Uptake Studies CellzDirect, Life Technologies (RTP, NC) kindly provided freshly isolated human hepatocytes in suspension. Hepatocyte donors were a 60-yr-old female Caucasian and a 63-yr-old male Caucasian.
with no recent history of smoking or alcohol use. Hepatocyte viability, as determined by trypan blue exclusion, was 89 and 90%. Cells were suspended in cold modified Hank’s buffer with 10 mM Tris/5 mM glucose (pH = 7.4) or Na⁺-free choline buffer (10mM Tris, 5 mM glucose, 5.4 mM KCl, 1.8mM CaCl₂, 0.9 mM MgSO₄, 10 mM HEPES and 137 mM choline; pH = 7.4) and stored on ice prior to conducting uptake studies (Leslie et al., 2007). Isolated hepatocytes were suspended in the same buffer (1 x 10⁶ cells/ml), placed on ice, and used immediately in experiments. Hepatocyte suspensions (1 ml; n = 2 livers, in triplicate) were pre-incubated in 16 x 100 mm glass test tubes at 37˚C for 3 min; 0.1% DMSO or chemical inhibitor was added 1 min before [¹⁴C]sorafenib (0.9 µM; 3.86 nCi; 0.9% methanol). The following concentrations of inhibitors were selected based upon reported affinities for the given active transport processes: 20 µM rifamycin SV (OATP1B1, 1B3 and 2B1 inhibitor), 5 µM decynium 22 (OCT inhibitor) and 10 µM ketoprofen (OAT2 inhibitor). Aliquots (100 µL) of the suspension were removed at timed intervals (up to 2.5 min), placed in 0.4-ml polyethylene tubes, and centrifuged immediately through a top layer of silicone oil:mineral oil (82:18, v/v; 100 µL) into a bottom layer of 3M KOH (50 µL). [¹⁴C]Sorafenib in the cell pellet and supernatant were analyzed by liquid scintillation counting. Adherent fluid volume was estimated with [¹⁴C]inulin as described previously (Baur et al., 1975). Protein concentrations for individual hepatocyte suspensions were determined with the BCA protein assay reagent kit (Pierce) as instructed by the manufacturer. BSA, as supplied by the manufacturer, was used as a standard (0.2 – 1 mg/mL).

**Transport Studies in hOCT1-Expressing CHO Cells** Transport studies were carried out five days post-seeding, as previously described (Ming et al., 2009). Briefly, stably
transfected CHO cells were grown as monolayers in 24-well plates and the medium was changed every other day. Cells were pre-incubated for 30 min at 37°C in transport buffer (HBSS with calcium chloride, 25 mM D-glucose and 10 mM HEPES, pH 7.4). Experiments were initiated by replacement of the transport buffer with 0.4 mL of varying amounts of radiolabeled dose solutions in transport buffer. Initially, time-dependent experiments were conducted for up to 30 min to determine the linear uptake range (data not shown). For concentration-dependent experiments, uptake was determined in the mock cells or CHO-OCT1 cells over a 10-min period. Inhibition of OCT1-mediated uptake was performed in mock or CHO-OCT1 cells by concomitantly incubating 500 µM MPP+ with the substrate, [14C]sorafenib. After incubation, dose solutions were aspirated and cells were washed four times with 4°C transport buffer. Cells were lysed with 500 µL of 0.1 N NaOH/0.1% sodium dodecyl sulfate (SDS) for 4 h on an orbital shaker, and samples were analyzed by liquid scintillation counting. Data were normalized to protein concentration in each well, determined in duplicate aliquots using BCA protein assay reagent kit, as detailed above.

For estimation of Michaelis-Menten parameters, OCT1-mediated uptake was determined as the difference in cell associated radioactivity in the hOCT1-transfected and mock cells at each substrate concentration. The Km and Vmax values were obtained by fitting the Michaelis-Menten equation V = Vmax • [S]/(Km + [S]) to the data using WinNonlin v.5.2.1 (Pharsight, Mountain View, CA), where V represents the velocity of substrate transport, [S] refers to the concentration of substrate, and Km is defined as the concentration of substrate at the half-maximal transport rate (Vmax).
Sandwich-Cultured Human Hepatocyte Studies B-CLEAR®-Human kits were purchased from Qualyst, Inc. (RTP, NC). Human hepatocytes isolated from two different individuals (Table 1) were seeded ~1.75 x 10^6 cells/well on 6-well BioCoat™ plates in DMEM without phenol red supplemented with 2 mM L-glutamine, 1% (v/v) MEM non-essential amino acids, 100 units penicillin G sodium, 100 µg streptomycin sulfate, 1 µM dexamethasone, 5% (v/v) FBS, and 10 µM insulin (day 0 of culture), and allowed to attach for 2-6 h in a humidified incubator (95% O_2, 5% CO_2) at 37°C. After cell attachment, culture plates were swirled gently and the culture medium was replaced with the same medium. Cells were overlaid 16-24 h (day 1 of culture) after seeding with ice-cold Matrigel™ basement membrane matrix (0.25 mg/mL) in 2 mL/well cold serum-free DMEM containing 2 mM L-glutamine, 1% (v/v) MEM non-essential amino acids, 100 units penicillin G sodium, 100 µg streptomycin sulfate, 1 µM dexamethasone, and 1% (v/v) ITS+™. The culture medium was changed every 24 h until experiments were performed on day 7 of culture.

Accumulation Studies The method to determine substrate accumulation in sandwich-cultured hepatocytes has been described previously (Leslie et al., 2007; Wolf et al., 2008). Cells were incubated for 20 min at 37°C with 1.5 mL of sorafenib solution (1 and 10 µM). Medium samples were collected immediately, and hepatocytes were rinsed vigorously three times with 2 mL ice-cold standard buffer following the incubation. Substrate uptake was corrected for nonspecific binding by subtracting uptake on blank six-well BioCoat™ plates overlaid with Matrigel™. Data were normalized to protein concentration in each well, determined in duplicate with the BCA protein assay reagent kit. Due to incompatibility of the protein assay with organic solvent, the average protein
concentration for standard HBSS or Ca²⁺-free HBSS incubations in the same liver preparation was used to normalize sorafenib content. Sorafenib-treated hepatocytes were stored immediately at -80°C until analysis. The cells were lysed with 1 mL of mobile phase containing internal standard, scraped off the plates and centrifuged at 10,000 g for 5 min before analysis by LC/MS/MS.

**Sample Analysis** Sorafenib and sorafenib N-oxide concentrations were determined by a LC-MS/MS assay using a LTQ Orbitrap XL (Thermo Scientific, Bremen, Germany) coupled to an Agilent 1200 system (Waldbronn, Germany). Sorafenib and its metabolites were eluted from a Synergi Hydro RP 2.5 µm column (20 x 2 mm i.d., Phenomenex, Torrance, CA, USA) using a mobile phase gradient at a flow rate of 0.3 mL/min (A: 0.05% formic acid in water, B: 0.05% formic acid in acetonitrile); 0 min 30% B, 5 min 60% B, 5.3 min 30% B. The column effluent was monitored using a LTQ Orbitrap XL (Thermo Scientific, Bremen, Germany) by quantification of the exact mass of sorafenib, internal standard, sorafenib N-oxide and sorafenib glucuronide. The calibration ranged from 1 ng/ml to 1000 ng/ml. The LLOQ for sorafenib was 2 ng/ml and 1 ng/ml for sorafenib N-oxide.

**Data Analysis** For accumulation studies in sandwich-cultured hepatocytes, the biliary excretion index (BEI, %) and *in vitro* biliary clearance (*in vitro* Cl<sub>biliary</sub>) were calculated using B-CLEAR® technology [Qualyst, Inc., Raleigh, NC; (Liu et al., 1999)]:

\[
BEI = \frac{\text{Accumulation}_{\text{Cells+Bile}} - \text{Accumulation}_{\text{Cells}}}{\text{Accumulation}_{\text{Cells+Bile}}} \times 100
\]
where substrate accumulation in the cells+bile compartments was determined in hepatocytes preincubated in standard buffer; cellular accumulation of substrate was determined in hepatocytes preincubated in Ca\(^{2+}\)-free HBSS.

\[
\text{In Vitro } Cl_{\text{biliary}} = \frac{\text{Accumulation}_{\text{Cells+Bile}} - \text{Accumulation}_{\text{Cells}}}{\text{AUC}_{0-T}}
\]

where AUC\(_{0-T}\) was calculated using the log trapezoidal method; the theoretical dosing concentration was used for t=0 and the final medium concentration for t=incubation time. \textit{In vitro} C_{l\text{biliary}} values were scaled per kilogram body weight using 0.948 (Liver 1) and 1.35 (Liver 2) mg of protein per well: assuming the following: 1 mg protein/1.75 \times 10^6 cells, 107 \times 10^6 hepatocytes/g of human liver tissue, and 25.7 g of liver tissue per kg of body weight, as previously described (Davies and Morris, 1993).

Statistically significant differences in sorafenib uptake in transfected CHO cells were determined by a two-way analysis of variance followed by the Bonferroni post-hoc test. The criterion for significance in all cases was \(p < 0.05\).
Results

Uptake of Sorafenib in Suspended Human Hepatocytes  Initial uptake of $[^{14}\text{C}]$sorafenib into suspended human hepatocytes was linear up to ~1.5 min (Fig. 2.A and B). Uptake at 4°C was reduced by ~61-63% of the uptake at 37°C (Fig. 2.A - D). $[^{14}\text{C}]$Sorafenib uptake at all timepoints sampled (Fig. 2.C and D) did not exhibit sodium dependence (average $[^{14}\text{C}]$sorafenib uptake was ~4, 13, and 14% greater than control values when sodium was replaced with choline in the uptake buffer at 0.5, 1.5 and 2.5 min, respectively), and was not influenced significantly by ketoprofen (uptake was decreased by only 4% compared to control uptake). Initial $[^{14}\text{C}]$sorafenib uptake was reduced by 26, 46, and 42% of control values in the presence of the OATP inhibitor rifamycin SV at 0.5, 1.5, and 2.5 min, respectively, and reduced by 25, 30, and 39% of control values in the presence of the OCT inhibitor decynium 22 at 0.5, 1.5, and 2.5 min, respectively (Fig. 2.C and D; 2.5-min data not shown).

Transport of Sorafenib in hOCT1 Transfected CHO cells  As expected, uptake of 10 $\mu$M $[^{14}\text{C}]$metformin (data not shown) and 5 $\mu$M $[^{14}\text{C}]$TEA in hOCT1-transfected CHO cells was increased ~7-fold compared to mock cells, confirming OCT1 function in these cells (Fig. 3.A). The uptake of 5 $\mu$M $[^{14}\text{C}]$TEA was completely abated in the presence of 500 $\mu$M MPP$^+$ (Fig. 3.A).

$[^{14}\text{C}]$Sorafenib uptake was significantly higher in hOCT1-transfected CHO cells compared to mock cells over the concentration range examined (0.5 to 5 $\mu$M). OCT1-mediated uptake was saturable with a $K_m$ of 3.80 ± 2.53 $\mu$M and $V_{max}$ of 116 ± 42 pmol/mg/min. The OCT inhibitor, MPP$^+$, decreased $[^{14}\text{C}]$sorafenib uptake in OCT1-
transfected and mock CHO cells, suggesting that other MPP⁺ sensitive transport processes are involved in sorafenib uptake (Fig. 3B). [¹⁴C]Sorafenib uptake in mock cells was reduced to ~49-63% by MPP⁺, suggesting that passive diffusion plays a role in sorafenib uptake, consistent with data generated in suspended human hepatocytes at 4°C.

**Hepatobiliary Disposition of Sorafenib in Human Sandwich-Cultured Hepatocytes**

The hepatobiliary disposition of [³H]taurocholate and sorafenib was measured in human sandwich-cultured hepatocytes. Following a 10-min incubation with 1 µM [³H]taurocholate, the BEI and *in vitro* Clbiliary for both livers (Table 1) were consistent with previous data generated in this model system. The cellular accumulation of sorafenib appeared to be dose-dependent (Table 2). Sorafenib cellular accumulation was approximately two orders of magnitude greater than the primary metabolite sorafenib N-oxide after a 20-min incubation at the 1 µM sorafenib dose, and greater than one order of magnitude at the 10 µM sorafenib dose (Table 2).

The BEI of sorafenib in sandwich-cultured human hepatocytes was low (~11%). The sorafenib *in vitro* Clbiliary was moderately low at 1 and 10 µM sorafenib (~11 mL/min/kg), ranging from approximately one-third to one-fifth of the taurocholate *in vitro* Clbiliary values in each of the liver donors (Tables 1 and 2). After a 20-min incubation with either 1 or 10 µM sorafenib, sorafenib N-oxide concentrations were below the detection limit (<1 ng/mL) in medium, except for the 10 µM dose in hepatocytes prepared from the second liver; however, longer incubation times of 60 and 120 min resulted in slightly higher medium concentrations of sorafenib N-oxide (Fig. 4). The BEI of sorafenib glucuronide at the 1 µM dose was negligible for both liver donors at 20 min;
sorafenib glucuronide was detected in medium at all time points, and increased with the longer incubation time. The biliary excretion of sorafenib glucuronide increased with incubation time (BEI = 0, 42, and 40% at 20, 60 and 120 min, respectively. Fig. 4).

Discussion

Hepatic transport proteins are recognized increasingly as important determinants of the pharmacokinetics of many drugs, as well as key sites of drug-drug interactions (Soars et al., 2009). Genetic polymorphisms of uptake transport proteins also have been implicated in inter-individual differences in the pharmacokinetics and pharmacodynamics of clinically relevant drugs such as the statins (Ieiri et al., 2009). In the present study, the transport proteins involved in the hepatic uptake of sorafenib were investigated, and the hepatobiliary disposition of sorafenib and metabolites was assessed.

Sorafenib is a very lipophilic compound (log D_7 = 5.16; predicted properties SciFinder Scholar version 2007). The initial uptake of sorafenib in human hepatocytes was examined at 37°C vs. 4°C to assess the contribution of passive diffusion to overall uptake. The initial uptake of [^{14}C]sorafenib at 4°C was reduced 61 and 63% at 0.5 and 1.5 min, respectively, compared to 37°C, which suggests a high degree of passive diffusion (Fig. 2.A - C). The contribution of passive diffusion vs carrier mediated uptake remains unclear due to the effect of temperature on both processes. There was also a high degree of passive diffusion in CHO cells (Fig. 3.B). Furthermore, >54% of the sorafenib dose partitioned into human sandwich-cultured hepatocytes after a 20-min incubation with 1 μM sorafenib based on the mass of drug remaining in the media at the
end of the incubation period in relation to the initial dose (Table 2). These findings are in agreement with the reported high Papp in the absorptive direction of 16.4 ± 12.3 and 33.5 ± 16.1 x 10^-6 cm/s for 0.1 and 1 µM sorafenib, respectively, determined in Caco-2 cells (Gnoth et al., 2010).

The active uptake of [14C]sorafenib (0.9 µM) was investigated with transport protein modulators. Rifamycin SV (20 µM) was selected as an inhibitor of all the relevant human isoforms of OATP expressed in the liver: OATP1A2, OATP1B1, OATP1B3 and OATP2B1 (Vavricka et al., 2002). Decynium 22 (5 µM) was used as an OCT inhibitor (Zhang et al., 1997; Hayer-Zillgen et al., 2002), and OAT2 function was inhibited with ketoprofen (10 µM) (Morita et al., 2001; Ohtsuki et al., 2002). To assess Na+-dependent transport by NTCP, choline-based buffer was substituted for Na+-based buffer in suspended hepatocytes. The sensitivity of the transport proteins and specificity to the inhibitors rifamycin SV and decynium 22 were confirmed in the presence and absence of the model probe substrates [3H]estradiol-17-β-D-glucuronide (OATP substrate) and [14C]TEA (OCT substrate), as published previously (Swift et al., 2010). Sorafenib uptake at all timepoints sampled was sensitive to rifamycin SV and decynium 22, suggesting that the OATPs and OCTs are involved in the hepatic uptake this tyrosine kinase inhibitor (Fig. 2.C and D). Contribution of OATP1B1 and OATP1B3 to the hepatic uptake of sorafenib has been confirmed in vitro (Zimmerman et al., 2013). The involvement of OCT1 in sorafenib uptake was investigated further using a hOCT1-expressing CHO cell line. This finding contradicts work by Hu et al., who reported no appreciable uptake of sorafenib by X. laevis oocytes expressing OCT1, OATP1A2, OATP1B1 or OATP1B3 (Hu et al., 2009). This apparent discrepancy could be
explained by experimental differences. For example, in the present studies, sorafenib uptake into CHO cells was saturable after 10 min; Hu et al., incubated sorafenib with *X. laevis* oocytes for 1 hr, possibly masking the active uptake component. Furthermore, different *in vitro* model systems may yield conflicting data. For example, Agarwal et al. conclusively demonstrated transport of sorafenib by Bcrp both *in vitro* and *in vivo*, in contrast to the data generated in LLC-PK1 cells transfected with BCRP (Hu et al., 2009; Agarwal et al., 2011). Imatinib, another tyrosine kinase inhibitor, is an OCT1 substrate in the human T-lymphoblastoid cell line CCRF-CEM (Thomas et al., 2004). Some substrate overlap exists between OCTs and OATPs, which have affinity for numerous type II (bulky) cations such as N-methylquinine (van Montfoort et al., 1999). Furthermore the class of tyrosine kinase inhibitors has been shown to inhibit metformin uptake in OCT transfected cell lines (Minematsu and Giacomini, 2011).

Decynium 22 inhibition of sorafenib uptake in suspended human hepatocytes was likely due to OCT1 based on further studies demonstrating that OCT1-mediated uptake of sorafenib was significantly higher in hOCT1-transfected CHO cells compared to mock cells over the concentration range examined (0.5 to 5 µM; Fig 3B). These results are the first to demonstrate that sorafenib is a substrate of hOCT1 with a *K*_m* of 3.8 µM. Interestingly, sorafenib uptake in non-transfected mock cells was inhibited partially by MPP⁺, suggesting that other MPP⁺-sensitive endogenous transport proteins in the CHO cell line are involved in sorafenib uptake. The unknown transport protein(s) that is/are sensitive to MPP⁺ in mock CHO cells may be present in human hepatocytes. We cannot rule out the possibility that rifamycin SV inhibited the uptake of sorafenib by this unknown transport protein(s) in the suspended hepatocyte experiments.
To investigate the hepatobiliary disposition of sorafenib, studies were performed in human sandwich-cultured hepatocytes. The dosing concentrations (1 and 10 µM) used in these studies were in the range of the reported total maximum plasma concentration (5 to 21 µM) after multiple oral doses of sorafenib (100 to 600 mg twice daily) (Strumberg et al., 2005), but higher than the expected unbound plasma concentration of sorafenib based on reported binding to plasma proteins (99.5% bound; package insert). Sorafenib, a P-gp and Bcrp substrate (Hu et al., 2009; Gnoth et al., 2010; Agarwal et al., 2011), exhibited a relatively low BEI (up to 11%; Table 2) and in vitro Cl\textsubscript{biliary} (up to 11.5 ml/min/kg), which is not surprising due to the extent of CYP3A4- and UGT1A9-mediated metabolism observed in vivo (Lathia et al., 2006). The model bile acid [\textsuperscript{3}H]taurocholate, which is generally considered to have a high hepatic clearance, was included as a system control in the two liver donors, but also serves as a good reference point for compounds with high BEI (64.8 and 62.6%) and high in vitro Cl\textsubscript{biliary} (59.9 and 32.4 mL/min/kg) (Table 1).

Biotransformation of sorafenib to the N-oxide is mediated primarily by CYP3A4 (Lathia et al., 2006; Ghassabian et al., 2012). The low formation of sorafenib N-oxide in day 7 human sandwich-cultured hepatocytes may be due to lower cytochrome P450 enzyme activity after isolation and culture (Hoen et al., 2000; Boess et al., 2003). Dexamethasone is a prototypical CYP inducer that is added to cell culture medium. In the present studies, dexamethasone concentrations in the culture medium were only 1 µM, which is much lower than the 10 µM or higher concentrations utilized in some human and rat sandwich-cultured hepatocyte studies to induce CYP3A4 and Cyp3A1/2 protein expression and increase activity of CYP3A4 and Cyp3A1/2, as measured by
testosterone 6β-hydroxylation formation (LeCluyse et al., 1996). Sorafenib N-oxide is the primary circulating metabolite in human plasma (Lathia et al., 2006); concentrations of sorafenib N-oxide in medium, a surrogate for blood, increased with the longer incubation times. Although no glucuronide was detected in the bile of sandwich-cultured hepatocytes after a 20-min incubation, sorafenib glucuronide was excreted into bile after incubation of hepatocytes with sorafenib for 60 and 120 min, as demonstrated with the higher BEI (40-42%; Fig. 4). The increased formation and biliary excretion of sorafenib glucuronide after longer incubation times may partially explain the significant amount of parent drug recovered in feces after oral dosing [~77% of a 100 mg oral dose was excreted in feces, of which 51% was the parent drug (package insert)]. Based on our results, we hypothesize that sorafenib glucuronide undergoes biliary excretion, a portion of the glucuronide conjugate is cleaved in the gastrointestinal tract and subsequently, generated sorafenib is reabsorbed. This hypothesis is supported by the clinical observation of secondary peaks in the sorafenib plasma concentration-time profile (Lathia et al., 2006). Sorafenib glucuronide also was detected in the medium of sandwich-cultured hepatocytes (Fig. 4), in agreement with the findings that glucuronidated metabolites of sorafenib are recovered in human urine after oral administration.

Sorafenib metabolites, specifically the glucuronide conjugates, require transport proteins for biliary excretion and basolateral efflux. As mentioned sorafenib is a P-gp and Bcrp substrate, and may also be an MRP2 substrate (Shibayama et al., 2011), suggesting that these transport proteins may play a role in the biliary excretion of sorafenib and/or metabolites. MRP2 is responsible for the biliary excretion of many
glucuronide conjugates of drugs, as well as bilirubin conjugates (Kamisako et al., 1999), and may transport sorafenib glucuronide into bile. Clinically relevant drug interactions associated with impaired biliary clearance have been reported for digoxin due to coadministration of the P-gp inhibitors quinidine, verapamil and ritonavir (Fenner et al., 2009). Furthermore, it is well recognized that patients with liver disease develop adaptive changes in transport protein expression, which protect the hepatocyte from the intracellular accumulation of toxic compounds such as bile acids. In fact, many patients with hepatocellular carcinoma develop cirrhosis, which results in down-regulation of basolateral uptake transport proteins often coupled with up-regulation of canalicular and basolateral efflux proteins (Zollner et al., 2003; Zollner et al., 2007). This highlights the importance of understanding the mechanisms of sorafenib hepatobiliary disposition.

In conclusion, sorafenib uptake in suspended human hepatocytes, CHO cells and sandwich-cultured human hepatocytes was extensive. Uptake into human hepatocytes was temperature dependent and decreased ~61-63% at 4°C, suggesting a high degree of passive diffusion. The active portion of hepatic uptake was sensitive to rifamycin SV and decynium 22. OCT1-mediated uptake of sorafenib was confirmed in OCT1 overexpressing CHO cells. Sorafenib undergoes modest biliary excretion as the parent compound; biliary excretion of the major metabolites, N-oxide and glucuronide conjugate(s), is increased with incubation time in sandwich-cultured hepatocytes.
Authorship Contributions

Participated in research design: Swift, Proctor, Thakker, Gnoth, Radtke, Brouwer

Conducted Experiments: Swift, Lee, Han, Proctor

Contributed new reagents or analytical tools: Swift, Thakker, Gnoth, Lang

Performed data analysis: Swift, Nebot, Brouwer

Wrote or contributed to the writing off the manuscript: Swift, Nebot, Gnoth, Brouwer
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Footnotes.

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b. This work was presented in part at the 2010 annual meeting for the American Association of Pharmaceutical Scientists in New Orleans, Louisiana.

c. Reprint Requests: Kim L. R. Brouwer UNC Eshelman School of Pharmacy, The University of North Carolina at Chapel Hill, 311 Pharmacy Lane, CB#7569, 3205 Kerr Hall, Chapel Hill, NC 27599-7569. Tel: (919)962-7030. Fax: (919)962-0644. E-mail: kbrouwer@unc.edu.

Conflict Of Interest

Dr. Kim Brouwer is chair of the Scientific Advisory Board of Qualyst Transporter Solutions, which has exclusively licensed the sandwich-cultured hepatocyte technology for quantification of biliary excretion (B-CLEAR®). None of the other authors has conflicts of interest to declare.
Legend to Figures

Figure 1  Chemical structure of sorafenib and metabolic pathways.

Figure 2  Uptake of \( [^{14}C] \)sorafenib (0.9 \( \mu \)M) in suspended human hepatocytes from two separate donors (A and B) over 2.5 min. Hepatocytes were incubated at 37°C (●) or 4°C (○) in standard buffer (mean ± SD; n= 2 livers in triplicate). Initial uptake of \( [^{14}C] \)sorafenib (0.9 \( \mu \)M) at 0.5 min (C) and 1.5 min (D) in suspended human hepatocytes incubated at 37°C in standard buffer, unless otherwise specified, and in the presence of transport protein modulators including choline buffer, inhibitors (rifamycin SV, decynium 22, and ketoprofen) and lower incubation temperature (n=2 livers; mean percentage ± range).

Figure 3  Uptake of the positive control (A) \( [^{14}C] \)TEA (5 \( \mu \)M) was assessed in CHO-hOCT1 in the absence (white bar) and presence of 500 \( \mu \)M MPP\(^+\) (hatched bar) and mock cells (black bar). Uptake of (B) \( [^{14}C] \)sorafenib (1.0 to 5 \( \mu \)M) in CHO-hOCT1 cells. CHO-hOCT1 cells were incubated in the absence (▲) and presence (●) of 500 \( \mu \)M MPP\(^+\), and mock cells in the absence (●) and presence (○) of 500 \( \mu \)M MPP\(^+\) at 10 min. (inset) OCT1-mediated \( [^{14}C] \)sorafenib transport determined as the difference in uptake in CHO-hOCT1 and mock cells at each substrate concentration. The curve represents the best fit of the Michaelis-Menten equation to the OCT1-mediated uptake data. Data represent mean ± SD (n=3); * \( p < 0.001 \) hOCT1 vs mock; † \( p < 0.001 \) hOCT1 vs hOCT1+MPP\(^+\); †† \( p < 0.001 \) mock vs mock+MPP\(^+\); when error bars are not visible, they are smaller than the symbol.

Figure 4  Ratio of amount of sorafenib and formed metabolites in (cells + bile)/(cells + bile + medium) in day 7 sandwich-cultured human hepatocytes from Liver 2 incubated with 1 \( \mu \)M sorafenib for 20 (solid bars), 60 (open bars) and 120 (hatched bars) min. The BEI was calculated after triplicate determination of substrate accumulation in cells and cells + bile. A standard was unavailable for sorafenib glucuronide, so the peak area under the curve divided by the internal standard area under the curve was used.
### Table 1 Demographics, BEI and in vitro Cl_{biliary} of [3H]Taurocholate in Human Sandwich-Cultured Hepatocytes.

<table>
<thead>
<tr>
<th>Liver donor identification</th>
<th>Age (years)</th>
<th>Gender</th>
<th>Race</th>
<th>BMI kg/m^2</th>
<th>BEI %</th>
<th>Taurocholate (mL/min/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver 1</td>
<td>44</td>
<td>Female</td>
<td>Caucasian</td>
<td>24</td>
<td>64.8</td>
<td>59.9</td>
</tr>
<tr>
<td>Liver 2</td>
<td>48</td>
<td>Female</td>
<td>Caucasian</td>
<td>21.7</td>
<td>62.6</td>
<td>32.4</td>
</tr>
</tbody>
</table>

Donors had no history of tobacco or alcohol use or co-medications; Body mass Index (BMI); SCH were incubated with 1 μM [3H]taurocholate (10 min). Results are presented as representative data from triplicate determinations in two livers.
Table 2 Accumulation, BEI and *in vitro* $C_{\text{biliary}}$ of sorafenib or sorafenib N-Oxide in Sandwich-Cultured Human Hepatocytes.

<table>
<thead>
<tr>
<th>Liver donor identification</th>
<th>Compound</th>
<th>Medium Concentration (pmol/mL)</th>
<th>Accumulation Cells + Bile (pmol/mg)</th>
<th>Accumulation Cells (pmol/mg)</th>
<th>BEI (%)</th>
<th>$C_{\text{biliary}}$ mL/min/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver 1</td>
<td>Sorafenib 1 μM</td>
<td>39.1 ± 2.3</td>
<td>1210 ± 230</td>
<td>1570 ± 70</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Liver 2</td>
<td>460 ± 16</td>
<td>917 ± 41</td>
<td>819 ± 23</td>
<td>11</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Liver 1</td>
<td>Sorafenib 10 μM</td>
<td>475 ± 59</td>
<td>7200 ± 130</td>
<td>6760 ± 550</td>
<td>6</td>
<td>11.1</td>
</tr>
<tr>
<td>Liver 2</td>
<td>1600 ± 75</td>
<td>6430 ± 130</td>
<td>5760 ± 240</td>
<td>10</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Liver 1</td>
<td>N-oxide (Sorafenib 1 μM)</td>
<td>BLQ (&lt;1.00)</td>
<td>9.89 ± 2.62</td>
<td>12.3 ± 0.5</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Liver 2</td>
<td>BLQ (&lt;1.00)</td>
<td>6.91 ± 0.22</td>
<td>6.14 ± 0.22</td>
<td>11</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Liver 1</td>
<td>N-oxide (Sorafenib 10 μM)</td>
<td>BLQ (&lt;1.00)</td>
<td>80.8 ± 5.1</td>
<td>63.2 ± 12.9</td>
<td>22</td>
<td>NA</td>
</tr>
<tr>
<td>Liver 2</td>
<td>11.8 ± 4.6</td>
<td>361 ± 13</td>
<td>346 ± 27</td>
<td>4</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

Sandwich-cultured hepatocytes were incubated with 1 and 10 μM sorafenib for 20 min. Results are presented as mean ± standard deviation from triplicate experiments from two livers. BLQ=below the limit of quantitation. NA=not applicable.
Figure 1

Sorafenib

Glucuronide

N-oxide
Figure 4

![Bar chart showing BEI(%) and [(Cells+Bile)/(Cells+Bile+Medium)] for Sorafenib, N-oxide, and Glucuronide]