

Organic Anion Transporting Polypeptides: Emerging Roles in Cancer Pharmacology

Rachael R. Schulte and Richard H. Ho

Department of Pediatrics, Division of Pediatric Hematology-Oncology, Vanderbilt University Medical
Center, Nashville, TN (R.R.S., R.H.H.)

OATPs and Cancer Pharmacology

Corresponding Author:

Richard H. Ho, MD MSCI

397 PRB

2220 Pierce Avenue

Vanderbilt University Medical Center

Nashville, Tennessee 37232

Tel: (615) 936-2802

Fax: (615) 875-1478

Email: richard.ho@vumc.org

Number of pages of text: 24

Number of tables: 3

Number of figures: 1

References: 204

Number of words:

Abstract: 201

Introduction: 1386

Discussion: 7737

ABBREVIATIONS:

ASBT, apical sodium dependent bile acid transporter; AUC, area under the plasma time:concentration curve; BCRP, breast cancer related protein; BSP, bromosulfophthalein; CCK-8, cholecystokinin octapeptide; DHEAS, dehydroepiandrosterone sulfate; DPDPE, [D-penicillamine^{2,5}] enkephalin; E2G, estradiol-17 β -glucuronide; E3S, estrone-3-sulfate; ENT, equilibrative nucleoside transporter; GCA, glycocholate; HEK, human embryonic kidney; IVS, intervening sequence (notation for intronic mutations); LD, linkage disequilibrium; MATE, multidrug and toxic compound extrusion; MCT, monocarboxylate

transporter; MDCKII, Madin-Darby canine kidney II; MRP, multidrug resistance-associated protein; NTCP, sodium/taurocholate cotransporting polypeptide; OAT, organic anion transporter; OATP, organic anion transporting polypeptide; OCT, organic cation transporter; OST, organic solute and steroid transporter; PEPT, peptide transporter; PFS, progression-free survival; PGE₁, prostaglandin E₁; PGE₂, prostaglandin E₂; PGF_{2α}, prostaglandin F_{2α}; P-gp, P-glycoprotein; *SLCO*, organic anion transporting polypeptide gene family name; SNP, single nucleotide polymorphism; STS, steroid sulfatase; T₃, triiodothyronine; T₄, thyroxine; TCA, taurocholate; TKI, tyrosine kinase inhibitor

ABSTRACT

The organic anion transporting polypeptides (OATPs) are a superfamily of drug transporters involved in the uptake and disposition of a wide array of structurally divergent endogenous and exogenous substrates, including steroid hormones, bile acids, and commonly used drugs, such as anti-infectives, anti-hypertensives, and cholesterol lowering agents. In the past decade, OATPs, primarily OATP1A2, OATP1B1, and OATP1B3, have emerged as potential mediators of chemotherapy disposition, including drugs such as methotrexate, doxorubicin, paclitaxel, docetaxel, irinotecan and its important metabolite SN-38, and certain tyrosine kinase inhibitors. Furthermore, OATP family members are polymorphic and numerous studies have shown OATP variants to have differential uptake, disposition, and/or pharmacokinetics of numerous drug substrates with important implications for interindividual differences in efficacy and toxicity. Additionally, certain OATPs have been found to be overexpressed in a variety of human solid tumors, including breast, liver, colon, pancreatic and ovarian cancers suggesting potential roles for OATPs in tumor development, progression and as novel targets for cancer therapy. This review focuses on the emerging roles for selected OATPs in cancer pharmacology, including preclinical and clinical studies suggesting roles in chemotherapy disposition, the pharmacogenetics of OATPs in cancer therapy, and OATP overexpression in various tumor tissues with implications for OATPs as therapeutic targets.

INTRODUCTION

The solute carrier (*SLC*) superfamily encompasses many transporters that play important roles in the uptake and distribution of both endogenous compounds and xenobiotics (Hagenbuch and Stieger, 2013). Among these are the organic anion transporting polypeptides (OATPs), classified in the *SLCO* family, which transport a large number of structurally diverse amphipathic substrates including steroid hormones (which are important for proliferation of hormone-dependent cancers) (De Bruyn et al., 2011), bile acids, statins, anti-hypertensives, antibiotics, antifungals, and chemotherapeutic agents (Hagenbuch and Stieger, 2013). Since the discovery of the first OATP in 1994 (Jacquemin et al., 1994), over 300 OATP family members have been identified in over 40 species, including 11 human transporters and many transporters in rats and mice (Hagenbuch and Stieger, 2013).

While many human OATPs have direct rodent orthologues, this is not necessarily the case for OATP1A2, OATP1B1, and OATP1B3, in which the rodent transporters have high sequence homology to the human transporters but are not direct orthologues. There are four known members of the *Oatp1a* family in mice (*Oatp1a1*, *Oatp1a4*, *Oatp1a5*, and *Oatp1a6*), contrasting with one human member (OATP1A2), but only one mouse *Oatp1b* transporter (*Oatp1b2*) compared to two human transporters (OATP1B1 and OATP1B3). Based on localization patterns of these transporters, it is thought that murine *Oatp1b2* is the closest orthologue to human OATP1B1 and OATP1B3, but *Oatp1a1* and *Oatp1a4* may also fulfill similar functions. For OATP1A2, the closest murine isoform *Oatp1a4* exhibits 72% amino acid sequence homology but additional isoforms *Oatp1a1*, *Oatp1a5*, and *Oatp1a6* may also have similar roles based on tissue localization. While *Oatp1b2* null mice are often used to mimic the loss of OATP1B1 and OATP1B3 function, this is potentially problematic because the *Oatp1a* transporters may be able to partially recover substrate transport when *Oatp1b2* is absent. For this reason, the utilization of *Oatp1a/Oatp1b* null mice to prevent compensation from *Oatp1a* transporters when studying the impact of the loss of *Oatp1b* function on substrate transport may be a significant factor to consider (Iusuf et al., 2012). Additionally, several humanized mouse strains have been created using *Oatp1a/Oatp1b* null mice with expression of human OATP1A2, OATP1B1, or OATP1B3 in the liver parenchymal cells. These humanized mice have allowed for better study of the effect of each human transporter individually. The limitations for the use of these mouse models was summarized in a recent review and should be considered when interpreting data from

mouse model studies given the lack of direct rodent orthologues for important OATP transporters (Durmus et al., 2016). To date, no mouse model has been published for OATP2B1.

The genes encoding several human OATPs (*SLCO1B1*, *SLCO1B3*, and *SLCO1A2* in particular) are located on chromosome 12, while genes for other OATPs are spread throughout the rest of the genome. All members of the OATP family contain 12 putative transmembrane domains with conserved cysteine residues in an extracellular loop between transmembrane domains 9 and 10, as well as signature sequences containing *N*-glycosylation sites in other extracellular loops (Hagenbuch and Meier, 2004; Konig, 2011). The OATPs are organized into families (in which members have at least 40% sequence homology; denoted by a number) and subfamilies (at least 60% sequence homology; denoted by a letter), with individual members of each subfamily identified numerically. The OATP designation is used for human transporters, while *Oatp* is used for non-human transporters (Hagenbuch and Meier, 2004).

Because of their wide range of transported substrates, OATPs have important roles both in the kinetics of drug disposition and in drug-drug interactions when two or more xenobiotics that are a substrate for the same OATP are given concurrently (Kindla et al., 2009; Konig et al., 2013; Shitara, 2011). Additionally, several drugs are known to inhibit the function of one or more OATPs, notably inhibition of OATP1B1 and OATP1B3 by macrolide antibiotics and rifampicin, inhibition of OATP1B1 by cyclosporine (Clarke and Cherrington, 2012; Konig et al., 2013), and inhibition of all OATPs by rifamycin (Hagenbuch and Meier, 2004). Intestinal OATP2B1 is inhibited by baicalin, cefixime, and fruit juices (most notably apple juice, also orange and grapefruit juices) (Clarke and Cherrington, 2012; Dresser et al., 2002; Fujita et al., 2016; Shirasaka et al., 2013), while OATP1A2 is inhibited by grapefruit juice (specifically its component naringin) (Clarke and Cherrington, 2012; Glaeser et al., 2007; Rebello et al., 2012). Testosterone and progesterone (and steroid hormones closely related to them) inhibit OATP2B1-mediated transport but are not substrates for OATP2B1 (Grube et al., 2006a). These inhibitors may be clinically useful as a therapeutic strategy to increase oral bioavailability and increase systemic exposure for drugs with high first-pass metabolism by the liver given the important role of OATPs in taking up substrates into hepatocytes for further processing (Hagenbuch and Stieger, 2013). The International Transporter Consortium has published guidelines regarding recommended testing to determine if new drugs are inhibitors of OATPs (International Transporter et al., 2010). Difficulty can arise when studying the effect of OATP inhibitors as

some of these compounds also inhibit CYP enzymes and other transporters (Koenen et al., 2011). Additionally, data for localization of and transport of compounds by OATPs can vary based on the cell type and method of detection utilized, which likely contributes to some conflicting results in the literature that are summarized in this review.

Transport by OATPs is sodium-independent, pH-dependent, and electroneutral, and OATP substrates tend to be highly albumin-bound in plasma circulation (Hagenbuch and Meier, 2004). The exact mechanism of transport by OATPs is not fully known and may vary by substrate for an individual transporter (Hagenbuch and Stieger, 2013). Closely related OATPs may have different substrate profiles, as is the case for OATP1B1 and OATP1B3 which each have unique substrates. However, they also have shared substrate transport capacity for classes of drugs such as statins, angiotensin receptor antagonists and HIV protease inhibitors. OATPs have been found in nearly every human tissue, commonly but not always located in the basolateral membrane of polarized cells (Konig, 2011). Certain OATPs, such as OATP1B1, OATP1B3, OATP1A2 and OATP2B1, are primarily expressed in tissues important to drug disposition, including liver, kidney, intestine and at the blood-brain barrier (Figure 1). The regulation of OATP expression is complex, with both transcriptional and post-transcriptional components (Hagenbuch and Stieger, 2013). This review will focus on four widely-studied OATPs and their roles in cancer pharmacology: OATP1A2, OATP1B1, OATP1B3, and OATP2B1. Table 1 provides an overview of each of these key OATPs including major sites of expression in normal tissues and prototypical substrates.

OATP1A2 is found predominantly in the brain at the blood-brain barrier (Gao et al., 2000; Kusuvara and Sugiyama, 2005; Tamai et al., 2000), testis (Tamai et al., 2000), renal proximal tubule cells (Kullak-Ublick et al., 1995), liver cholangiocytes but not hepatocytes (Lee et al., 2005), prostate (Tamai et al., 2000), and ciliary body epithelium (Gao 2005). There is conflicting data regarding intestinal expression of OATP1A2 but it is generally not considered to be highly expressed in this tissue (Drozdik et al., 2014; Glaeser et al., 2007; Groer et al., 2013; Hilgendorf et al., 2007; Meier et al., 2007; Tamai, 2012; Tamai et al., 2000). OATP1B1 and OATP1B3 are found almost exclusively at the basolateral membrane of hepatocytes under normal conditions (Cui et al., 2003; Iusuf et al., 2012; Konig, 2011; Tamai et al., 2000). However, one study found low OATP1B3 mRNA expression in the kidney (Hilgendorf et al., 2007) and there is conflicting data indicating expression in the intestine with one study finding OATP1B1 and OATP1B3

mRNA expression in the small intestine (Glaeser et al., 2007) and another finding neither protein nor mRNA expression of these transporters along the entire intestinal tract (Drozdik et al., 2014).

Among all hepatic transporters, OATP1B1 and OATP1B3 were found to have the highest and second highest, respectively, protein abundance in healthy Caucasian subjects (Burt et al., 2016); in another study OATP1B1 was among the most abundant transporters in terms of liver protein levels while OATP1B3 protein levels were moderate compared to other transporters (Hilgendorf et al., 2007). OATP2B1 is ubiquitously expressed in fetal and adult tissues and notably is found at the apical membrane of enterocytes (Iusuf et al., 2012; Kobayashi et al., 2003; Meier et al., 2007; Sai et al., 2006; Tamai, 2012), the basolateral membrane of hepatocytes (Kullak-Ublick et al., 2001), the apical membrane of renal proximal tubule cells, and at the blood-brain barrier (Iusuf et al., 2012), as well as in the heart (Grube et al., 2006b), pancreas, lung, ovary, testis, spleen (Tamai et al., 2000), ciliary body epithelium (Gao et al., 2005), and placenta (St-Pierre et al., 2002).

THE ROLE OF OATP TRANSPORTERS IN CHEMOTHERAPY DISPOSITION

It is widely known that OATPs represent an important family of transporters with important roles in drug uptake and distribution. A growing number of chemotherapeutic agents have been shown to be transported by OATP1A2, OATP1B1, OATP1B3, and OATP2B1, primarily in preclinical studies utilizing *in vitro* cell-based systems or *in vivo* animal models (Durmus et al., 2016; Thakkar et al., 2015). Emerging data suggest potential roles for these OATPs to the clinical pharmacology of specific chemotherapeutic agents. In addition, chemotherapy agents may affect the transport of other substances by OATPs and contribute to drug-drug interactions. There is little published data regarding chemotherapeutic agent-specific transporter-mediated drug-drug interactions. Marada *et al* used HEK cells stably transfected with human OATP1B1 and OATP1B3 to study the interaction of 26 different chemotherapy drugs with these transporters by assessing the change in transport of prototypic substrates - estrone-3-sulfate (E3S) for OATP1B1, cholecystinin octapeptide (CCK-8) for OATP1B3 - before and after addition of the chemotherapy agent. For OATP1B1, transport of E3S was significantly increased by irinotecan and decreased by paclitaxel and vinblastine; for OATP1B3, transport of CCK-8 was significantly decreased by chlorambucil, paclitaxel, vinblastine, vincristine, mitoxantrone, and etoposide (Marada et al., 2015). This

study suggests that the transport of OATP substrates may be affected by co-administration of chemotherapeutic agents with potential implications for clinically significant drug-drug interactions; this is an area that needs further study to assess if clinically relevant concentrations of these agents affect OATP substrate pharmacokinetics. A preclinical mouse model for such studies has been developed using methotrexate as an OATP substrate (Durmus et al., 2015).

Methotrexate

Methotrexate is an antimetabolite chemotherapy agent whose primary mechanism of action is via inhibition of dihydrofolate reductase, a key enzyme in the folate pathway, leading to termination of DNA synthesis. The methotrexate disposition pathway is complex, with many transporters and enzymes involved (Mikkelsen et al., 2011). While the main path for excretion of methotrexate is renally mediated, it also undergoes hepatic uptake and enterohepatic recirculation which contributes to its overall disposition (Walling, 2006). In recent years, variants in genes encoding the hepatic transporters OATP1B1 and OATP1B3 have been found to have a significant effect on methotrexate clearance in several large GWAS studies, with OATP1B1 variants having a larger effect than variation in any other gene (Ramsey et al., 2012; Ramsey et al., 2013; Trevino et al., 2009).

Methotrexate is transported *in vitro* by OATP1B1, OATP1B3 (Abe et al., 2001; Durmus et al., 2015; van de Steeg et al., 2010), and OATP1A2 (Badagnani et al., 2006; van de Steeg et al., 2010). Oatp1a/1b deficient mice have significantly higher plasma methotrexate levels and reduced liver methotrexate levels compared to wild-type (van de Steeg et al., 2011), with these differences able to be partially or completely rescued by transgenic expression of human OATP1B1, OATP1B3, or OATP1A2 (van de Steeg et al., 2012; van de Steeg et al., 2009). OATP1A2 transport of methotrexate is noted to be both saturable and pH-dependent, with 7-fold higher transport in the presence of an acidic extracellular environment (Badagnani et al., 2006). Transport of methotrexate by OATB1B1 and OATP1B3 is inhibited by rifampicin (Durmus et al., 2015).

Taxanes

The taxane chemotherapy agents are mitotic inhibitors that work by disrupting microtubule function. Docetaxel pharmacokinetics are widely variable (Baker et al., 2006), which has clinical implications since reduced clearance is associated with increased risk of dose-limiting toxicities (Bruno et al., 1998; Bruno et al., 2003) and clearance may also impact survival (Bruno et al., 2003). There are several differences in the pharmacokinetics of docetaxel and paclitaxel, but both are metabolized by CYP3A4 and other CYP enzymes and are transported by ABCB1, ABCG2, ABCC1, and ABCC2 in addition to OATPs (Baker et al., 2006; Oshiro et al., 2009).

Docetaxel is predominantly dependent on hepatic disposition in humans; ~75% is excreted in bile but only ~5% in urine (Cortes and Pazdur, 1995). Docetaxel is transported *in vitro* by OATP1B3 (de Graan et al., 2012; Iusuf et al., 2015; Lee et al., 2015; Nieuweboer et al., 2014; Obaidat et al., 2012; Oshiro et al., 2009; Smith et al., 2005; Yamada et al., 2014). Significantly decreased docetaxel transport into prostate cancer cells was seen in patient-derived xenografts found to have downregulation of OATP1B3 (de Morree et al., 2016). There is conflicting data for OATP1B1 with some studies showing no transport (Baker et al., 2009; Smith et al., 2005; Yamada et al., 2014) and other more recent studies suggesting that OATP1B1-mediated docetaxel transport occurs (de Graan et al., 2012; Lee et al., 2015; Nieuweboer et al., 2014). Docetaxel is transported by mouse Oatp1b2 (de Graan et al., 2012; Lee et al., 2015). *Slco1b2* knockout mice show significantly higher plasma levels and decreased liver-to-plasma ratios of docetaxel (Iusuf et al., 2015; Lee et al., 2015). Oatp1b2-deficient mice have markedly increased docetaxel AUC (de Graan et al., 2012) and Oatp1a/1b knockout mice have higher plasma AUC and reduced liver-to-plasma AUC ratios compared to wild-type with intestinal absorption of docetaxel not affected (Iusuf et al., 2015). Collectively, this data suggests OATP1B transporters are involved in hepatic docetaxel uptake and clearance.

Paclitaxel is transported significantly by OATP1B3 (Oshiro et al., 2009; Park et al., 2016; Smith et al., 2005; Svoboda et al., 2011). There is conflicting data for OATP1B1-mediated transport of paclitaxel, with some negative data (Smith et al., 2005) and other data showing paclitaxel transport by OATP1B1 *in vitro* and the ability of OATP1B1 or OATP1B3 transfected into cells to improve cytotoxicity of paclitaxel (Svoboda et al., 2011). Paclitaxel is also transported by mouse Oatp1a/1b (van de Steeg et al., 2010), with *Slco1a/1b* null mice having higher AUC and lower liver uptake for paclitaxel compared to wild-type and

transport was noted to be saturable at the highest doses of paclitaxel (van de Steeg et al., 2011). Human hepatoma HepG2 cells with significantly reduced OATP1B3 expression show paclitaxel resistance (Takano et al., 2009). The clinically-used drug vehicle Cremophor inhibits OATP1B3 transport of paclitaxel (Smith et al., 2005) which has the potential to cause drug-drug interaction.

Irinotecan/SN-38

Irinotecan is a camptothecin derivative that exerts antitumor effect by inhibition of topoisomerase I, resulting in double-stranded DNA breaks and cell death. It is spontaneously converted to an active metabolite, SN-38, by hepatic carboxylesterase and butyrylcholinesterase (de Man et al., 2018). SN-38 is believed to play a role in both the efficacy and toxicity associated with irinotecan-containing regimens, especially diarrhea (Fujita et al., 2016; Kehrer et al., 2001). SN-38 is further metabolized to an inactive form, SN-38-glucuronide, by uridine diphosphate glucuronosyltransferases, most prominently by the 1A1 isoform (UGT1A1); this glucuronide form is transported to the intestinal lumen via bile (de Man et al., 2018; Lokiec, 1995). Other transporters and enzymes, besides OATPs, involved in irinotecan disposition include ABCB1, ABCC1-2, ABCG2, CYP3A4, and CYP3A5. Irinotecan is primarily eliminated in the bile (66%), but irinotecan and its metabolites can also be found in the urine (de Man et al., 2018).

The parent drug irinotecan does not seem to be a substrate for OATP1B1 (Iusuf et al., 2014; Nozawa et al., 2005a; Oostendorp et al., 2009) or OATP1B3 (Iusuf et al., 2014), but these transporters are important for disposition of the active metabolite SN-38 (Fujita et al., 2014; Obaidat et al., 2012; Oostendorp et al., 2009; Yamaguchi et al., 2008). OATP1B1 does not transport SN-38 glucuronide (Nozawa et al., 2005a). OATP2B1 transports SN-38 in *Xenopus* oocytes (Fujita et al., 2016) but not in HEK293 cells (Fujita et al., 2014). *Oatp1a/1b* null mice have markedly increased plasma exposure of irinotecan and SN-38 and significantly decreased liver-to-plasma ratios of these compounds compared to wild-type. When the human transporters OATP1B1 or OATP1B3 were introduced into these mice, SN-38 plasma levels reverted to the same levels as in the wild-type mice, but irinotecan plasma levels were not affected, suggesting that SN-38, but not irinotecan, is a substrate for OATP1B1 and OATP1B3 *in vivo* (Iusuf et al., 2014).

Gastrointestinal toxicity (such as diarrhea) is the most common dose-limiting side effect of irinotecan and is due to SN-38 accumulation in intestinal tissues (Fujita et al., 2016). SN-38 is transported

by OATP2B1 (Fujita et al., 2016) which is expressed in the intestines (Tamai, 2012). OATP2B1-mediated SN-38 transport is inhibited by apple juice (in a dose-dependent manner) and cefixime, among other compounds, with mice given apple juice concurrently with SN-38 having less gastrointestinal toxicity than control mice (Fujita et al., 2016). Additionally, the concurrent use of cyclosporine (a known potent OATP inhibitor) to reduce biliary excretion of irinotecan metabolites (through various transporters) has been shown to improve the toxicity profile of irinotecan in patients with metastatic colon cancer (Chester et al., 2003); the concept of utilizing an OATP inhibitor to alter the pharmacokinetic parameters of chemotherapeutic agents is an area that warrants additional investigation.

Tyrosine Kinase Inhibitors

Tyrosine kinase inhibitors (TKIs) are chemotherapy agents that disrupt cell signaling via inhibition of tyrosine kinases. There are numerous TKIs in routine clinical use which have slightly different pharmacokinetic properties, but all are transported into and out of cells by various members of the *SLC* and *ABC* families and primarily metabolized by various CYP enzymes (Gong et al., 2017; Neul et al., 2016). Transport of TKIs by OATPs has been the subject of many recent studies (Bauer et al., 2017; Bins et al., 2017; Hu et al., 2009; Hu et al., 2008; Hu et al., 2014; Obaidat et al., 2012; Vasilyeva et al., 2015; Yamakawa et al., 2011; Zimmerman et al., 2013). In general, eliminations of TKIs is primarily hepatic and mediated by CYP enzymes (O'Brien and Moghaddam, 2017) with renal clearance playing a small role for some agents (van Erp et al., 2009).

Erlotinib is transported by OATP2B1 *in vitro* (Bauer 2017). Sorafenib transport by OATP1B1 was negative in some studies (Bins et al., 2017; Hu et al., 2009), but another study showed that OATP1B1- and OATP1B3-transfected cells transported sorafenib significantly higher than vector control *in vitro*. However, their *in vivo* mouse data showed no difference in sorafenib pharmacokinetics between wild-type and *Oatp1b2*-deficient mice, and no change in sorafenib transport in humanized OATP1B1 or OATP1B3 mice compared to *Oatp1a/b* null mice (Zimmerman et al., 2013). Sorafenib is not transported by OATP1A2 or OATP1B3 (Hu et al., 2009). Sorafenib has an important metabolite, sorafenib- β -D-glucuronide (SG), which is transported into hepatocytes by OATP1B1 (Bins et al., 2017) and mouse *Oatp1a/1b* (Vasilyeva et al., 2015). In contrast to the sorafenib data in the Zimmerman study, SG transport was affected in *Oatp1b2*

deficient or *Oatp1a/1b* null mice with these mice having significantly higher SG plasma AUC compared to wild-type, and this difference in AUC partially corrected to wild-type in mice transgenic for human OATP1B1 or OATP1B3. The Zimmerman data overall suggests that *in vivo* OATP1B1 and OATP1B3 are not important for sorafenib transport but are important for transport of its glucuronide metabolite (Zimmerman et al., 2013). Imatinib is transported by OATP1A2 and OATP1B3 (Hu et al., 2008; Obaidat et al., 2012; Yamakawa et al., 2011). However, while imatinib transport by OATP1A2 is seen *in vitro*, imatinib absorption in cancer patients was not found to be associated with function-altering OATP1A2 variants or with co-administration of rosuvastatin (a known OATP1A2 inhibitor), suggesting that an alternate transport pathway may also be important *in vivo* (Eechoute et al., 2011).

TKIs also have implications in drug-drug interactions involving OATPs. Sorafenib and other TKIs (axitinib, nilotinib, pazopanib, lapatinib) are inhibitors of OATP1B1 *in vitro*, though *in vivo* data is conflicting and it is likely that transport through other mechanisms becomes important when OATP1B1 is inhibited in these cases (Hu et al., 2014; Polli et al., 2008). Co-administration of sorafenib changes the pharmacokinetics of docetaxel, a known OATP substrate, which may have clinical implications as sorafenib is being incorporated into protocols for many different solid tumors due to its favorable side effect profile and efficacy against these tumors (Awada et al., 2012).

Anthracyclines

The anthracyclines, including doxorubicin, daunorubicin, and mitoxantrone, have several mechanisms that contribute to cytotoxicity: disruption of DNA and RNA synthesis via intercalation, inhibition of topoisomerase II, generation of free oxygen radicals, and interference with histone function. Approximately 50% of doxorubicin's disposition is mediated by biliary elimination, suggesting hepatic uptake and clearance play important roles in its disposition (Danesi et al., 2002). Multiple transporters are involved in doxorubicin disposition, including uptake by SLC22A16 and efflux by ABCC1, ABCG2, and ABCB1. It also undergoes metabolism via several pathways (Thorn et al., 2011).

Recent studies have evaluated the role of OATPs in doxorubicin disposition (Durmus et al., 2014; Lee et al., 2017). Doxorubicin uptake and transport by OATPs *in vitro* varies according to the model system that is utilized. Doxorubicin is transported by OATP1A2-expressing HEK293 (Durmus et al., 2014), HeLa,

and MDCKII cells (Lee et al., 2017), while OATP1B1- and OATP1B3-mediated doxorubicin transport is seen in MDCKII cells (Lee et al., 2017) but not in HeLa (Lee et al., 2017) or HEK293 cells (Durmus et al., 2014). Results of *in vivo* studies in rodents have shown that doxorubicin uptake and disposition is significantly decreased in *Oatp1a/1b* null mice compared to wild-type (Durmus et al., 2014; Lee et al., 2017) and that transgenic expression of human OATPs either completely (for OATP1A2) or partially (for OATP1B1 and OATP1B3) reverts doxorubicin pharmacokinetics to wild-type values (Durmus et al., 2014). These data together suggest that OATP1A2, OATP1B1, and OATP1B3 are all involved in doxorubicin transport. The related agents daunorubicin and mitoxantrone are transported by OATP1B1 *in vitro* and deficiency of mouse *Oatp1b2* results in significantly increased plasma AUC of both drugs (Drenberg et al., 2016).

Platins

The platinum chemotherapy agents work by crosslinking DNA and therefore disrupting DNA synthesis and repair. These compounds are transported by *SLC31A1*, *ABCC2*, *ABCG2*, *MDR1* (P-glycoprotein) (Dasari and Tchounwou, 2014; Marsh et al., 2009), and importantly by organic cation transporters *OCT1*, *OCT2*, and *OCT3* encoded by *SLC22* genes (Wagner et al., 2016). A number of enzymes are involved in converting platinum-based chemotherapy drugs to inactive metabolites, such as myeloperoxidase and superoxide dismutase (Marsh et al., 2009). The elimination of platinum agents is almost exclusively through the kidneys (Burger et al., 2011).

Cisplatin, carboplatin, and oxaliplatin are transported *in vitro* by OATP1B1 and OATP1B3, and cytotoxicity of these agents in human tumor cells was found to be enhanced with increasing OATP1B3 mRNA expression (Lancaster et al., 2013). *Oatp1b2* knockout mice have significantly reduced liver-to-plasma ratios of cisplatin compared to wild-type (Lancaster et al., 2013). Bile acid-cisplatin derivatives have been developed as liver-trophic drugs that could become concentrated in bile and help overcome resistance to platinum agents (Criado et al., 2000; Criado et al., 1997). Two of these, Bamet-R2 and Bamet-UD2 are transported by OATP1B1 and, to a lesser extent, OATP1A2 (Briz et al., 2002).

Summary: OATPs in Chemotherapy Disposition

While a growing number of chemotherapeutic agents have been shown to be OATP substrates *in vitro*, it remains yet to be determined that OATPs are important to the clinical pharmacology of all these purported anticancer agents. Yet, series of follow up or complementary studies in animal models using Oatp knockout mice or transgenic human OATP mice have suggested OATP transporters are important to the clinical pharmacology of agents such as methotrexate, taxanes, and anthracyclines. Additional studies to evaluate the roles of OATP transporters in chemotherapy disposition are warranted due to the narrow therapeutic indices associated with these cancer therapeutics. A more comprehensive evaluation and understanding of the clinical pharmacology of these drugs would yield important knowledge to better optimize chemotherapy dosing and combination therapies that may improve therapeutic efficacy while mitigating serious drug-mediated adverse effects.

PHARMACOGENETICS OF OATP TRANSPORTERS

The *SLCO* genes are polymorphic, with common (minor allele frequency >5%) variants identified in OATP1B1, OATP1B3, and OATP1A2. Some of these variants affect the expression, localization, and/or function of the transporter and can significantly alter the disposition of xenobiotics and endogenous substrates (Konig, 2011). Table 2 contains information on functional consequences of selected polymorphisms in *SLCO1A2*, *SLCO1B1*, *SLCO1B3*, and *SLCO2B1*, and this topic was also reviewed in detail recently (Zhou et al., 2017).

OATP1A2

Multiple function-altering variants in *SLCO1A2* have been reported (Lee et al., 2005; Zhou et al., 2015). Several *SLCO1A2* variants show altered transport of methotrexate, including the hyperfunctional c.38T>C variant, hypofunctional c.516A>C, and c.502C>T variants, and nonfunctional c.833delA variant (Badagnani et al., 2006). The c.516A>C variant has been reported as hypofunctional for other substrates as well, and some *SLCO1A2* variants have substrate-specific alteration of transport (Lee et al., 2005). Imatinib clearance is significantly affected by several single nucleotide polymorphisms (SNPs) in *SLCO1A2*, with patients carrying at least one copy of each of the intronic variants c.-1167G>A and c.-1094G>A having

significantly reduced drug clearance compared to wild-type, and patients with the who do not have the intronic variant c.-423G>A (homozygous wildtype) have increased clearance (Yamakawa et al., 2011). The clinical significance of altered drug transport function associated with *SLCO1A2* variants has not been determined to date. Further study of *SLCO1A2* variation as it relates to chemotherapy disposition will be helpful in the future given this transporter's role at the blood-brain barrier and the importance of developing chemotherapeutic agents that penetrate the brain tissue for certain diagnoses, most notably malignant brain tumors.

OATP1B1

SLCO1B1 variants have been widely studied with regards to impact on the pharmacokinetics of many drugs (Shitara 2011, Niemi 2011) and notably in the incidence of adverse drug reactions in patients treated with statins (Link 2008, Jiang 2016). The *SLCO1B1* c.521T>C variant, which has a minor allele frequency of 12-18% in European and East Asian populations with lower frequency (1.9%) in sub-Saharan African populations (Pasanen 2008), has been studied the most extensively of the *SLCO1B1* variants and is associated with significantly impaired hepatic uptake, and thus corresponding increased plasma levels, of many substrates (Ho et al., 2007; Kameyama et al., 2005; Katz et al., 2006; Mwinyi et al., 2004; Niemi et al., 2005a; Niemi et al., 2005b; Niemi et al., 2004; Nishizato, 2003; Nozawa et al., 2005a; Tirona et al., 2001; Xiang et al., 2009; Zhang et al., 2007). The c.521T>C variant has been identified as a significant risk factor for statin-induced myopathy (Link 2008) and other statin-induced adverse drug reactions (Jiang 2016). A case-control analysis of patients in the large randomized trial SEARCH (Study of the Effectiveness of Additional Reductions in Cholesterol and Homocysteine) found an odds ratio for myopathy of 4.5 per copy of the variant C allele, and homozygous variant (CC) patients had an odds ratio of 16.9 for development of myopathy compared to TT patients (Link 2008). Another commonly studied *SLCO1B1* variant is the c.388A>G variant (Tirona et al., 2001) which has no apparent relationship with statin adverse drug reactions (Jiang et al., 2016).

Several *SLCO1B1* haplotypes with differential drug transport compared to wild-type have been identified. *SLCO1B1**1a is the reference allele, with the *1b haplotype including the c.388A>G variant, the *5 haplotype having the c.521T>C variant, and the *15 haplotype containing both the c.388A>G and

c.521T>C variants (Tirona et al., 2001). There is conflicting data regarding function of the *1b haplotype, with transport of some substrates being no different compared to transport by the wild-type protein (Iwai et al., 2004; Lee et al., 2015; Michalski et al., 2002; Nozawa et al., 2002; Tirona et al., 2001), while in other studies it appears to be hyperfunctional for some substrates (Crona et al., 2016; Drenberg et al., 2016; Ieiri et al., 2009; Michalski et al., 2002; Mwinyi et al., 2004; Nies et al., 2013) and hypofunctional for others (Drenberg et al., 2016; Michalski et al., 2002). Some data suggests that the c.388A>G variant causes increased expression of OATP1B1 at the plasma membrane (Nies et al., 2013; Nozawa et al., 2002). The *5 and *15 haplotypes are hypofunctional, including significantly reduced *in vitro* transport of cytarabine, daunorubicin, etoposide, mitoxantrone (Drenberg et al., 2016), and docetaxel (de Graan et al., 2012; Lee et al., 2015). However, in a clinical study, no effect on docetaxel clearance was found for patients carrying the *SLCO1B1* variants g.21130388G>A (promoter variant), c.388A>G, or c.521T>C compared to wild-type (de Graan et al., 2012).

The effect of other *SLCO1B1* variants on chemotherapy disposition has been studied. Several studies have examined the relationship between *SLCO1B1* genotype and the high interpatient variability seen in methotrexate clearance (Lopez-Lopez et al., 2011; Ramsey et al., 2012; Ramsey et al., 2013; Trevino et al., 2009). In 115 pediatric leukemia patients, those who were homozygous for the intronic *SLCO1B1* variants c.1865+248G>A or c.1865+4846T>C had significantly higher plasma methotrexate levels following high-dose methotrexate therapy compared to patients with the wild-type or heterozygous variant genotypes, though the number of patients homozygous for these variants was low. High methotrexate plasma levels at 72 hours after the start of infusion were significantly correlated with development of global toxicity, vomiting, and renal toxicity suggesting genetic variants which affect methotrexate plasma levels may also increase rates of methotrexate-associated toxicities (Lopez-Lopez et al., 2011).

A large clinical study (Trevino et al., 2009) and a follow-up including additional patients (Ramsey et al., 2013), utilizing a GWAS approach, found that SNPs in *SLCO1B1* were significantly associated with methotrexate clearance. The *SLCO1B1* variants c.1865+248G>A and c.1865+4846T>C were in linkage disequilibrium (LD) with each other and with c.521T>C, all of which were associated with decreased methotrexate clearance (Trevino et al., 2009). Interestingly, those carrying wild-type alleles as these

positions had increased incidence of GI toxicity (per National Cancer Institute Cancer Therapy Evaluation Program toxicity grading) compared to those with variant alleles, presumably due to enhanced clearance and resultant lower plasma exposure with corresponding higher GI tract methotrexate exposure via elimination pathways. In the follow-up study, the SNP most significantly associated with methotrexate clearance was c.521T>C for which homozygous variant (CC) patients had methotrexate clearance that was on average 13% lower than homozygous wild-type (TT) patients, and this genotype explained 2% of variation in methotrexate clearance, a higher proportion explained than that for age and sex combined. In this study, three other significant SNPs in *SLCO1B1* were in significant LD with c.521T>C (Ramsey et al., 2013). Another study utilizing the same patient population indicated that, after controlling for c.521T>C, 15 additional SNPs in *SLCO1B1*, all non-synonymous and some rare (MAF <5%), were significantly associated with methotrexate clearance, with these SNPs either causing increased or decreased clearance compared to wild-type. This data showed that even rare damaging SNPs can have a significant impact on methotrexate clearance (Ramsey et al., 2012).

A separate study replicated the finding that c.1865+248G>A and c.1865+4846T>C are associated with methotrexate disposition; in this study, these variants were associated with higher average plasma methotrexate levels, including levels above the upper limit of the desired range (Li et al., 2015). A recent study in adult patients with hematological malignancies receiving high dose methotrexate suggests patients with *SLCO1B1* variants c.388A>G or c.521T>C exhibit differential urinary endogenous metabolomic profiles that may interact with renal OAT transporters to modulate risk for methotrexate induced toxicities, illustrating the link between *SLCO1B1* SNPs and methotrexate clearance and/or toxicity may be multifactorial and more complex than previously thought (Martinez et al., 2018).

Regarding irinotecan and SN-38 disposition, *Xenopus* oocytes expressing the *SLCO1B1**15 allele showed markedly reduced transport for SN-38, while the *5 allele conferred a more modest reduction in SN-38 transport (Nozawa et al., 2005a). Patients with the *15 haplotype had a 3-fold reduction in irinotecan clearance and significantly higher AUC for both irinotecan and SN-38 compared to *1a/*1a (Xiang et al., 2006). In patients with non-small cell lung cancer treated with irinotecan and cisplatin, the *SLCO1B1* variants c.521T>C and g.21130388G>A were found to affect pharmacokinetics of SN-38. Patients carrying at least one copy of the c.521T>C variant allele or those homozygous for the g.21130388G>A promoter

variant had a significantly higher AUC of the important irinotecan metabolite SN-38 compared to wild-type patients. Additionally, SN-38 clearance was significantly lower in the g.21130388AA patients and there was a trend toward lower clearance in patients with at least one copy of the c.521T>C variant. None of the variants in this study were associated with tumor response or pharmacokinetics of the parent drug irinotecan (Han et al., 2008). However, in another study, the *SLCO1B1**5 haplotype was associated with significantly increased irinotecan AUC but neither the *SLCO1B1**1b or *SLCO1B1**5 haplotypes were associated with SN-38 pharmacokinetics (Innocenti et al., 2009). In a study by Crona *et al*, the c.521T>C variant was associated with increased irinotecan AUC in a discovery cohort of patients but this finding did not replicate in a validation cohort, and this variant was not associated with SN-38 pharmacokinetics (Crona et al., 2016). Thus, the relationship between these *SLCO1B1* variants and the pharmacokinetics of irinotecan and SN-38 is not consistently defined and warrants further study in larger populations of patients to determine whether *SLCO1B1* variants influence irinotecan and/or SN-38 pharmacokinetics.

However, *SLCO1B1* variants have been linked to irinotecan-induced toxicities. The *SLCO1B1* c.521T>C variant was associated with increased risk of irinotecan-induced grade 3/4 neutropenia in a cohort of adult Japanese patients with various cancers who were treated either with irinotecan monotherapy or irinotecan plus cisplatin (Sai et al., 2010). A patient with the *SLCO1B1**15/15 genotype as well as another at-risk genotype was reported to have excessive accumulation of SN-38 in the plasma circulation which led to life-threatening diarrhea and neutropenia (Takane et al., 2009). Patients with at least one copy of the c.521T>C variant allele who were treated with irinotecan had higher rates of grade 4 neutropenia compared to wild-type, and patients homozygous for the c.388A>G variant had higher rates of grade 3 diarrhea following irinotecan therapy (Han et al., 2008). In advanced cancer patients treated with single-agent irinotecan, the *SLCO1B1**1b haplotype was associated with a lower ANC nadir when comparing *1b/1b patients to *1a/1a or *1a/1b patients (Innocenti et al., 2009); conversely, the c.388A>G variant was associated with a protective effect against neutropenia following irinotecan therapy in another study (Crona et al., 2016). With regards to outcomes, patients with the c.521T>C variant had increased SN-38 exposure compared to wild-type, and those with the *SLCO1B1* c.388GG genotype had significantly longer progression-free survival (PFS) compared to the c.388AA genotype (Teff et al., 2015). Collectively, these genetic association studies demonstrate that *SLCO1B1* variation may play an important role in the

interindividual variability in chemotherapy disposition and response for several OATP1B1 chemotherapeutic substrates.

OATP1B3

The functional consequences of various *SLCO1B3* variants have been studied, especially the c.334T>G and c.699G>A variants for which there are substrate-specific alterations in transport compared to wild-type (Letschert et al., 2004; Schwarz et al., 2011). OATP1B3 transports testosterone *in vitro*, and cells expressing OATP1B3 containing either the c.334T>G or c.699G>A variant transported testosterone at a similar rate compared to wild-type, while the presence of both variants concurrently resulted in significant impairment of testosterone transport (Hamada et al., 2008). This has potential implications for the growth of hormone-dependent tumors such as prostate cancer.

Several *SLCO1B3* variants have been found to affect docetaxel transport compared to wild-type, including c.699G>A, c.1559A>C, c.1679T>C, and the haplotype containing c.334T>G and c.699G>A *in vitro* (Lee et al., 2015), but results from clinical studies on the effect of *SLCO1B3* variants on docetaxel elimination are mixed. In a study of the effect of *SLCO1B3* haplotype on docetaxel pharmacokinetics in cancer patients, the variants c.359+76G>A (intronic), c.699G>A, c.1599-5676A>G (intronic), and c.*347_*348insA were used to construct haplotypes that had a significant impact on docetaxel clearance and AUC. These haplotypes explained 29% and 22% of the variability in docetaxel clearance and AUC, respectively; specifically, one haplotype resulted in a 30% decrease in clearance and 40% increase in AUC, while another haplotype increased clearance by 50% compared to the reference haplotype (Chew et al., 2012). However, in a study of patients treated with docetaxel, no relationship was found between the c.699G>A, c.1559A>C, c.1679T>C, c.334T>G, c.439A>G, or c.767G>C variants and docetaxel pharmacokinetics (Baker et al., 2009). Patients with nasopharyngeal carcinoma who were homozygous for the intronic *SLCO1B3* variant c.1599-5676A>G had significantly higher AUC and lower clearance of docetaxel in one study, while multiple other *SLCO1B3* variants (including c.334T>G, c.1559A>C, c.1679T>C, c.699G>A, and c.1599-5676A>G) had no effect on docetaxel pharmacokinetics, though the number of patients with these variants in this study was low (Chew et al., 2011). Another study similarly

found no effect of the variants c.334T>G, c.699G>A, or c.1599-5676A>G on docetaxel clearance (de Graan et al., 2012).

Taxane-induced transport and toxicities have been studied with respect to *SLCO1B3* variation. For paclitaxel, significantly reduced transport was found for oocytes expressing the c.699A>G variant while no effect on paclitaxel transport was found for the c.334A>G variant (Park et al., 2016). A clinical study found no relationship between paclitaxel-associated neurotoxicity and the *SLCO1B3* variants c.334T>G and c.699G>A in 118 cancer patients after adjusting for age and treatment schedule (Leskela et al., 2011). The c.1599-5676A>G variant in *SLCO1B3* has been associated with grade 3/4 docetaxel-induced leukopenia and neutropenia in some studies (Kiyotani et al., 2008; Yamada et al., 2014) but had no effect on these toxicities or other hematologic abnormalities in another study (Choi et al., 2015). Thus, the consequences of *SLCO1B3* variation to taxane-induced differential transport or risk for drug-mediated toxicity have not been clearly defined yet.

OATP EXPRESSION IN TUMOR TISSUES AND THEIR POTENTIAL AS THERAPEUTIC TARGETS

The differential expression of OATPs in cancerous versus normal tissues has been studied as a way to develop novel diagnostic or therapeutic strategies for these tumors (Okabe et al., 2008). OATPs that are highly expressed in cancerous tissues with little to no expression in corresponding normal tissues may be useful as diagnostic markers and/or therapeutic targets, as malignant tissues that have upregulation of OATPs that transport chemotherapeutic substrates may be more sensitive to the cytotoxic effects of these agents. This makes screening for OATP expression prior to starting therapy an attractive way to increase the chance of response to a chemotherapy regimen (Buxhofer-Ausch et al., 2013). Table 3 contains information on the overexpression of OATP1A2, OATP1B1, OATP1B3, and OATP2B1 in various cancer tissues, which has recently been reviewed in more detail (Thakkar et al., 2015).

While OATP1B3 is predominantly expressed in liver under normal conditions, it has been detected in various malignant tissues including tumors of the cervix, intestines, liver, lung, pancreas, and genitourinary tract (Lancaster et al., 2013). A cancer-specific form of OATP1B3 (csOATP1B3), also referred to as cancer-type OATP1B3 (ctOATP1B3), has been identified in which an alternative splice site is utilized, resulting a protein that is structurally different than that found in normal liver; the csOATP1B3 transcript has

been detected in malignant tissues from the colon (Han et al., 2013; Nagai et al., 2012; Sun et al., 2014; Thakkar et al., 2013), pancreas (Han et al., 2013; Thakkar et al., 2013), and lung (Nagai et al., 2012; Sun et al., 2014). Some commonly used detection methods for wild-type OATP1B3 do not detect this cancer-specific OATP1B3, so studies that do not show expression of OATP1B3 in cancerous tissues must be interpreted with caution if they did not search for the cancer-specific variant (Evangelini et al., 2017). The transport function of csOATP1B3 for at least some substrates is significantly decreased or abolished (Sun et al., 2014; Thakkar et al., 2013) though transport of other substrates is similar to that of the wild-type transporter (Imai et al., 2013).

Additionally, OATP1A2, OATP1B1, OATP1B3, and OATP2B1 transport many endogenous steroid hormones and hormone conjugates including estradiol, estrone-3-sulfate (E3S), and dehydroepiandrosterone sulfate (DHEAS) (Buxhofer-Ausch et al., 2013; Cui et al., 2001; De Bruyn et al., 2011; Grube et al., 2006a; König et al., 2000; Kullak-Ublick et al., 1998; Kullak-Ublick et al., 2001; Maeda et al., 2010; Miyagawa et al., 2009; Nozawa et al., 2004a; Nozawa et al., 2004b; Pizzagalli et al., 2003; Tamai et al., 2001; Yang et al., 2011). Steroid hormones and their conjugates are important for the proliferation of tumor cells in hormone-dependent malignancies (Hamada et al., 2008; Hong and Chen, 2011; Nozawa et al., 2004b; Nozawa et al., 2005b). However, there is generally redundant transport of these hormones by one or more OATPs in addition to other transporters; for example, in one study OATP1B3 transported E3S efficiently but only accounted for 6% of total E3S transport in breast cancer cells (Maeda et al., 2010). The expression of OATPs in hormone-dependent cancers has been studied and linked to the level of differentiation in the tumor specimens, which may be used as a marker of disease stage (Pressler et al., 2011).

Breast Tumors

OATP1A2, OATP1B1, OATP1B3, and OATP2B1 have all been found in breast cancer cells at levels similar to or higher than those found in normal breast tissue (Al Sarakbi et al., 2006; Banerjee et al., 2012; Bleasby et al., 2006; Buxhofer-Ausch et al., 2013; Kindla et al., 2014; Meyer zu Schwabedissen et al., 2008; Miki et al., 2006; Muto et al., 2007; Pizzagalli et al., 2003; Stute et al., 2012). Treatment with chemotherapy changes the expression levels of these transporters in a cell line-dependent manner (Stute

et al., 2012). Hormone-dependent breast tumor cells have been shown to have increased transport of E3S compared to hormone-independent tumors, possibly due to increased OATP expression in hormone-dependent tumors (Banerjee et al., 2012; Banerjee et al., 2013; Banerjee et al., 2014).

Estrogens are important for development and growth of hormone-dependent breast cancers, with certain estrogen derivatives being taken up into tumor cells to be converted to their active forms *in situ* (Hong and Chen, 2011). Estrogen concentrations in tumors have been found to be significantly higher than levels in the plasma circulation, suggesting an active process resulting in accumulation of intratumoral estrogens (Pasqualini et al., 1996). E3S is an important source of estrogen for breast cancer cells and is found at particularly high levels in postmenopausal breast cancer patients (Pasqualini et al., 1996). E3S is converted to estradiol in a series of enzymatic reactions, and estradiol drives cell proliferation (Banerjee et al., 2013; Matsumoto et al., 2015; Nozawa et al., 2004b; Nozawa et al., 2005b). E3S transport into breast cancer cells is apparently by an active carrier-mediated process given its uptake kinetics (Nozawa et al., 2004b). Due to their transport of steroid hormones, OATPs have been considered important to proliferation in breast cancer cells (Banerjee et al., 2012).

OATP-mediated transport of hormone conjugates may be useful as a therapeutic target (Banerjee et al., 2012). A study examining the plasma levels of estrone, estrone conjugates, and androstenedione in postmenopausal women with resected early-stage estrogen receptor positive breast cancer (prior to aromatase inhibitor therapy) found that several genetic variants in *SLCO1B1*, including c.521T>C and c.463C>A, were associated with higher levels of these hormones compared to wild-type. This is clinically relevant because estrone conjugates are converted to estrone by the enzyme steroid sulfatase (STS), and STS inhibitors are available for clinical use (Dudenkov et al., 2017). Additionally, expression of OATPs in tumor specimens may be associated with disease prognosis. Overexpression of OATPs has also been associated with higher tumor grade (Al Sarakbi et al., 2006; Matsumoto et al., 2015). However, increased OATP expression may also make breast tumors more susceptible to chemotherapeutic agents that are transported by that OATP, as was suggested in a study where OATP1B3 expression was associated with improved prognosis in estrogen receptor positive patients only, possibly due to increased uptake of tamoxifen in these patients (Muto et al., 2007). Recently, it has been shown that OATP1A2 expression may

predict pathologic response to neoadjuvant chemotherapy in triple-negative breast cancer patients as well (Hashimoto et al., 2014).

Prostate and Other Genitourinary Tumors

Prostate cancer specimens have been found to have increased protein and/or mRNA expression of OATP1B1 (Buxhofer-Ausch et al., 2013) and OATP1B3 (Buxhofer-Ausch et al., 2013; Hamada et al., 2008; Lancaster et al., 2013; Pressler et al., 2011) compared to normal prostate or benign prostatic hyperplasia specimens. Increased OATP1B3 expression has been correlated with increased tumor grade (Pressler et al., 2011). OATP1B1 and OATP1B3 expression is increased in metastatic lesions from prostate cancer that has not responded to androgen deprivation therapy compared to untreated prostate cancer (Wright et al., 2011).

Androgen-depleting therapies are the current mainstay of treatment for prostate cancer; however, over time, many patients become resistant to this therapy and progress to castration-resistant prostate cancer which can be fatal (Cho et al., 2014). Upregulation of some OATPs is also believed to allow prostate cancer cells to continue to grow by more effectively scavenging low levels of circulating androgens and other steroids such as E3S during androgen-depleting therapies; thus, therapies to reduce OATP-mediated steroid hormone transport could represent a treatment strategy for resistant prostate cancer (Cho et al., 2014). The adrenal steroid hormone DHEAS, which is not affected by androgen-depleting therapies, has also been considered as a possible pharmacological target given its role in cell proliferation under androgen-depleted conditions, which can cause tumor resistance to anti-androgen therapies (Arakawa et al., 2012; Evaul et al., 2010). DHEAS is transported by OATP1A2, OATP1B1, OATP1B3, and OATP2B1 (Cui et al., 2001; Grube et al., 2006a; Kullak-Ublick et al., 1998; Kullak-Ublick et al., 2001; Pizzagalli et al., 2003; Yang et al., 2011). Under conditions of androgen depletion, the expression of OATP1A2 significantly increases, and in OATP1A2 knockdown cells, DHEAS does not stimulate cell growth, suggesting that OATP1A2 is important for DHEAS-mediated growth of prostate cancer cells (Arakawa et al., 2012). In contrast, two docetaxel-resistant patient-derived xenografts were found to have marked decrease in *SLCO1B3* expression which reduced the uptake of docetaxel into these cells (de Morree et al., 2016); thus,

up- and downregulation of OATP transporters in prostate cancer cells may have varying effects depending on if a cytotoxic agent or tumor growth-promoting endogenous substrate is being transported.

Due to their role in steroid transport, OATPs may impact prostate cancer prognosis. In one study, carriers of the rs12422149 SNP in *SLCO1B1* or the rs4149117 SNP in *SLCO1B3* had a higher rate of prostate cancer-specific mortality compared to wild-type (Wright et al., 2011). In men with prostate cancer, those with at least one copy of the *SLCO1B3* c.334T>G variant have been shown to have longer time to response to androgen deprivation therapy (Sharifi et al., 2008) and a trend toward shorter time to progression to castration-resistant prostate cancer (Fujimoto et al., 2013) compared to wild type, likely due to increased transport of testosterone into the tumor by the T allele (Sharifi et al., 2008). In another study, patients with the *SLCO1B3* c.334GG/699AA haplotype had longer median survival (8.5 vs 6.4 years) and improved survival to 10 years (42% vs 23%) compared to patients with TT/AA or TG/GA haplotypes (Hamada et al., 2008). This evidence suggests that *SLCO1B3* variation may aid in prognostication for prostate cancer.

The *SLCO2B1* variant c.935G>A has been shown to affect DHEAS uptake, with the variant transporter having less DHEAS transport compared to wild-type; accordingly, a cell growth assay showed that the wild-type transporter was associated with increased cell proliferation (Yang et al., 2011). Patients with prostate cancer with at least one copy of the variant allele at rs12422149 in *SLCO2B1* have longer time to progression on anti-androgen therapy, suggesting an improved prognosis conferred by the variant genotype, likely due to reduced transport of DHEAS into the tumor by the variant allele (Fujimoto et al., 2013; Yang et al., 2011). Two other *SLCO2B1* variants (rs1077858 and rs1789693) also affect time to progression in prostate cancer, with the variant alleles being associated with longer time to progression. Patients with more than one risk genotype in *SLCO2B1*, or with an at-risk genotype in both *SLCO1B3* (which did not reach significance on their own) and *SLCO2B1*, had progressively worse outcomes as the number of at-risk genotypes increased (Yang et al., 2011).

Hepatic Tumors

OATP1B1 and OATP1B3, while highly expressed in normal liver tissues, are generally downregulated in hepatic tumors to varying degrees in different studies (Buxhofer-Ausch et al., 2013; Cui

et al., 2003; Kinoshita and Miyata, 2002; Libra et al., 2006; Pressler et al., 2011; Vasuri et al., 2011; Vavricka et al., 2004; Wlcek et al., 2011; Zollner et al., 2005). In one study, 45% of hepatocellular carcinoma specimens lacked staining for both OATP1B1 and OATP1B3 (Vasuri et al., 2011). In addition, the pattern of OATP1B3 staining is different in malignant cells (cytoplasmic) versus normal tissue (membranous) (Libra et al., 2006), and progressive loss of OATP1B3 staining is seen as tumor grade increases, suggesting that the lowest OATP1B3 expression is associated with the most aggressive tumors (Lockhart et al., 2008). Neither OATP1B1 nor OATP1B3 expression was found in lymph node metastases of hepatocellular carcinoma or in liver metastases from adenocarcinoma of the colon, rectum, or pancreas, and normal liver tissue surrounding these metastatic lesions maintained normal OATP1B1 and OATP1B3 expression (Cui et al., 2003). OATP2B1 mRNA levels were found to be lower in malignant versus normal cells in some studies (Pressler et al., 2011; Wlcek et al., 2011), but in another study OATP2B1 mRNA expression was similar or higher in malignant versus normal hepatic cells (Libra et al., 2006). Other OATPs are also overexpressed in malignant versus normal hepatic tissue (Wlcek et al., 2011).

The conjugation of drugs to bile acids has been studied as a way to selectively deliver these drugs, including chemotherapy agents, to the liver (Kramer et al., 1992). There is evidence that uptake of bile acid derivatives into human hepatic cancer cells is OATP mediated (Kullak-Ublick et al., 1997; Kullak-Ublick et al., 1996). An imaging agent that is a bile acid derivative is transported by OATP1B3, which is significantly underexpressed in liver tumors compared to normal liver; thus, the use of this agent could allow for improved visualization of liver tumors (Libra et al., 2006). Decreased protein expression of these OATP transporters in malignant tissues may be important given the role of these transporters in the uptake of chemotherapy agents, with reduced expression leading to decreased tumoral uptake of these drugs.

Colorectal and Other Gastrointestinal Tumors

OATP1A2 mRNA has been detected in colon adenocarcinoma specimens (Tamai et al., 2000) but was found to be expressed at lower levels in colon neoplasia specimens compared to normal colon which has implications for the use of chemotherapy agents transported by OATP1A2 for the management of gastrointestinal cancers (Ballesterio et al., 2006). OATP1B1 and OATP1B3 mRNA are highly expressed in various cancers of the gastrointestinal tract including the colon despite not being found in normal colon

tissue (Abe et al., 2001; Ballesteros et al., 2006; Buxhofer-Ausch et al., 2013), with higher OATP1B1 expression associated with higher tumor grade in colon cancer specimens (Pressler et al., 2011). OATP1B3 has been detected in gastric and gallbladder cancers (Abe et al., 2001; Lancaster et al., 2013). In one study, out of 30 colorectal cancer specimens studied, 27 were positive for OATP1B3 by immunohistochemistry, with the remaining 3 specimens expressing a mutant form of OATP1B3 that caused the antibody binding for the immunohistochemical staining to fail; the OATP1B3 staining in these samples was primarily cytoplasmic, in contrast to the membranous pattern found in normal liver (Evangeli et al., 2017). Another study similarly found that while none of the normal colon specimens had OATP1B3 mRNA present, four out of the seven colon cancer specimens studied had detectable OATP1B3 mRNA that was almost exclusively a cancer-specific different isoform different than that found in normal liver (Nagai et al., 2012).

Overexpression of OATP1B3 mRNA in a colorectal cancer cell line was associated with reduced drug-induced apoptosis of these cells and reduced transcriptional activity of the tumor suppressor p53; these functions are apparently directly related to OATP1B3-mediated transport, as inclusion of a point mutation that abolishes OATP1B3 transport also removed the anti-apoptosis and reduced p53 features of these cells (Lee et al., 2008). OATP2B1 mRNA has been detected in colon adenocarcinoma samples (Bleasby et al., 2006; Kleberg et al., 2012; Tamai et al., 2000) with higher expression in neoplastic colon specimens compared to normal colon (Kleberg et al., 2012).

Pancreatic Tumors

OATP1B3 is expressed in pancreatic cancer samples at higher levels than in normal pancreas (Abe et al., 2001; Buxhofer-Ausch et al., 2013; Hays et al., 2013; Kounnis et al., 2015; Kounnis et al., 2011; Lancaster et al., 2013). OATP1A2 (Kounnis et al., 2011) and OATP1B1 (Kounnis et al., 2015; Kounnis et al., 2011) are also highly expressed in pancreatic tumors. OATP1B3 expression was found to be highest in the non-malignant conditions of pancreatic hyperplasia and pancreatitis, and was also high in stage 1 pancreatic adenocarcinoma, with lower levels of expression seen in stage 2 or 3 adenocarcinoma, suggesting that OATP1B3 expression could be useful as a marker to detect pre-malignant lesions or early stage pancreatic cancer (Hays et al., 2013).

Lung Tumors

OATP1A2 (Brenner et al., 2015) and OATP2B1 (Bleasby et al., 2006; Brenner et al., 2015) mRNA are expressed at low levels in normal lung epithelium. OATP1A2 mRNA was found at similar (Monks et al., 2007) or lower (Brenner et al., 2015) levels in malignant lung tissue compared to normal tissue, while OATP2B1 mRNA was found to be upregulated in malignant lung tissue compared to normal in one study (Brenner et al., 2015) and downregulated in malignant tissue in another study (Monks et al., 2007). Minor OATP2B1 mRNA expression in lung tumor specimens was detected in another study though quantification compared to normal tissue was not done (Bleasby et al., 2006). OATP1B1 and OATP1B3 have also been shown to be expressed in some lung tumor specimens (Buxhofer-Ausch et al., 2013), and *SLCO1B3* mRNA was found in malignant lung cells (Lancaster et al., 2013). No mRNA expression of OATP1B3 was found in normal lung tissues, while the cancer-specific OATP1B3 was found in two out of five lung cancer specimens studied (Nagai et al., 2012).

CONCLUSIONS

Over the past two decades, OATPs have increasingly become recognized as important mediators of drug uptake and disposition. More recently it has become apparent that OATPs have potentially important emerging roles in cancer pharmacology. Transport of many chemotherapy agents is mediated by OATPs which may have significant implications for chemotherapy disposition and drug-drug interactions. OATPs are polymorphic with numerous function-altering variants which can alter the disposition, efficacy, and toxicity profiles of chemotherapy agents, which is especially notable for drugs that traditionally have narrow therapeutic indices and has important implications for personalized and precision medicine initiatives. OATPs are widely and differentially expressed in several normal and neoplastic tissues and transport many substrates that are of importance to cancer therapy and tumor progression. Transport of endogenous steroid hormones is associated with cell proliferation in some hormone-dependent cancers, and overexpression of OATPs in these tumors may lead to more aggressive disease. Differential expression of OATPs in neoplastic tissues may provide novel therapeutic strategies to preferentially deliver chemotherapy to tumor tissues with OATP overexpression to enhance tumor killing while minimizing damage to normal tissues.

ACKNOWLEDGMENTS

The authors would like to thank Michael L. Schulte, PhD, for assistance with figure preparation.

AUTHORSHIP CONTRIBUTIONS

Wrote or contributed to the writing of the manuscript: Schulte and Ho

REFERENCES

- Abe T, Unno M, Onogawa T, Tokui T, Kondo TN, Nakagomi R, Adachi H, Fujiwara K, Okabe M, Suzuki T, Nunoki K, Sato E, Kakyo M, Nishio T, Sugita J, Asano N, Tanemoto M, Seki M, Date F, Ono K, Kondo Y, Shiiba K, Suzuki M, Ohtani H, Shimosegawa T, Iinuma K, Nagura H, Ito S and Matsuno S (2001) LST-2, a human liver-specific organic anion transporter, determines methotrexate sensitivity in gastrointestinal cancers. *Gastroenterology* **120**(7): 1689-1699.
- Al Sarakbi W, Mokbel R, Salhab M, Jiang WG, Reed MJ and Mokbel K (2006) The role of STS and OATP-B mRNA expression in predicting the clinical outcome in human breast cancer. *Anticancer Res* **26**(6C): 4985-4990.
- Arakawa H, Nakanishi T, Yanagihara C, Nishimoto T, Wakayama T, Mizokami A, Namiki M, Kawai K and Tamai I (2012) Enhanced expression of organic anion transporting polypeptides (OATPs) in androgen receptor-positive prostate cancer cells: possible role of OATP1A2 in adaptive cell growth under androgen-depleted conditions. *Biochem Pharmacol* **84**(8): 1070-1077.
- Awada A, Hendlitz A, Christensen O, Lathia CD, Bartholomeus S, Lebrun F, de Valeriola D, Brendel E, Radtke M, Delaunoy T, Piccart-Gebhart M and Gil T (2012) Phase I trial to investigate the safety, pharmacokinetics and efficacy of sorafenib combined with docetaxel in patients with advanced refractory solid tumours. *Eur J Cancer* **48**(4): 465-474.
- Badagnani I, Castro RA, Taylor TR, Brett CM, Huang CC, Stryke D, Kawamoto M, Johns SJ, Ferrin TE, Carlson EJ, Burchard EG and Giacomini KM (2006) Interaction of methotrexate with organic-anion transporting polypeptide 1A2 and its genetic variants. *J Pharmacol Exp Ther* **318**(2): 521-529.
- Baker SD, Sparreboom A and Verweij J (2006) Clinical pharmacokinetics of docetaxel: Recent developments. *Clin Pharmacokinet* **45**(3): 235-252.
- Baker SD, Verweij J, Cusatis GA, van Schaik RH, Marsh S, Orwick SJ, Franke RM, Hu S, Schuetz EG, Lamba V, Messersmith WA, Wolff AC, Carducci MA and Sparreboom A (2009) Pharmacogenetic pathway analysis of docetaxel elimination. *Clin Pharmacol Ther* **85**(2): 155-163.
- Ballester MR, Monte MJ, Briz O, Jimenez F, Gonzalez-San Martin F and Marin JJ (2006) Expression of transporters potentially involved in the targeting of cytostatic bile acid derivatives to colon cancer and polyps. *Biochem Pharmacol* **72**(6): 729-738.

- Banerjee N, Allen C and Bendayan R (2012) Differential role of organic anion-transporting polypeptides in estrone-3-sulphate uptake by breast epithelial cells and breast cancer cells. *J Pharmacol Exp Ther* **342**(2): 510-519.
- Banerjee N, Fonge H, Mikhail A, Reilly RM, Bendayan R and Allen C (2013) Estrone-3-sulphate, a potential novel ligand for targeting breast cancers. *PLoS One* **8**(5): e64069.
- Banerjee N, Miller N, Allen C and Bendayan R (2014) Expression of membrane transporters and metabolic enzymes involved in estrone-3-sulphate disposition in human breast tumour tissues. *Breast Cancer Res Treat* **145**(3): 647-661.
- Bauer M, Matsuda A, Wulkersdorfer B, Philippe C, Traxl A, Ozvegy-Laczka C, Stanek J, Nics L, Klebermass EM, Poschner S, Jager W, Patik I, Bakos E, Szakacs G, Wadsak W, Hacker M, Zeitlinger M and Langer O (2017) Influence of OATPs on hepatic disposition of erlotinib measured with positron emission tomography. *Clin Pharmacol Ther*.
- Bins S, van Doorn L, Phelps MA, Gibson AA, Hu S, Li L, Vasilyeva A, Du G, Hamberg P, Eskens F, de Bruijn P, Sparreboom A, Mathijssen R and Baker SD (2017) Influence of OATP1B1 function on the disposition of sorafenib-beta-D-glucuronide. *Clin Transl Sci* **10**(4): 271-279.
- Bleasby K, Castle JC, Roberts CJ, Cheng C, Bailey WJ, Sina JF, Kulkarni AV, Hafey MJ, Evers R, Johnson JM, Ulrich RG and Slatter JG (2006) Expression profiles of 50 xenobiotic transporter genes in humans and pre-clinical species: a resource for investigations into drug disposition. *Xenobiotica* **36**(10-11): 963-988.
- Brenner S, Klameth L, Riha J, Scholm M, Hamilton G, Bajna E, Ausch C, Reiner A, Jager W, Thalhammer T and Buxhofer-Ausch V (2015) Specific expression of OATPs in primary small cell lung cancer (SCLC) cells as novel biomarkers for diagnosis and therapy. *Cancer Lett* **356**(2 Pt B): 517-524.
- Briz O, Serrano MA, Riebollo N, Hagenbuch B, Meier PJ, Koepsell H and Marin J (2002) Carriers involved in targeting the cytostatic bile acid-cisplatin derivatives cis-diammine-chloro-cholyglycinate-platinum(II) and cis-diammine-bisursodeoxycholate-platinum(II) toward liver cells. *Mol Pharmacol* **61**(4): 853-860.
- Bruno R, Hille D, Riva A, Vivier N, ten Bokkel Huinnink WW, van Oosterom AT, Kaye SB, Verweij J, Fossella FV, Valero V, Rigas JR, Seidman AD, Chevallier B, Fumoleau P, Burris HA, Ravdin PM and L.B.

- S (1998) Population pharmacokinetics/pharmacodynamics of docetaxel in phase II studies in patients with cancer. *J Clin Oncol* **16**(1): 187-196.
- Bruno R, Olivares R, Berille J, Chaikin P, Vivier N, Hammershaimb L, Rhodes GR and Rigas JR (2003) Alpha-1-acid glycoprotein as an independent predictor for treatment effects and a prognostic factor of survival in patients with non-small cell lung cancer treated with docetaxel. *Clin Cancer Res* **9**(3): 1077-1082.
- Burger H, Loos WJ, Eechoute K, Verweij J, Mathijssen RH and Wiemer EA (2011) Drug transporters of platinum-based anticancer agents and their clinical significance. *Drug Resist Updat* **14**(1): 22-34.
- Burt HJ, Riedmaier AE, Harwood MD, Crewe HK, Gill KL and Neuhoff S (2016) Abundance of hepatic transporters in Caucasians: a meta-analysis. *Drug Metab Dispos* **44**(10): 1550-1561.
- Buxhofer-Ausch V, Secky L, Wlcek K, Svoboda M, Kounnis V, Briasoulis E, Tzakos AG, Jaeger W and Thalhammer T (2013) Tumor-specific expression of organic anion-transporting polypeptides: transporters as novel targets for cancer therapy. *J Drug Deliv* **2013**: 863539.
- Chester JD, Joel SP, Cheeseman SL, Hall GD, Braun MS, Perry J, Davis T, Button CJ and Seymour MT (2003) Phase I and pharmacokinetic study of intravenous irinotecan plus oral ciclosporin in patients with fluorouracil-refractory metastatic colon cancer. *J Clin Oncol* **21**(6): 1125-1132.
- Chew SC, Sandanaraj E, Singh O, Chen X, Tan EH, Lim WT, Lee EJ and Chowbay B (2012) Influence of SLCO1B3 haplotype-tag SNPs on docetaxel disposition in Chinese nasopharyngeal cancer patients. *Br J Clin Pharmacol* **73**(4): 606-618.
- Chew SC, Singh O, Chen X, Ramasamy RD, Kulkarni T, Lee EJ, Tan EH, Lim WT and Chowbay B (2011) The effects of CYP3A4, CYP3A5, ABCB1, ABCC2, ABCG2 and SLCO1B3 single nucleotide polymorphisms on the pharmacokinetics and pharmacodynamics of docetaxel in nasopharyngeal carcinoma patients. *Cancer Chemother Pharmacol* **67**(6): 1471-1478.
- Cho E, Montgomery RB and Mostaghel EA (2014) SLCO and ABC transporters: a role for steroid transport in prostate cancer progression. *Endocrinology* **155**(11): 4124-4132.
- Choi JR, Kim JO, Kang DR, Shin JY, Zhang XH, Oh JE, Park JY, Kim KA and Kang JH (2015) Genetic Variations of Drug Transporters Can Influence on Drug Response in Patients Treated with Docetaxel Chemotherapy. *Cancer Res Treat* **47**(3): 509-517.

- Clarke JD and Cherrington NJ (2012) Genetics or environment in drug transport: the case of organic anion transporting polypeptides and adverse drug reactions. *Expert Opin Drug Metab Toxicol* **8**(3): 349-360.
- Cortes JE and Pazdur R (1995) Docetaxel. *J Clin Oncol* **13**(10): 2643-2655.
- Criado JJ, Dominguez MF, Medarde M, Fernandez ER, Macias RIR and Marin JJG (2000) Structural characterization, kinetic studies, and in vitro biological activity of new cis-diamminebis-cholyglycinate(O,O') Pt(II) and cis-diamminebis-ursodeoxycholate(O,O') Pt(II) complexes. *Bioconjug Chem* **11**: 167-174.
- Criado JJ, Herrera MC, Palomero MF, Medarde M, Rodriguez E and Marin JJG (1997) Synthesis and characterization of a new bile acid and platinum(II) complex with cytostatic activity. *J Lipid Res* **38**: 1022-1032.
- Crona DJ, Ramirez J, Qiao W, de Graan AJ, Ratain MJ, van Schaik RH, Mathijssen RH, Rosner GL and Innocenti F (2016) Clinical validity of new genetic biomarkers of irinotecan neutropenia: an independent replication study. *Pharmacogenomics J* **16**(1): 54-59.
- Cui Y, König J and Keppler D (2001) Vectorial transport by double-transfected cells expressing the human uptake transporter SLC21A8 and the apical export pump ABCB2. *Mol Pharmacol* **60**(5): 934-943.
- Cui Y, König J, Nies AT, Pfannschmidt M, Hergt M, Franke WW, Alt W, Moll R and Keppler D (2003) Detection of the human organic anion transporters SLC21A6 (OATP2) and SLC21A8 (OATP8) in liver and hepatocellular carcinoma. *Lab Invest* **83**(4): 527-538.
- Danesi R, Fogli S, Gennari A, Conte P and Del Tacca M (2002) Pharmacokinetic-pharmacodynamic relationships of the anthracycline anticancer drugs. *Clin Pharmacokinet* **41**(6): 431-444.
- Dasari S and Tchounwou PB (2014) Cisplatin in cancer therapy: molecular mechanisms of action. *Eur J Pharmacol* **740**: 364-378.
- De Bruyn T, Ye ZW, Peeters A, Sahi J, Baes M, Augustijns PF and Annaert PP (2011) Determination of OATP-, NTCP- and OCT-mediated substrate uptake activities in individual and pooled batches of cryopreserved human hepatocytes. *Eur J Pharm Sci* **43**(4): 297-307.
- de Graan AJ, Lancaster CS, Obaidat A, Hagenbuch B, Elens L, Friberg LE, de Bruijn P, Hu S, Gibson AA, Bruun GH, Corydon TJ, Mikkelsen TS, Walker AL, Du G, Loos WJ, van Schaik RH, Baker SD,

- Mathijssen RH and Sparreboom A (2012) Influence of polymorphic OATP1B-type carriers on the disposition of docetaxel. *Clin Cancer Res* **18**(16): 4433-4440.
- de Man FM, Goey AKL, van Schaik RHN, Mathijssen RHJ and Bins S (2018) Individualization of irinotecan treatment: A review of pharmacokinetics, pharmacodynamics, and pharmacogenetics. *Clin Pharmacokinet* **57**(10): 1229-1254.
- de Morree ES, Bottcher R, van Soest RJ, Aghai A, de Ridder CM, Gibson AA, Mathijssen RH, Burger H, Wiemer EA, Sparreboom A, de Wit R and van Weerden WM (2016) Loss of SLCO1B3 drives taxane resistance in prostate cancer. *Br J Cancer* **115**(6): 674-681.
- Drenberg CD, Paugh SW, Pounds SB, Shi L, Orwick SJ, Li L, Hu S, Gibson AA, Ribeiro RC, Rubnitz JE, Evans WE, Sparreboom A and Baker SD (2016) Inherited variation in OATP1B1 is associated with treatment outcome in acute myeloid leukemia. *Clin Pharmacol Ther* **99**(6): 651-660.
- Dresser GK, Bailey DG, Leake BF, Schwarz UI, Dawson PA, Freeman DJ and Kim RB (2002) Fruit juices inhibit organic anion transporting polypeptide-mediated drug uptake to decrease the oral availability of fexofenadine. *Clin Pharmacol Ther* **71**(1): 11-20.
- Drozdik M, Groer C, Penski J, Lapczuk J, Ostrowski M, Lai Y, Prasad B, Unadkat JD, Siegmund W and Oswald S (2014) Protein abundance of clinically relevant multidrug transporters along the entire length of the human intestine. *Mol Pharm* **11**(10): 3547-3555.
- Dudenkova TM, Ingle JN, Buzdar AU, Robson ME, Kubo M, Ibrahim-Zada I, Batzler A, Jenkins GD, Pietrzak TL, Carlson EE, Barman P, Goetz MP, Northfelt DW, Moreno-Aspita A, Williard CV, Kalari KR, Nakamura Y, Wang L and Weinshilboum RM (2017) SLCO1B1 polymorphisms and plasma estrone conjugates in postmenopausal women with ER+ breast cancer: genome-wide association studies of the estrone pathway. *Breast Cancer Res Treat* **164**(1): 189-199.
- Durmus S, Lozano-Mena G, van Esch A, Wagenaar E, van Tellingen O and Schinkel AH (2015) Preclinical mouse models to study human OATP1B1- and OATP1B3-mediated drug-drug interactions in vivo. *Mol Pharm* **12**(12): 4259-4269.
- Durmus S, Naik J, Buil L, Wagenaar E, van Tellingen O and Schinkel AH (2014) In vivo disposition of doxorubicin is affected by mouse Oatp1a/1b and human OATP1A/1B transporters. *Int J Cancer* **135**(7): 1700-1710.

- Durmus S, van Hoppe S and Schinkel AH (2016) The impact of organic anion-transporting polypeptides (OATPs) on disposition and toxicity of antitumor drugs: insights from knockout and humanized mice. *Drug Resist Updat* **27**: 72-88.
- Eechoute K, Franke RM, Loos WJ, Scherkenbach LA, Boere I, Verweij J, Gurney H, Kim RB, Tirona RG, Mathijssen RH and Sparreboom A (2011) Environmental and genetic factors affecting transport of imatinib by OATP1A2. *Clin Pharmacol Ther* **89**(6): 816-820.
- Evangelis L, Ioannis S, Valentinos K, Antigony M, Elli I, Eleftheria H, Vasiliki G and Evangelos B (2017) SLCO1B3 screening in colorectal cancer patients using High-Resolution Melting Analysis method and immunohistochemistry. *Tumour Biol* **39**(3): 1010428317691176.
- Evaul K, Li R, Papari-Zareei M, Auchus RJ and Sharifi N (2010) 3beta-hydroxysteroid dehydrogenase is a possible pharmacological target in the treatment of castration-resistant prostate cancer. *Endocrinology* **151**(8): 3514-3520.
- Fujimoto N, Kubo T, Inatomi H, Bui HT, Shiota M, Sho T and Matsumoto T (2013) Polymorphisms of the androgen transporting gene SLCO2B1 may influence the castration resistance of prostate cancer and the racial differences in response to androgen deprivation. *Prostate Cancer Prostatic Dis* **16**(4): 336-340.
- Fujita D, Saito Y, Nakanishi T and Tamai I (2016) Organic anion transporting polypeptide (OATP)2B1 contributes to gastrointestinal toxicity of anticancer drug SN-38, active metabolite of irinotecan hydrochloride. *Drug Metab Dispos* **44**(1): 1-7.
- Fujita K, Sugiura T, Okumura H, Umeda S, Nakamichi N, Watanabe Y, Suzuki H, Sunakawa Y, Shimada K, Kawara K, Sasaki Y and Kato Y (2014) Direct inhibition and down-regulation by uremic plasma components of hepatic uptake transporter for SN-38, an active metabolite of irinotecan, in humans. *Pharm Res* **31**(1): 204-215.
- Gao B, Hagenbuch B, Kullak-Ublick GA, Benke D, Aguzzi A and Meier PJ (2000) Organic anion-transporting polypeptides mediate transport of opioid peptides across blood-brain barrier. *J Pharmacol Exp Ther* **294**(1): 73-79.

- Gao B, Huber RD, Wenzel A, Vavricka SR, Ismail MG, Reme C and Meier PJ (2005) Localization of organic anion transporting polypeptides in the rat and human ciliary body epithelium. *Exp Eye Res* **80**(1): 61-72.
- Glaeser H, Bailey DG, Dresser GK, Gregor JC, Schwarz UI, McGrath JS, Jolicoeur E, Lee W, Leake BF, Tirona RG and Kim RB (2007) Intestinal drug transporter expression and the impact of grapefruit juice in humans. *Clin Pharmacol Ther* **81**(3): 362-370.
- Gong IY and Kim RB (2013) Impact of genetic variation in OATP transporters to drug disposition and response. *Drug Metab Pharmacokinet* **28**(1): 4-18.
- Gong L, Giacomini MM, Giacomini C, Maitland ML, Altman RB and Klein TE (2017) PharmGKB summary: sorafenib pathways. *Pharmacogenet Genomics* **27**(6): 240-246.
- Groer C, Bruck S, Lai Y, Paulick A, Busemann A, Heidecke CD, Siegmund W and Oswald S (2013) LC-MS/MS-based quantification of clinically relevant intestinal uptake and efflux transporter proteins. *J Pharm Biomed Anal* **85**: 253-261.
- Grube M, Kock K, Karner S, Reuther S, Ritter CA, Jedlitschky G and Kroemer HK (2006a) Modification of OATP2B1-mediated transport by steroid hormones. *Mol Pharmacol* **70**(5): 1735-1741.
- Grube M, Kock K, Oswald S, Draber K, Meissner K, Eckel L, Bohm M, Felix SB, Vogelgesang S, Jedlitschky G, Siegmund W, Warzok R and Kroemer HK (2006b) Organic anion transporting polypeptide 2B1 is a high-affinity transporter for atorvastatin and is expressed in the human heart. *Clin Pharmacol Ther* **80**(6): 607-620.
- Hagenbuch B and Meier PJ (2004) Organic anion transporting polypeptides of the OATP/SLC21 family: phylogenetic classification as OATP/SLCO superfamily, new nomenclature and molecular/functional properties. *Pflugers Arch* **447**(5): 653-665.
- Hagenbuch B and Stieger B (2013) The SLCO (former SLC21) superfamily of transporters. *Mol Aspects Med* **34**(2-3): 396-412.
- Hamada A, Sissung T, Price DK, Danesi R, Chau CH, Sharifi N, Venzon D, Maeda K, Nagao K, Sparreboom A, Mitsuya H, Dahut WL and Figg WD (2008) Effect of SLCO1B3 haplotype on testosterone transport and clinical outcome in caucasian patients with androgen-independent prostatic cancer. *Clin Cancer Res* **14**(11): 3312-3318.

- Han JY, Lim HS, Shin ES, Yoo YK, Park YH, Lee JE, Kim HT and Lee JS (2008) Influence of the organic anion-transporting polypeptide 1B1 (OATP1B1) polymorphisms on irinotecan-pharmacokinetics and clinical outcome of patients with advanced non-small cell lung cancer. *Lung Cancer* **59**(1): 69-75.
- Han S, Kim K, Thakkar N, Kim D and Lee W (2013) Role of hypoxia inducible factor-1alpha in the regulation of the cancer-specific variant of organic anion transporting polypeptide 1B3 (OATP1B3), in colon and pancreatic cancer. *Biochem Pharmacol* **86**(6): 816-823.
- Hashimoto Y, Tatsumi S, Takeda R, Naka A, Ogane N, Kameda Y, Kawachi K, Shimizu S, Sakai M and Kamoshida S (2014) Expression of organic anion-transporting polypeptide 1A2 and organic cation transporter 6 as a predictor of pathologic response to neoadjuvant chemotherapy in triple negative breast cancer. *Breast Cancer Res Treat* **145**(1): 101-111.
- Hays A, Apte U and Hagenbuch B (2013) Organic anion transporting polypeptides expressed in pancreatic cancer may serve as potential diagnostic markers and therapeutic targets for early stage adenocarcinomas. *Pharm Res* **30**(9): 2260-2269.
- Hilgendorf C, Ahlin G, Seithel A, Artursson P, Ungell AL and Karlsson J (2007) Expression of thirty-six drug transporter genes in human intestine, liver, kidney, and organotypic cell lines. *Drug Metab Dispos* **35**(8): 1333-1340.
- Ho RH, Choi L, Lee W, Mayo G, Schwarz UI, Tirona RG, Bailey DG, Stein CM and Kim RB (2007) Effect of drug transporter genotypes on pravastatin disposition in European- and African-American participants. *Pharmacogenet Genomics* **17**(8): 647-656.
- Ho RH and Kim RB (2010) Uptake Transporters, in *Comprehensive Toxicology* (McQueen CA ed) pp 519-556, Elsevier, Oxford.
- Ho RH, Leake BF, Kim RB and Wang Y (2006) OATP2B1 allelic variants differentially transport rosuvastatin in vitro. *Drug Metabolism Reviews* **38**: 240-241.
- Hong Y and Chen S (2011) Aromatase, estrone sulfatase, and 17beta-hydroxysteroid dehydrogenase: structure-function studies and inhibitor development. *Mol Cell Endocrinol* **340**(2): 120-126.

- Hu S, Chen Z, Franke R, Orwick S, Zhao M, Rudek MA, Sparreboom A and Baker SD (2009) Interaction of the multikinase inhibitors sorafenib and sunitinib with solute carriers and ATP-binding cassette transporters. *Clin Cancer Res* **15**(19): 6062-6069.
- Hu S, Franke RM, Filipinski KK, Hu C, Orwick SJ, de Bruijn EA, Burger H, Baker SD and Sparreboom A (2008) Interaction of imatinib with human organic ion carriers. *Clin Cancer Res* **14**(10): 3141-3148.
- Hu S, Mathijssen RH, de Bruijn P, Baker SD and Sparreboom A (2014) Inhibition of OATP1B1 by tyrosine kinase inhibitors: in vitro-in vivo correlations. *Br J Cancer* **110**(4): 894-898.
- Ieiri I, Higuchi S and Sugiyama Y (2009) Genetic polymorphisms of uptake (OATP1B1, 1B3) and efflux (MRP2, BCRP) transporters: implications for inter-individual differences in the pharmacokinetics and pharmacodynamics of statins and other clinically relevant drugs. *Expert Opin Drug Metab Toxicol* **5**(7): 703-729.
- Imai S, Kikuchi R, Tsuruya Y, Naoi S, Nishida S, Kusuhara H and Sugiyama Y (2013) Epigenetic regulation of organic anion transporting polypeptide 1B3 in cancer cell lines. *Pharm Res* **30**(11): 2880-2890.
- Innocenti F, Kroetz DL, Schuetz E, Dolan ME, Ramirez J, Relling M, Chen P, Das S, Rosner GL and Ratain MJ (2009) Comprehensive pharmacogenetic analysis of irinotecan neutropenia and pharmacokinetics. *J Clin Oncol* **27**(16): 2604-2614.
- International Transporter C, Giacomini KM, Huang SM, Tweedie DJ, Benet LZ, Brouwer KL, Chu X, Dahlin A, Evers R, Fischer V, Hillgren KM, Hoffmaster KA, Ishikawa T, Keppler D, Kim RB, Lee CA, Niemi M, Polli JW, Sugiyama Y, Swaan PW, Ware JA, Wright SH, Yee SW, Zamek-Gliszczynski MJ and Zhang L (2010) Membrane transporters in drug development. *Nat Rev Drug Discov* **9**(3): 215-236.
- Iusuf D, Hendriks JJ, van Esch A, van de Steeg E, Wagenaar E, Rosing H, Beijnen JH and Schinkel AH (2015) Human OATP1B1, OATP1B3 and OATP1A2 can mediate the in vivo uptake and clearance of docetaxel. *Int J Cancer* **136**(1): 225-233.
- Iusuf D, Ludwig M, Elbatsh A, van Esch A, van de Steeg E, Wagenaar E, van der Valk M, Lin F, van Tellingen O and Schinkel AH (2014) OATP1A/1B transporters affect irinotecan and SN-38 pharmacokinetics and carboxylesterase expression in knockout and humanized transgenic mice. *Mol Cancer Ther* **13**(2): 492-503.

- Iusuf D, van de Steeg E and Schinkel AH (2012) Functions of OATP1A and 1B transporters in vivo: insights from mouse models. *Trends Pharmacol Sci* **33**(2): 100-108.
- Iwai M, Suzuki H, Ieiri I, Otsubo K and Sugiyama Y (2004) Functional analysis of single nucleotide polymorphisms of hepatic organic anion transporter OATP1B1 (OATP-C). *Pharmacogenetics* **14**(11): 749-757.
- Jacquemin E, Hagenbuch B, Stieger B, Wolkoff AW and Meier PJ (1994) Expression cloning of a rat liver Na(+)-independent organic anion transporter. *Proc Natl Acad Sci U S A* **91**(1): 133-137.
- Jiang J, Tang Q, Feng J, Dai R, Wang Y, Yang Y, Tang X, Deng C, Zeng H, Zhao Y and Zhang F (2016) Association between SLCO1B1 -521T>C and -388A>G polymorphisms and risk of statin-induced adverse drug reactions: A meta-analysis. *Springerplus* **5**(1): 1368.
- Kameyama Y, Yamashita K, Kobayashi K, Hosokawa M and Chiba K (2005) Functional characterization of SLCO1B1 (OATP-C) variants, SLCO1B1*5, SLCO1B1*15 and SLCO1B1*15 + C1007G, by using transient expression systems of HeLa and HEK293 cells. *Pharmacogenet Genomics* **15**: 513-522.
- Katz DA, Carr R, Grimm DR, Xiong H, Holley-Shanks R, Mueller T, Leake B, Wang Q, Han L, Wang PG, Edeki T, Sahelijo L, Doan T, Allen A, Spear BB and Kim RB (2006) Organic anion transporting polypeptide 1B1 activity classified by *SLCO1B1* genotype influences atrasentan pharmacokinetics. *Clin Pharmacol Ther* **79**(3): 186-196.
- Kehrer DFS, Sparreboom A, Verweij J, de Bruijn P, Nierop CA, van de Schraaf J, Ruijgrok EJ and de Jonge MJA (2001) Modulation of irinotecan-induced diarrhea by cotreatment with neomycin in cancer patients. *Clin Cancer Res* **7**(5): 1136-1141.
- Kindla J, Fromm MF and König J (2009) In vitro evidence for the role of OATP and OCT uptake transporters in drug-drug interactions. *Expert Opin Drug Metab Toxicol* **5**(5): 489-500.
- Kindla J, Rau TT, Jung R, Fasching PA, Strick R, Stoehr R, Hartmann A, Fromm MF and König J (2014) Expression and localization of the uptake transporters OATP2B1, OATP3A1 and OATP5A1 in non-malignant and malignant breast tissue. *Cancer Biol Ther* **11**(6): 584-591.
- Kinoshita M and Miyata M (2002) Underexpression of mRNA in human hepatocellular carcinoma focusing on eight loci. *Hepatology* **36**(2): 433-438.

- Kiyotani K, Mushiroda T, Kubo M, Zembutsu H, Sugiyama Y and Nakamura Y (2008) Association of genetic polymorphisms in SLCO1B3 and ABCC2 with docetaxel-induced leukopenia. *Cancer Sci* **99**(5): 967-972.
- Kleberg K, Jensen GM, Christensen DP, Lundh M, Grunnet LG, Knuhtsen S, Poulsen SS, Hansen MB and Bindselev N (2012) Transporter function and cyclic AMP turnover in normal colonic mucosa from patients with and without colorectal neoplasia. *BMC Gastroenterol* **12**: 78.
- Kobayashi D, Nozawa T, Imai K, Nezu J, Tsuji A and Tamai I (2003) Involvement of human organic anion transporting polypeptide OATP-B (SLC21A9) in pH-dependent transport across intestinal apical membrane. *J Pharmacol Exp Ther* **306**(2): 703-708.
- Koenen A, Kroemer HK, Grube M and Meyer zu Schwabedissen HE (2011) Current understanding of hepatic and intestinal OATP-mediated drug-drug interactions. *Expert Rev Clin Pharmacol* **4**(6): 729-742.
- Konig J (2011) Uptake transporters of the human OATP family: molecular characteristics, substrates, their role in drug-drug interactions, and functional consequences of polymorphisms, in *Drug Transporters* (Fromm MF and Kim RB eds) pp 1-28, Springer-Verlag Berlin Heidelberg.
- Konig J, Cui Y, Nies AT and Keppler D (2000) Localization and genomic organization of a new hepatocellular organic anion transporting polypeptide. *J Biol Chem* **275**(30): 23161-23168.
- Konig J, Muller F and Fromm MF (2013) Transporters and drug-drug interactions: important determinants of drug disposition and effects. *Pharmacol Rev* **65**(3): 944-966.
- Kounnis V, Chondrogiannis G, Mantzaris MD, Tzakos AG, Fokas D, Papanikolaou NA, Galani V, Sainis I and Briasoulis E (2015) Microcystin LR shows cytotoxic activity against pancreatic cancer cells expressing the membrane OATP1B1 and OATP1B3 transporters. *Anticancer Res* **35**(11): 5857-5865.
- Kounnis V, Ioachim E, Svoboda M, Tzakos A, Sainis I, Thalhammer T, Steiner G and Briasoulis E (2011) Expression of organic anion-transporting polypeptides 1B3, 1B1, and 1A2 in human pancreatic cancer reveals a new class of potential therapeutic targets. *Onco Targets Ther* **4**: 27-32.

- Kramer W, Wess G, Schubert G, Bickel M, Girbig F, Gutjahr U, Kowalewski S, Baringhaus KH, Enhsen A, Glombik H, Mullner S, Neckermann G, Schulz S and Petzinger E (1992) Liver-specific drug targeting by coupling to bile acids. *J Biol Chem* **267**(26): 18598-18604.
- Kullak-Ublick G, Glasa J, Boker C, Oswald M, Grutzner U, Hagenbuch B, Stieger B, Meier PJ, Beuers U, Kramer W, Wess G and Paumgartner G (1997) Chlorambucil-taurocholate is transported by bile acid carriers expressed in human hepatocellular carcinomas. *Gastroenterology* **113**(4): 1295-1305.
- Kullak-Ublick GA, Beuers U and Paumgartner G (1996) Molecular and functional characterization of bile acid transport in human hepatoblastoma HepG2 cells. *Hepatology* **23**(5): 1053-1060.
- Kullak-Ublick GA, Fisch T, Oswald M, Hagenbuch B, Meier PJ, Beuers U and Paumgartner G (1998) Dehydroepiandrosterone sulfate (DHEAS): identification of a carrier protein in human liver and brain. *FEBS Lett* **424**(3): 173-176.
- Kullak-Ublick GA, Hagenbuch B, Stieger B, Schteingart CD, Hofmann AF, Wolkoff AW and Meier PJ (1995) Molecular and functional characterization of an organic anion transporting polypeptide cloned from human liver. *Gastroenterology* **109**(4): 1274-1282.
- Kullak-Ublick GA, Ismail MG, Stieger B, Landmann L, Huber R, Pizzagalli F, Fattinger K, Meier PJ and Hagenbuch B (2001) Organic anion-transporting polypeptide B (OATP-B) and its functional comparison with three other OATPs of human liver. *Gastroenterology* **120**(2): 525-533.
- Kusuhara H and Sugiyama Y (2005) Active efflux across the blood-brain barrier: role of the solute carrier family. *NeuroRx* **2**(1): 73-85.
- Lancaster CS, Sprowl JA, Walker AL, Hu S, Gibson AA and Sparreboom A (2013) Modulation of OATP1B-type transporter function alters cellular uptake and disposition of platinum chemotherapeutics. *Mol Cancer Ther* **12**(8): 1537-1544.
- Lee HH, Leake BF, Kim RB and Ho RH (2017) Contribution of organic anion-transporting polypeptides 1A/1B to doxorubicin uptake and clearance. *Mol Pharmacol* **91**(1): 14-24.
- Lee HH, Leake BF, Teft W, Tirona RG, Kim RB and Ho RH (2015) Contribution of hepatic organic anion-transporting polypeptides to docetaxel uptake and clearance. *Mol Cancer Ther* **14**(4): 994-1003.

- Lee W, Belkhiri A, Lockhart AC, Merchant N, Glaeser H, Harris EI, Washington MK, Brunt EM, Zaika A, Kim RB and El-Rifai W (2008) Overexpression of OATP1B3 confers apoptotic resistance in colon cancer. *Cancer Res* **68**(24): 10315-10323.
- Lee W, Glaeser H, Smith LH, Roberts RL, Moeckel GW, Gervasini G, Leake BF and Kim RB (2005) Polymorphisms in human organic anion-transporting polypeptide 1A2 (OATP1A2): implications for altered drug disposition and central nervous system drug entry. *J Biol Chem* **280**(10): 9610-9617.
- Leskela S, Jara C, Leandro-Garcia LJ, Martinez A, Garcia-Donas J, Hernando S, Hurtado A, Vicario JC, Montero-Conde C, Landa I, Lopez-Jimenez E, Cascon A, Milne RL, Robledo M and Rodriguez-Antona C (2011) Polymorphisms in cytochromes P450 2C8 and 3A5 are associated with paclitaxel neurotoxicity. *Pharmacogenomics J* **11**(2): 121-129.
- Letschert K, Keppler D and Konig J (2004) Mutations in the *SLCO1B3* gene affecting the substrate specificity of the hepatocellular uptake transporter OATP1B3 (OATP8). *Pharmacogenetics* **14**(7): 441-452.
- Li J, Wang XR, Zhai XW, Wang HS, Qian XW, Miao H and Zhu XH (2015) Association of *SLCO1B1* gene polymorphisms with toxicity response of high dose methotrexate chemotherapy in childhood acute lymphoblastic leukemia. *Int J Clin Exp Med* **8**(4): 6109-6113.
- Libra A, Ferneti C, Lorusso V, Visigalli M, Anelli PL, Staud F, Tiribelli C and Pascolo L (2006) Molecular determinants in the transport of a bile acid-derived diagnostic agent in tumoral and nontumoral cell lines of human liver. *J Pharmacol Exp Ther* **319**(2): 809-817.
- Lockhart AC, Harris E, Lafleur BJ, Merchant NB, Washington MK, Resnick MB, Yeatman TJ and Lee W (2008) Organic anion transporting polypeptide 1B3 (OATP1B3) is overexpressed in colorectal tumors and is a predictor of clinical outcome. *Clin Exp Gastroenterol* **1**: 1-7.
- Lokiec F (1995) Pharmacokinetics of irinotecan and its metabolites in human blood, bile, and urine. *Cancer Chemother Pharmacol* **36**(1): 79-82.
- Lopez-Lopez E, Martin-Guerrero I, Ballesteros J, Pinan MA, Garcia-Miguel P, Navajas A and Garcia-Orad A (2011) Polymorphisms of the *SLCO1B1* gene predict methotrexate-related toxicity in childhood acute lymphoblastic leukemia. *Pediatr Blood Cancer* **57**(4): 612-619.

- Maeda T, Irokawa M, Arakawa H, Kuraoka E, Nozawa T, Tateoka R, Itoh Y, Nakanishi T and Tamai I (2010) Uptake transporter organic anion transporting polypeptide 1B3 contributes to the growth of estrogen-dependent breast cancer. *J Steroid Biochem Mol Biol* **122**(4): 180-185.
- Marada VV, Florl S, Kuhne A, Burckhardt G and Hagos Y (2015) Interaction of human organic anion transporter polypeptides 1B1 and 1B3 with antineoplastic compounds. *Eur J Med Chem* **92**: 723-731.
- Marsh S, McLeod H, Dolan E, Shukla SJ, Rabik CA, Gong L, Hernandez-Boussard T, Lou XJ, Klein TE and Altman RB (2009) Platinum pathway. *Pharmacogenet Genomics* **19**(7): 563-564.
- Martinez D, Muhrez K, Woillard JB, Berthelot A, Gyan E, Choquet S, Andres CR, Marquet P and Barin-Le Guellec C (2018) Endogenous metabolites-mediated communication between OAT1/OAT3 and OATP1B1 may explain the association between SLCO1B1 SNPs and methotrexate toxicity. *Clin Pharmacol Ther* **104**(4): 687-698.
- Matsumoto J, Ariyoshi N, Sakakibara M, Nakanishi T, Okubo Y, Shiina N, Fujisaki K, Nagashima T, Nakatani Y, Tamai I, Yamada H, Takeda H and Ishii I (2015) Organic anion transporting polypeptide 2B1 expression correlates with uptake of estrone-3-sulfate and cell proliferation in estrogen receptor-positive breast cancer cells. *Drug Metab Pharmacokinet* **30**(2): 133-141.
- Meier Y, Eloranta JJ, Darimont J, Ismail MG, Hiller C, Fried M, Kullak-Ublick GA and Vavricka SR (2007) Regional distribution of solute carrier mRNA expression along the human intestinal tract. *Drug Metab Dispos* **35**(4): 590-594.
- Meyer zu Schwabedissen HE, Tirona RG, Yip CS, Ho RH and Kim RB (2008) Interplay between the nuclear receptor pregnane X receptor and the uptake transporter organic anion transporter polypeptide 1A2 selectively enhances estrogen effects in breast cancer. *Cancer Res* **68**(22): 9338-9347.
- Michalski C, Cui Y, Nies AT, Nuessler AK, Neuhaus P, Zanger UM, Klein K, Eichelbaum M, Keppler D and Konig J (2002) A naturally occurring mutation in the *SLC21A6* gene causing impaired membrane localization of the hepatocyte uptake transporter. *J Biol Chem* **277**(45): 43058-43063.
- Miki Y, Suzuki T, Kitada K, Yabuki N, Shibuya R, Moriya T, Ishida T, Ohuchi N, Blumberg B and Sasano H (2006) Expression of the steroid and xenobiotic receptor and its possible target gene, organic anion transporting polypeptide-A, in human breast carcinoma. *Cancer Res* **66**(1): 535-542.

- Mikkelsen TS, Thorn CF, Yang JJ, Ulrich CM, French D, Zaza G, Dunnenberger HM, Marsh S, McLeod HL, Giacomini K, Becker ML, Gaedigk R, Leeder JS, Kager L, Relling MV, Evans W, Klein TE and Altman RB (2011) PharmGKB summary: methotrexate pathway. *Pharmacogenet Genomics* **21**(10): 679-686.
- Miyagawa M, Maeda K, Aoyama A and Sugiyama Y (2009) The eighth and ninth transmembrane domains in organic anion transporting polypeptide 1B1 affect the transport kinetics of estrone-3-sulfate and estradiol-17beta-D-glucuronide. *J Pharmacol Exp Ther* **329**(2): 551-557.
- Monks NR, Liu S, Xu Y, Yu H, Bendelow AS and Moscow JA (2007) Potent cytotoxicity of the phosphatase inhibitor microcystin LR and microcystin analogues in OATP1B1- and OATP1B3-expressing HeLa cells. *Mol Cancer Ther* **6**(2): 587-598.
- Muto M, Onogawa T, Suzuki T, Ishida T, Rikiyama T, Katayose Y, Ohuchi N, Sasano H, Abe T and Unno M (2007) Human liver-specific organic anion transporter-2 is a potent prognostic factor for human breast carcinoma. *Cancer Sci* **98**(10): 1570-1576.
- Mwinyi J, Johne A, Bauer S, Roots I and Gerloff T (2004) Evidence for inverse effects of OATP-C (SLC21A6) 5 and 1b haplotypes on pravastatin kinetics. *Clin Pharmacol Ther* **75**(5): 415-421.
- Nagai M, Furihata T, Matsumoto S, Ishii S, Motohashi S, Yoshino I, Ugajin M, Miyajima A, Matsumoto S and Chiba K (2012) Identification of a new organic anion transporting polypeptide 1B3 mRNA isoform primarily expressed in human cancerous tissues and cells. *Biochem Biophys Res Commun* **418**(4): 818-823.
- Neul C, Schaeffeler E, Sparreboom A, Laufer S, Schwab M and Nies AT (2016) Impact of Membrane Drug Transporters on Resistance to Small-Molecule Tyrosine Kinase Inhibitors. *Trends Pharmacol Sci* **37**(11): 904-932.
- Niemi M, Backman JT, Kajosaari LI, Leathart JB, Neuvonen M, Daly AK, Eichelbaum M, Kivisto KT and Neuvonen PJ (2005a) Polymorphic organic anion transporting polypeptide 1B1 is a major determinant of repaglinide pharmacokinetics. *Clin Pharmacol Ther* **77**(6): 468-478.
- Niemi M, Kivisto KT, Hofmann U, Schwab M, Eichelbaum M and Fromm MF (2005b) Fexofenadine pharmacokinetics are associated with a polymorphism of the SLCO1B1 gene (encoding OATP1B1). *Br J Clin Pharmacol* **59**(5): 602-604.

- Niemi M, Schaeffeler E, Lang T, Fromm MF, Neuvonen M, Kyrklund C, Backman JT, Kerb R, Schwab M, Neuvonen PJ, Eichelbaum M and Kivist KT (2004) High plasma pravastatin concentrations are associated with single nucleotide polymorphisms and haplotypes of organic anion transporting polypeptide-C (OATP-C, SLCO1B1). *Pharmacogenetics* **14**(7): 429-440.
- Nies AT, Niemi M, Burk O, Winter S, Zanger UM, Stieger B, Schwab M and Schaeffeler E (2013) Genetics is a major determinant of expression of the human hepatic uptake transporter OATP1B1, but not of OATP1B3 and OATP2B1. *Genome Med* **5**(1).
- Nieuweboer AJ, Hu S, Gui C, Hagenbuch B, Ghobadi Moghaddam-Helmantel IM, Gibson AA, de Bruijn P, Mathijssen RH and Sparreboom A (2014) Influence of drug formulation on OATP1B-mediated transport of paclitaxel. *Cancer Res* **74**(11): 3137-3145.
- Nishizato Y (2003) Polymorphisms of OATP-C (SLC21A6) and OAT3 (SLC22A8) genes: consequences for pravastatin pharmacokinetics. *Clin Pharmacol Ther* **73**(6): 554-565.
- Nozawa T, Imai K, Nezu J, Tsuji A and Tamai I (2004a) Functional characterization of pH-sensitive organic anion transporting polypeptide OATP-B in human. *J Pharmacol Exp Ther* **308**(2): 438-445.
- Nozawa T, Minami H, Sugiura S, Tsuji A and Tamai I (2005a) Role of organic anion transporter OATP1B1 (OATP-C) in hepatic uptake of irinotecan and its active metabolite, 7-ethyl-10-hydroxycamptothecin: in vitro evidence and effect of single nucleotide polymorphisms. *Drug Metab Dispos* **33**(3): 434-439.
- Nozawa T, Nakajima M, Tamai I, Noda K, Nezu J, Sai Y, Tsuji A and Yokoi T (2002) Genetic polymorphisms of human organic anion transporters OATP-C (SLC21A6) and OATP-B (SLC21A9): allele frequencies in the Japanese population and functional analysis. *J Pharmacol Exp Ther* **302**(2): 804-813.
- Nozawa T, Suzuki M, Takahashi K, Yabuuchi H, Maeda T, Tsuji A and Tamai I (2004b) Involvement of estrone-3-sulfate transporters in proliferation of hormone-dependent breast cancer cells. *J Pharmacol Exp Ther* **311**(3): 1032-1037.
- Nozawa T, Suzuki M, Yabuuchi H, Irokawa M, Tsuji A and Tamai I (2005b) Suppression of cell proliferation by inhibition of estrone-3-sulfate transporter in estrogen-dependent breast cancer cells. *Pharm Res* **22**(10): 1634-1641.

- O'Brien Z and Moghaddam MF (2017) A systematic analysis of physicochemical and ADME properties of all small molecule kinase inhibitors approved by US FDA from January 2001 to October 2015. *Curr Med Chem* **24**(29): 3159-3184.
- Obaidat A, Roth M and Hagenbuch B (2012) The expression and function of organic anion transporting polypeptides in normal tissues and in cancer. *Annu Rev Pharmacol Toxicol* **52**: 135-151.
- Okabe M, Szakacs G, Reimers MA, Suzuki T, Hall MD, Abe T, Weinstein JN and Gottesman MM (2008) Profiling SLCO and SLC22 genes in the NCI-60 cancer cell lines to identify drug uptake transporters. *Mol Cancer Ther* **7**(9): 3081-3091.
- Oostendorp RL, van de Steeg E, van der Kruijssen CM, Beijnen JH, Kenworthy KE, Schinkel AH and Schellens JH (2009) Organic anion-transporting polypeptide 1B1 mediates transport of Gimatecan and BNP1350 and can be inhibited by several classic ATP-binding cassette (ABC) B1 and/or ABCG2 inhibitors. *Drug Metab Dispos* **37**(4): 917-923.
- Oshiro C, Marsh S, McLeod H, Carrillo MW, Klein T and Altman R (2009) Taxane pathway. *Pharmacogenet Genomics* **19**(12): 979-983.
- Park HS, Lim SM, Shin HJ, Cho A, Shin JG, Lee MG, Kim HR, Kim JH and Cho BC (2016) Pharmacogenetic analysis of advanced non-small-cell lung cancer patients treated with first-line paclitaxel and carboplatin chemotherapy. *Pharmacogenet Genomics* **26**(3): 116-125.
- Pasqualini JR, Chetrite G, Blacker C, Feinstein MC, Delalonde L, Talbi M and Maloche C (1996) Concentrations of estrone, estradiol, and estrone sulfate and evaluation of sulfatase and aromatase activities in pre- and postmenopausal breast cancer patients. *J Clin Endocrinol Metab* **81**(4): 1460-1464.
- Pizzagalli F, Varga Z, Huber RD, Folkers G, Meier PJ and St-Pierre MV (2003) Identification of steroid sulfate transport processes in the human mammary gland. *J Clin Endocrinol Metab* **88**(8): 3902-3912.
- Polli JW, Humphreys JE, Harmon KA, Castellino S, O'Mara MJ, Olson KL, John-Williams LS, Koch KM and Serabjit-Singh CJ (2008) The role of efflux and uptake transporters in [N-{3-chloro-4-[(3-fluorobenzyl)oxy]phenyl}-6-[5-[[2-(methylsulfonyl)ethyl]amino]methyl]-2-furyl]-4-quinazolinamine (GW572016, lapatinib) disposition and drug interactions. *Drug Metab Dispos* **36**(4): 695-701.

- Pressler H, Sissung TM, Venzon D, Price DK and Figg WD (2011) Expression of OATP family members in hormone-related cancers: potential markers of progression. *PLoS One* **6**(5): e20372.
- Ramsey LB, Bruun GH, Yang W, Trevino LR, Vattathil S, Scheet P, Cheng C, Rosner GL, Giacomini KM, Fan Y, Sparreboom A, Mikkelsen TS, Corydon TJ, Pui CH, Evans WE and Relling MV (2012) Rare versus common variants in pharmacogenetics: SLCO1B1 variation and methotrexate disposition. *Genome Res* **22**(1): 1-8.
- Ramsey LB, Panetta JC, Smith C, Yang W, Fan Y, Winick NJ, Martin PL, Cheng C, Devidas M, Pui CH, Evans WE, Hunger SP, Loh M and Relling MV (2013) Genome-wide study of methotrexate clearance replicates SLCO1B1. *Blood* **121**(6): 898-904.
- Rebello S, Zhao S, Hariry S, Dahlke M, Alexander N, Vapurcuyan A, Hanna I and Jarugula V (2012) Intestinal OATP1A2 inhibition as a potential mechanism for the effect of grapefruit juice on aliskiren pharmacokinetics in healthy subjects. *Eur J Clin Pharmacol* **68**(5): 697-708.
- Sai K, Saito Y, Maekawa K, Kim SR, Kaniwa N, Nishimaki-Mogami T, Sawada J, Shirao K, Hamaguchi T, Yamamoto N, Kunitoh H, Ohe Y, Yamada Y, Tamura T, Yoshida T, Matsumura Y, Ohtsu A, Saijo N and Minami H (2010) Additive effects of drug transporter genetic polymorphisms on irinotecan pharmacokinetics/pharmacodynamics in Japanese cancer patients. *Cancer Chemother Pharmacol* **66**(1): 95-105.
- Sai Y, Kaneko Y, Ito S, Mitsuoka K, Kato Y, Tamai I, Artursson P and Tsuji A (2006) Predominant contribution of organic anion transporting polypeptide OATP-B (OATP2B1) to apical uptake of estrone-3-sulfate by human intestinal Caco-2 cells. *Drug Metab Dispos* **34**(8): 1423-1431.
- Schwarz UI, Meyer zu Schwabedissen HE, Tirona RG, Suzuki A, Leake BF, Mokrab Y, Mizuguchi K, Ho RH and Kim RB (2011) Identification of novel functional organic anion-transporting polypeptide 1B3 polymorphisms and assessment of substrate specificity. *Pharmacogenet Genomics* **21**(3): 103-114.
- Sharifi N, Hamada A, Sissung T, Danesi R, Venzon D, Baum C, Gulley JL, Price DK, Dahut WL and Figg WD (2008) A polymorphism in a transporter of testosterone is a determinant of androgen independence in prostate cancer. *BJU Int* **102**(5): 617-621.

- Shirasaka Y, Shichiri M, Murata Y, Mori T, Nakanishi T and Tamai I (2013) Long-lasting inhibitory effect of apple and orange juices, but not grapefruit juice, on OATP2B1-mediated drug absorption. *Drug Metab Dispos* **41**(3): 615-621.
- Shitara Y (2011) Clinical importance of OATP1B1 and OATP1B3 in drug-drug interactions. *Drug Metab Pharmacokinet* **26**(3): 220-227.
- Smith NF, Acharya MR, Desai N, Figg WD and Sparreboom A (2005) Identification of OATP1B3 as a high-affinity hepatocellular transporter of paclitaxel. *Cancer Biol Ther* **4**(8): 815-818.
- St-Pierre MV, Hagenbuch B, Ugele B, Meier PJ and Stallmach T (2002) Characterization of an organic anion-transporting polypeptide (OATP-B) in human placenta. *J Clin Endocrinol Metab* **87**(4): 1856-1863.
- Stute P, Reichenbach A, Szuwart T, Kiesel L and Gotte M (2012) Impact of testosterone on the expression of organic anion transporting polypeptides (OATP-1A2, OATP-2B1, OATP-3A1) in malignant and non-malignant human breast cells in vitro. *Maturitas* **71**(4): 376-384.
- Sun Y, Furihata T, Ishii S, Nagai M, Harada M, Shimozato O, Kamijo T, Motohashi S, Yoshino I, Kamiichi A, Kobayashi K and Chiba K (2014) Unique expression features of cancer-type organic anion transporting polypeptide 1B3 mRNA expression in human colon and lung cancers. *Clin Transl Med* **3**: 37.
- Svoboda M, Wlcek K, Taferner B, Hering S, Stieger B, Tong D, Zeillinger R, Thalhammer T and Jager W (2011) Expression of organic anion-transporting polypeptides 1B1 and 1B3 in ovarian cancer cells: relevance for paclitaxel transport. *Biomed Pharmacother* **65**(6): 417-426.
- Takane H, Kawamoto K, Sasaki T, Moriki K, Moriki K, Kitano H, Higuchi S, Otsubo K and Ieiri I (2009) Life-threatening toxicities in a patient with UGT1A1*6/*28 and SLCO1B1*15/*15 genotypes after irinotecan-based chemotherapy. *Cancer Chemother Pharmacol* **63**(6): 1165-1169.
- Takano M, Otani Y, Tanda M, Kawami M, Nagai J and Yumoto R (2009) Paclitaxel-resistance conferred by altered expression of efflux and influx transporters for paclitaxel in the human hepatoma cell line, HepG2. *Drug Metab Pharmacokinet* **24**(5): 418-427.
- Tamai I (2012) Oral drug delivery utilizing intestinal OATP transporters. *Adv Drug Deliv Rev* **64**(6): 508-514.

- Tamai I, Nezu J, Uchino H, Sai Y, Oku A, Shimane M and Tsuji A (2000) Molecular identification and characterization of novel members of the human organic anion transporter (OATP) family. *Biochem Biophys Res Commun* **273**(1): 251-260.
- Tamai I, Nozawa T, Koshida M, Nezu J, Sai Y and Tsuji A (2001) Functional characterization of human organic anion transporting polypeptide B (OATP-B) in comparison with liver-specific OATP-C. *Pharm Res* **18**(9): 1262-1269.
- Teft WA, Welch S, Lenehan J, Parfitt J, Choi YH, Winqvist E and Kim RB (2015) OATP1B1 and tumour OATP1B3 modulate exposure, toxicity, and survival after irinotecan-based chemotherapy. *Br J Cancer* **112**(5): 857-865.
- Thakkar N, Kim K, Jang ER, Han S, Kim K, Kim D, Merchant N, Lockhart AC and Lee W (2013) A cancer-specific variant of the SLCO1B3 gene encodes a novel human organic anion transporting polypeptide 1B3 (OATP1B3) localized mainly in the cytoplasm of colon and pancreatic cancer cells. *Mol Pharm* **10**(1): 406-416.
- Thakkar N, Lockhart AC and Lee W (2015) Role of organic anion-transporting polypeptides (OATPs) in cancer therapy. *AAPS J* **17**(3): 535-545.
- Thorn CF, Oshiro C, Marsh S, Hernandez-Boussard T, McLeod H, Klein TE and Altman RB (2011) Doxorubicin pathways: pharmacodynamics and adverse effects. *Pharmacogenet Genomics* **21**(7): 440-446.
- Tirona RG, Leake BF, Merino G and Kim RB (2001) Polymorphisms in OATP-C: identification of multiple allelic variants associated with altered transport activity among European- and African-Americans. *J Biol Chem* **276**(38): 35669-35675.
- Trevino LR, Shimasaki N, Yang W, Panetta JC, Cheng C, Pei D, Chan D, Sparreboom A, Giacomini KM, Pui CH, Evans WE and Relling MV (2009) Germline genetic variation in an organic anion transporter polypeptide associated with methotrexate pharmacokinetics and clinical effects. *J Clin Oncol* **27**(35): 5972-5978.
- van de Steeg E, Stranecky V, Hartmannova H, Noskova L, Hrebicek M, Wagenaar E, van Esch A, de Waart DR, Oude Elferink RP, Kenworthy KE, Sticova E, al-Edreesi M, Knisely AS, Kmoch S, Jirsa M and

- Schinkel AH (2012) Complete OATP1B1 and OATP1B3 deficiency causes human Rotor syndrome by interrupting conjugated bilirubin reuptake into the liver. *J Clin Invest* **122**(2): 519-528.
- van de Steeg E, van der Kruijssen CM, Wagenaar E, Burggraaff JE, Mesman E, Kenworthy KE and Schinkel AH (2009) Methotrexate pharmacokinetics in transgenic mice with liver-specific expression of human organic anion-transporting polypeptide 1B1 (SLCO1B1). *Drug Metab Dispos* **37**(2): 277-281.
- van de Steeg E, van Esch A, Wagenaar E, van der Kruijssen CM, van Tellingen O, Kenworthy KE and Schinkel AH (2011) High impact of Oatp1a/1b transporters on in vivo disposition of the hydrophobic anticancer drug paclitaxel. *Clin Cancer Res* **17**(2): 294-301.
- van de Steeg E, Wagenaar E, van der Kruijssen CM, Burggraaff JE, de Waart DR, Elferink RP, Kenworthy KE and Schinkel AH (2010) Organic anion transporting polypeptide 1a/1b-knockout mice provide insights into hepatic handling of bilirubin, bile acids, and drugs. *J Clin Invest* **120**(8): 2942-2952.
- van Erp NP, Gelderblom H and Guchelaar HJ (2009) Clinical pharmacokinetics of tyrosine kinase inhibitors. *Cancer Treat Rev* **35**(8): 692-706.
- Vasilyeva A, Durmus S, Li L, Wagenaar E, Hu S, Gibson AA, Panetta JC, Mani S, Sparreboom A, Baker SD and Schinkel AH (2015) Hepatocellular shuttling and recirculation of sorafenib-glucuronide is dependent on Abcc2, Abcc3, and Oatp1a/1b. *Cancer Res* **75**(13): 2729-2736.
- Vasuri F, Golfieri R, Fiorentino M, Capizzi E, Renzulli M, Pinna AD, Grigioni WF and D'Errico-Grigioni A (2011) OATP 1B1/1B3 expression in hepatocellular carcinomas treated with orthotopic liver transplantation. *Virchows Arch* **459**(2): 141-146.
- Vavricka SR, Jung D, Fried M, Grützner U, Meier PJ and Kullak-Ublick GA (2004) The human organic anion transporting polypeptide 8 (SLCO1B3) gene is transcriptionally repressed by hepatocyte nuclear factor 3 β in hepatocellular carcinoma. *J Hepatol* **40**(2): 212-218.
- Wagner DJ, Hu T and Wang J (2016) Polyspecific organic cation transporters and their impact on drug intracellular levels and pharmacodynamics. *Pharmacol Res* **111**: 237-246.
- Walling J (2006) From methotrexate to pemetrexed and beyond: a review of the pharmacodynamic and clinical properties of antifolates. *Invest New Drugs* **24**(1): 37-77.

- Wlcek K, Svoboda M, Riha J, Zakaria S, Olszewski U, Dvorak Z, Sellner F, Ellinger I, Jäger W and Thalhammer T (2011) The analysis of organic anion transporting polypeptide (OATP) mRNA and protein patterns in primary and metastatic liver cancer. *Cancer Biol Ther* **11**(9): 801-811.
- Wright JL, Kwon EM, Ostrander EA, Montgomery RB, Lin DW, Vessella R, Stanford JL and Mostaghel EA (2011) Expression of SLCO transport genes in castration-resistant prostate cancer and impact of genetic variation in SLCO1B3 and SLCO2B1 on prostate cancer outcomes. *Cancer Epidemiol Biomarkers Prev* **20**(4): 619-627.
- Xiang X, Han Y, Neuvonen M, Pasanen MK, Kalliokoski A, Backman JT, Laitila J, Neuvonen PJ and Niemi M (2009) Effect of SLCO1B1 polymorphism on the plasma concentrations of bile acids and bile acid synthesis marker in humans. *Pharmacogenet Genomics* **19**(6): 447-457.
- Xiang X, Jada SR, Li HH, Fan L, Tham LS, Wong CI, Lee SC, Lim R, Zhou QY, Goh BC, Tan EH and Chowbay B (2006) Pharmacogenetics of SLCO1B1 gene and the impact of *1b and *15 haplotypes on irinotecan disposition in Asian cancer patients. *Pharmacogenet Genomics* **16**(9): 683-691.
- Yamada A, Maeda K, Kiyotani K, Mushiroda T, Nakamura Y and Sugiyama Y (2014) Kinetic interpretation of the importance of OATP1B3 and MRP2 in docetaxel-induced hematopoietic toxicity. *CPT Pharmacometrics Syst Pharmacol* **3**: e126.
- Yamaguchi H, Kobayashi M, Okada M, Takeuchi T, Unno M, Abe T, Goto J, Hishinuma T and Mano N (2008) Rapid screening of antineoplastic candidates for the human organic anion transporter OATP1B3 substrates using fluorescent probes. *Cancer Lett* **260**(1-2): 163-169.
- Yamakawa Y, Hamada A, Shuto T, Yuki M, Uchida T, Kai H, Kawaguchi T and Saito H (2011) Pharmacokinetic impact of SLCO1A2 polymorphisms on imatinib disposition in patients with chronic myeloid leukemia. *Clin Pharmacol Ther* **90**(1): 157-163.
- Yang M, Xie W, Mostaghel E, Nakabayashi M, Werner L, Sun T, Pomerantz M, Freedman M, Ross R, Regan M, Sharifi N, Figg WD, Balk S, Brown M, Taplin ME, Oh WK, Lee GS and Kantoff PW (2011) SLCO2B1 and SLCO1B3 may determine time to progression for patients receiving androgen deprivation therapy for prostate cancer. *J Clin Oncol* **29**(18): 2565-2573.

- Zhang W, He YJ, Gan Z, Fan L, Li Q, Wang A, Liu ZQ, Deng S, Huang YF, Xu LY and Zhou HH (2007) OATP1B1 polymorphism is a major determinant of serum bilirubin level but not associated with rifampicin-mediated bilirubin elevation. *Clin Exp Pharmacol Physiol* **34**(12): 1240-1244.
- Zhou F, Zhu L, Wang K and Murray M (2017) Recent advance in the pharmacogenomics of human Solute Carrier Transporters (SLCs) in drug disposition. *Adv Drug Deliv Rev* **116**: 21-36.
- Zhou Y, Yuan J, Li Z, Wang Z, Cheng D, Du Y, Li W, Kan Q and Zhang W (2015) Genetic polymorphisms and function of the organic anion-transporting polypeptide 1A2 and its clinical relevance in drug disposition. *Pharmacology* **95**(3-4): 201-208.
- Zimmerman EI, Hu S, Roberts JL, Gibson AA, Orwick SJ, Li L, Sparreboom A and Baker SD (2013) Contribution of OATP1B1 and OATP1B3 to the disposition of sorafenib and sorafenib-glucuronide. *Clin Cancer Res* **19**(6): 1458-1466.
- Zollner G, Wagner M, Fickert P, Silbert D, Fuchsbichler A, Zatloukal K, Denk H and Trauner M (2005) Hepatobiliary transporter expression in human hepatocellular carcinoma. *Liver Int* **25**(2): 367-379.

FOOTNOTES

This work was supported by the National Institutes of Health National Institute of General Medical Sciences [T32 award GM007569 (RRS), R01 award GM099924 (RHH)], National Institutes of Health National Cancer Institute [K12 award CA090625 (RRS)], Alex's Lemonade Stand Foundation [Young Investigator Award 17-00375 (RRS)], Rally Foundation [Fellowship Award (RRS)], and Hyundai Hope on Wheels [Scholar Award (RHH)].

Reprint requests are to be addressed to Richard Ho, MD, 2220 Pierce Avenue, 397 PRB, Vanderbilt University Medical Center, Nashville, TN 37232; richard.ho@vumc.org.

FIGURE LEGENDS

Figure 1. Organ-specific expression of drug transporters. The expression of transporters at the apical and basolateral membranes of various tissues plays a crucial role in the transport of both endogenous and exogenous substrates across membranes. In the liver and kidney, transporters mediate movement of substrates into hepatocytes or the proximal tubule cells, respectively, where the substrates may undergo biotransformation or be excreted unmodified into the bile or urine via other transporters. In the intestine, transporters are involved in the selective movement of substrates into and out of enterocytes which affects the oral bioavailability of drugs. In the capillary endothelial cells of the blood-brain barrier, transporters control which substrates can cross from the bloodstream into brain cells, thus limiting the ability of certain substrates to penetrate brain tissue. For the liver, the "bloodstream" compartment refers to the portal venous circulation. ASBT, apical sodium dependent bile acid transporter; BCRP, breast cancer resistance protein; ENT, equilibrative nucleoside transporter; MATE, multidrug and toxic compound extrusion; MCT, monocarboxylate transporter; MRP, multidrug resistance-associated protein; NTCP, sodium/taurocholate cotransporting polypeptide; OAT, organic anion transporter; OATP, organic anion transporting polypeptide; OCT, organic cation transporter; OST, organic solute and steroid transporter; PEPT, peptide transporter; P-gp, P-glycoprotein.

TABLES

Table 1. Overview of Selected *SLCO* Transporters

Gene Symbol	Protein	Normal Tissue Distribution	Cellular Localization^a	Example Substrates
<i>SLCO1A2</i> (formerly <i>SLC21A3</i>)	OATP1A2 (formerly OATP-A, OATP1)	Brain (blood-brain barrier), kidney, liver, intestine, eye, placenta, prostate, testis	BL (ciliary body epithelia); AP (kidney, hepatocytes, intestine)	Chemotherapy: atrasentan, chemotherapy-bile acid conjugates (i.e. Bamet-R2, Bamet-UD2, chlorambucil taurocholate), docetaxel, imatinib, methotrexate, microcystin-LR Other: Xenobiotics: BSP, deltorphin, fexofenadine, gadolinium dye for MRI, ouabain, rosuvastatin, levofloxacin, DPDPE, rocuronium, saquinavir; Endogenous: bile salts, T ₄ , T ₃ , PGE ₂ , E2G, E3S, DHEAS
<i>SLCO1B1</i> (formerly <i>SLC21A6</i>)	OATP1B1 (formerly LST-1, OATP-C, OATP2)	Liver, placenta	BL (hepatocytes)	Chemotherapy: daunorubicin, mitoxantrone, atrasentan, chemotherapy-bile acid conjugates (i.e. Bamet-R2, Bamet-UD2), cytarabine, etoposide, flavopiridol, gimatecan, hydroxyurea, methotrexate, microcystin-LR, carboplatin, cisplatin, oxaliplatin, SN-38 (irinotecan active metabolite), sorafenib-β-D-glucuronide, docetaxel, paclitaxel Other: Xenobiotics: olmesartan, valsartan, atrasentan, temocaprilat,

				<p>pitavastatin, pravastatin, cerivastatin, atorvastatin, rosuvastatin, rifampin, caspofungin, enalapril, BSP, phalloidin, troglitazone, bosentan, benzylpenicillin, nafcillin, some cephalosporins; <i>Endogenous</i>: bilirubin, bilirubin-glucuronides, GCA, leukotriene C₄, DHEAS, thromboxane B₂, T₄, T₃, PGE₂, TCA, E2G, E3S</p>
<p><i>SLCO1B3</i> (formerly <i>SLC21A8</i>)</p>	<p>OATP1B3 (formerly LST-2, OATP8)</p>	<p>Liver, placenta</p>	<p>BL (hepatocytes)</p>	<p>Chemotherapy: atrasentan, hydroxyurea, methotrexate, microcystin-LR, carboplatin, cisplatin, oxaliplatin, SN-38, docetaxel, paclitaxel, imatinib, sorafenib- β-D-glucuronide</p> <p>Other: Xenobiotics: fexofenadine, deltorphin, ouabain, digoxin, rosuvastatin, valsartan, pitavastatin, BSP, rifampin, repaglinide, telmisartan, olmesartan, enalapril, DPDPE; <i>Endogenous</i>: bilirubin conjugates, DHEAS, T₃, T₄, E2G, E3S, GCA, TCA, CCK-8</p>
<p><i>SLCO2B1</i> (formerly <i>SLC21A9</i>)</p>	<p>OATP2B1 (formerly OATP-B)</p>	<p>Widely expressed: liver, brain (blood-brain barrier), eye, small</p>	<p>BL (hepatocytes, ciliary body epithelium); AP (intestine)</p>	<p>Chemotherapy: erlotinib, SN-38</p> <p>Other: Xenobiotics: benzylpenicillin, bosentan, BSP, ezetimibe, fexofenadine, glibenclamide, glyburide, montelukast, statins,</p>

		intestine, heart, kidney, lung, ovary, pancreas, placenta, skeletal muscle, spleen, testis		sulfasalazine, telmisartan; <i>Endogenous:</i> E3S, DHEAS, TCA
--	--	---	--	---

^aBL, basolateral; AP, apical

Table adapted from other referenced works (Ho and Kim, 2010; Konig, 2011).

Table 2. Pharmacogenomics of OATPs: Selected Variants and Functional Consequences

Gene	Nucleotide Change	Amino Acid Change	rs number	Functional Consequences ^c	References
SLCO1A2	c.-1167G>A	Intronic	rs4148977	Decreased imatinib clearance	(Yamakawa et al., 2011)
	c.-1094G>A	Intronic	rs4148978	Decreased imatinib clearance	
	c.-423G>A	Intronic	rs3764043	Increased imatinib clearance	
	c.38T>C	Ile13Thr	rs10841795	Increased transport of multiple substrates including methotrexate	(Badagnani et al., 2006; Gong and Kim, 2013)
	c.404A>T	Asn135Ile	rs45502302	Decreased transport	(Badagnani et al., 2006; Gong and Kim, 2013)
	c.502C>T	Arg168Cys	rs11568564	Decreased transport of multiple substrates including methotrexate	
	c.516A>C	Glu172Asp	rs11568563	Decreased transport of multiple substrates including methotrexate	
	c.559G>A	Ala187Thr	rs750165758	Decreased transport	(Lee et al., 2005)
	c.833delA	Asn278Met	rs11568555	Decreased transport of multiple substrates including methotrexate	(Badagnani et al., 2006)

<i>SLCO1B1</i>	g.21130388G>A	Intronic	rs4149015	Decreased transport of multiple substrates including SN-38	(Han et al., 2008; Niemi et al., 2004)
	c.217T>C (*2)	Phe73Leu	rs56101265	Decreased transport of multiple substrates including docetaxel	(Gong and Kim, 2013; Lee et al., 2015; Tirona et al., 2001)
	c.245T>C	Val82Ala	rs56061388	Decreased transport	(Gong and Kim, 2013; Tirona et al., 2001)
	c.388A>G (*1b)	Asn130Asp	rs2306283	Decreased transport of some substrates including cytarabine; increased or unchanged transport for other substrates	(Drenberg et al., 2016; Gong and Kim, 2013; Han et al., 2008; Kameyama et al., 2005)
	c.467A>G	Glu156Gly	rs72559745	Decreased transport	(Gong and Kim, 2013; Tirona et al., 2001)
	c.521T>C (*5)	Val174Ala	rs4149056	Decreased transport of multiple substrates including SN-38, docetaxel, cytarabine, etoposide, mitoxantrone, and daunorubicin;	(Drenberg et al., 2016; Gong and Kim, 2013; Han et al., 2008; Kameyama et

				decreased clearance of methotrexate	al., 2005; Lee et al., 2015; Nozawa et al., 2005a; Ramsey et al., 2013; Tirona et al., 2001)
	c.578T>G	Leu193Arg	rs72559746	Decreased to abolished transport of some substrates	(Gong and Kim, 2013; Michalski et al., 2002)
	c.1007C>G	Pro336Arg	rs72559747	Decreased for some substrates, unchanged for others	(Gong and Kim, 2013; Nishizato, 2003)
	c.1058T>C	Ile353Thr	rs55901008	Decreased transport	(Gong and Kim, 2013; Tirona et al., 2001)
	c.1294A>G	Asn432Asp	rs56387224	Decreased transport	
	c.1463G>C	Gly488Ala	rs59502379	Decreased transport of multiple substrates including docetaxel	(Gong and Kim, 2013; Lee et al., 2015; Tirona et al., 2001)
	c.1964A>G	Asp655Gly	rs56199088	Decreased transport	(Gong and Kim, 2013; Lee et al., 2015; Tirona et al., 2001)

	c.2000A>G	Glu667Gly	rs55737008	Decreased transport	(Gong and Kim, 2013; Tirona et al., 2001)
	c.1865+248G>A	Intronic	rs4149081	Decreased methotrexate clearance	(Ramsey et al., 2013; Trevino et al., 2009)
	c.1865+4846T>C	Intronic	rs11045879	Decreased methotrexate clearance	
<i>SLCO1B3</i>	c.1599-5676A>G	Intronic	rs11045585	Decreased or unchanged docetaxel clearance	(Chew et al., 2011; de Graan et al., 2012)
	c.439A>G	Thr147Ala	rs57585902	Decreased or unchanged docetaxel transport	(Baker et al., 2009; Chew et al., 2011; Lee et al., 2015)
	c.699G>A	Met233Ile	rs7311358	Decreased transport of multiple substrates including paclitaxel	(Gong and Kim, 2013; Park et al., 2016; Schwarz et al., 2011)
	c.1559A>C	His520Pro	rs559692629	Decreased transport of multiple substrates; decreased or unchanged docetaxel transport	(Baker et al., 2009; Chew et al., 2011; Lee et al., 2015; Schwarz et al., 2011)

	c.1564G>T	Gly522Cys	rs72559743	Decreased transport	(Gong and Kim, 2013; Letschert et al., 2004)
	c.1679T>C	Val560Ala	rs12299012	Decreased transport of multiple substrates; decreased or unchanged docetaxel transport	(Baker et al., 2009; Chew et al., 2011; Gong and Kim, 2013; Lee et al., 2015; Schwarz et al., 2011)
<i>SLCO2B1</i>	c.601G>A	Val201Met	rs35199625	Decreased transport	(Ho et al., 2006)
	c.1175C>T	Thr392Ile	rs1621378	Decreased transport	(Gong and Kim, 2013; Nozawa et al., 2002)
	c.1457C>T	Ser486Phe	rs2306168	Decreased transport	(Gong and Kim, 2013; Nozawa et al., 2002)
	c.1526G>A	Arg509His	rs140407559	Decreased transport	(Nozawa et al., 2002)

^c “Increased” and “decreased” refer to transport function of the variant transporter compared to the corresponding wild-type transporter. For some variants, effect on transport function varies by substrate, in these cases, the predominant effect on transporter function is listed. *In vitro* and *in vivo* functional studies as well as pharmacokinetic:pharmacogenetic correlative studies were included in the literature review for this table.

Table 3. Differential OATP Protein Expression in Cancer Tissues

Protein	Malignant Tissue Distribution^b
OATP1A2	<i>Increased expression:</i> Breast, pancreas, bone, some lung cancer cell lines <i>Decreased expression:</i> Colon, some lung cell lines
OATP1B1	<i>Increased expression:</i> Breast, pancreas, prostate, ovary, lung, colon <i>Decreased expression:</i> Liver
OATP1B3	<i>Increased expression:</i> Colon, pancreas, lung, breast, prostate, ovary, lung, stomach, gallbladder <i>Decreased expression:</i> Liver
OATP2B1	<i>Increased expression:</i> Lung (conflicting evidence), breast, colon, bone <i>Decreased expression:</i> None reported

^b“Increased” and “decreased” refer to expression of the transporter in malignant tissue compared to normal tissue of the same type.

See text for references for this table.

FIGURES

Figure 1

