MULTIDRUG RESISTENCE-ASSOCIATED PROTEIN 3 (MRP3) PLAYS AN IMPORTANT ROLE IN PROTECTION AGAINST ACUTE TOXICITY OF DICLOFENAC

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Abstract

Diclofenac (DCF) is a non-steroidal anti-inflammatory drug commonly prescribed to reduce pain in acute and chronic inflammatory diseases. One of the main DCF metabolites is a reactive diclofenac acyl glucuronide (DCF-AG) that covalently binds to biological targets and may contribute to adverse drug reactions arising from DCF use. Cellular efflux of DCF-AG is partially mediated by multidrug resistance-associated proteins (Mrp). The importance of Mrp2 during DCF-induced toxicity has been established, yet the role of Mrp3 remains largely unexplored. In the present work, Mrp3-null (KO) mice were used to study the toxicokinetics and toxicodynamics of DCF and its metabolites. DCF-AG plasma concentrations were 90% lower in KO mice than in wild-type (WT) mice, indicating that Mrp3 mediates DCF-AG basolateral efflux. In contrast, there were no differences in DCF-AG biliary excretion between WT and KO suggesting that only DCF-AG basolateral efflux is compromised by Mrp3 deletion. Susceptibility to toxicity was also evaluated after a single high DCF dose. No signs of injury were detected in livers and kidneys, however ulcers were found in the small intestines. Furthermore, the observed intestinal injuries were consistently more severe in KO compared to WT. DCF covalent adducts were observed in liver and small intestines, however staining intensity did not correlate with the severity of injuries implying that tissues respond differently to covalent modification. Overall, the data provides strong evidence that (1) in vivo Mrp3 plays an important role in DCF-AG disposition and (2) compromised Mrp3 function can enhance injury in the gastrointestinal tract after DCF treatment.
Introduction

Diclofenac (DCF) is a non-steroidal anti-inflammatory drug (NSAID) that is prescribed to alleviate symptoms associated with ankylosing spondylitis, osteoarthritis, rheumatoid arthritis, and migraine (McNeely and Goa, 1999; Depomed, 2009; Novartis, 2011). DCF is generally well tolerated although long term usage has been implicated with a variety of adverse events in a subset of patients. The most common side effects of DCF are discomfort, ulceration, and bleeding in the gastrointestinal (GI) tract. These adverse events are related to DCF pharmacodynamics, namely chronic inhibition of cyclooxygenase (COX) enzymes causing a decrease of prostaglandins that protect the GI mucosa (Menasse et al., 1978; Wallace, 2008). NSAIDs as a group have a mean liver injury rate of 1 per 100,000 users. However, chronic DCF administration increases the risk of liver injury to 6 per 100,000 users (de Abajo et al., 2004). More recently, a meta-analysis of cardiovascular safety implicated DCF with a higher risk of cardiovascular death and stroke among a group of seven NSAIDs (Trelle et al., 2011).

DCF undergoes extensive first-pass metabolism in humans, and approximately 50% of the dose is systemically available (Willis et al., 1979). The majority of DCF is converted into metabolites of which 65% are eliminated in urine with the remainder excreted in bile (Riess et al., 1978; Novartis, 2011). Among the main products are hydroxylated metabolites, the predominant being 4′-hydroxy diclofenac (OH-DCF), that can form reactive quinoneimines that adduct and deplete glutathione causing a state of oxidative stress (Tang et al., 1999). Another key metabolite is the highly reactive diclofenac acyl glucuronide (DCF-AG), which is primarily catalyzed in humans by uridine 5′-diphospho-glucuronosyltransferase (UGT) 2B7 (King et al., 2001). It has been shown that inheritance of one or two copies of the UGT2B7*2 allele was
associated with an increased risk of DCF-induced hepatotoxicity compared to UGT2B7*1 homozygotes as the *2 variant possesses higher catalytic activity (Daly et al., 2007).

DCF-AG is initially formed as a $\beta$-1-$O$-acyl glucuronide ($\beta$-anomer) which can be cleaved by $\beta$-glucuronidase into DCF and glucuronic acid. $\beta$-anomers spontaneously isomerize into $\beta$-glucuronidase-resistant 2-, 3-, and 4-$O$-acyl isomers (Sallustio et al., 2000). DCF-AG undergoes these rearrangements as the pH changes from acidic to physiologic conditions such as those that occur in the GI tract (Ebner et al., 1999; Kenny et al., 2004). DCF-AG can form adducts with multiple proteins in the liver and GI tract, and dipeptidyl peptidase IV was identified as a DCF-AG target in rat liver where adduction resulted in decreased activity (Hargus et al., 1995). Furthermore, it was found that broad-acting UGT inhibitors can significantly diminish the covalent binding of DCF metabolite to hepatocellular proteins in vitro (Kretz-Rommel and Boelsterli, 1993). There is consensus that repeated exposure to DCF-AG contributes to the idiosyncratic drug reaction seen with clinical usage, however the exact nature of how DCF-AG contributes to these idiosyncracies remains unclear.

The potential for DCF-AG to cause extrahepatic covalent binding modifications is contingent upon active transport. For instance, DCF-AG was not detected in the bile of rats lacking canalicular multidrug resistance-associated protein 2/ATP-binding cassette transporter family c2 (Mrp2/Abcc2) (Seitz et al., 1998). A follow-up study revealed that Mrp2-null rats also had reduced intestinal ulceration compared to WT rats (Seitz and Boelsterli, 1998). These findings are important as they suggest that Mrp2 is at least partially responsible for DCF-AG excretion from hepatocytes into bile. The mechanism by which DCF-AG is transported from hepatocytes into blood remains less understood.
Among the MRPs that are expressed along the basolateral membrane, MRP3 (ABCC3) has been demonstrated to export glucuronide conjugates of other compounds (Zelcer et al., 2001; Zelcer et al., 2006). In a Caucasian sample pool, fifty-one single nucleotide polymorphisms (SNP) in MRP3 were found (Lang et al., 2004). A pharmacogenomic study of healthy Japanese subjects identified twenty-one novel SNPs, with two resulting in immature transcript due to insertion of a stop codon (Fukushima-Uesaka et al., 2007). Functional significance of MRP3 SNPs was demonstrated whereby several MRP3 SNPs expressed in an in vitro system had impaired transporter function either by reductions in transporter activity or disruption of intracellular transporter trafficking to the cell membrane (Kobayashi et al., 2008).

Because MRP3 has been shown to transport both endogenous and exogenous glucuronide conjugates, it can be hypothesized that perturbation of MRP3 expression or function may affect the disposition and toxicity of DCF-AG in vivo. To investigate the role of MRP3 in the disposition and toxicity of DCF, a mouse Mrp3-null model is used to assess the disposition of DCF-AG and whether Mrp3 deletion increases likelihood of injury.
Materials and Methods

Chemicals, Reagents, and Animals. DCF, OH-DCF, Dulbecco’s phosphate buffered saline (DPBS), formic acid, indomethacin, and sodium citrate were purchased from Sigma-Aldrich Corporation. (St. Louis, MO). DCF-AG was purchased from Toronto Research Chemicals Incorporated (Toronto, ON, Canada). Solutol® HS 15 was provided by the BASF Corporation (Florham Park, NJ). DCF antiserum was graciously donated by Dr. Dietmar Knopp (Technische Universität München, München, Germany). Mrp3-null mice of FVB 129/Ola background were provided by Dr. Piet Borst (Netherlands Cancer Institute, Amsterdam, Netherlands). An additional set of Mrp3-null mice having C57BL/6J background were generated at the University of Kansas Medical Center. Mice were housed in an American Animal Associations Laboratory Animal Care accredited facility of University of Kansas Medical Center under a standard temperature-, light-, and humidity-controlled environment. Mice had free access to Laboratory Rodent Chow 8604 (Harlan, Madison, WI) and drinking water. All animal studies were performed in accordance with the Guide for the Care and Use of Laboratory Animals using protocols reviewed and approved by the local Institutional Animal Care and Use Committee of University of Kansas Medical Center (Kansas City, KS).

In Vivo Studies. Toxicokinetics. Male 2-3 month old FVB 129/Ola WT and FVB 129/Ola KO mice were anesthetized intraperitoneally with a ketamine/midazolam mixture (100 and 5 mg/kg, respectively), and both the right carotid artery and the common bile duct were cannulated for sample collection. The mice received a single intraarterial dose of 75 mg/kg DCF in 10:90 (v/v) Solutol HS 15:DPBS at a dosing volume of 5 mL/kg. Bile flow was monitored, and bile fractions were collected in fifteen minute intervals from -15 to 0, 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 75, and 75 to 90 minutes post administration. Blood samples were collected into
heparinized tubes at 2, 7.5, 22.5, 37.5, 52.5, 67.5, and 90 minutes after administration, and the blood was subsequently centrifuged to yield plasma. The volumes of bile were determined gravimetrically, using 1.0 for specific gravity. Both bile and plasma were stored at -20 °C until analysis. At the conclusion of the study (90 min post-administration), animals were sacrificed by overdose with ketamine and midazolam. Livers were harvested and quickly frozen in liquid nitrogen prior to storage at -80 °C.

**Toxicodynamics.** 2-3 month old male WT and KO (C57BL/6 background) were injected a single intraperitoneal dose of either vehicle, 10:90 (v/v) Solutol HS15: DPBS, or 90 mg/kg DCF in vehicle at a dosing volume of 5 mL/kg. The mice were then allowed access to food and water *ad libitum.* Twenty four hours after dosing, the mice were anesthetized for sacrifice with an intraperitoneal injection of 50 to 70 mg/kg pentobarbital. Blood was collected and centrifuged to yield plasma and kept frozen at -20 °C. Kidneys, liver, and small intestines were harvested, fixed in buffered formalin for 24 hours with gentle shaking at room temperature, and then transferred into 70% ethanol. Tissues were subsequently paraffin embedded and sectioned onto glass slides for histopathology and immunohistochemistry.

**Bioanalytical Analysis. Sample Treatment.** Bile and plasma were diluted with 0.1% formic acid in water (Solvent A) for LC/MS/MS detection as well as to stabilize DCF-AG. Liver samples were homogenized by bead milling using Solvent A. A 50 µL aliquot of diluted biological matrix was then precipitated with 450 µL of 0.1% formic acid in acetonitrile (Solvent B) containing indomethacin as an internal standard. Standard curves using naïve matrices were prepared in a similar fashion. Samples and standards were vigorously vortex-mixed and centrifuged at 1350 × g for 10 min and 4 °C. A 200 µL aliquot of supernatant was removed and evaporated under Nitrogen gas at 45 °C. The resulting residue was reconstituted with 200 µL of
90:10 (v/v) A:B, vigorously vortex-mixed, and centrifuged prior to injection onto LC/MS/MS. The injection volume for all sample types was 10 µL.

**LC/MS/MS Method.** Chromatographic separation of analytes was performed on a Synergi™ 4 µm Max-RP 80 Å 50 x 2 mm column (Phenomenex Incorporated, Torrance, CA). The system front end consisted of a HTC PAL Autosampler outfitted with a Coolstack set to 4 °C (LEAP Technologies Incorporated, Carrboro, NC), a SCL-10Avp system controller, two LC10ADvp pumps, and a DGU-14A degasser (Shimadzu Scientific Instruments, Columbia, MD). Analytes of interest were eluted using a gradient profile that began with 10% solvent B for the first 1.0 min, which was then increased to 90% solvent B at 3.5 min using a linear gradient and held at this mixture for 0.5 min before reverting back to initial solvent conditions for 1.0 min to re-equilibrate the column. The flow rate was 0.4 mL/min, and the column effluent was directed to waste for the initial 1.5 min before switching to the mass spectrometer. Analytes were detected using an AB Sciex API™ 4000 LC/MS/MS triple quad mass-spectrometer with a TurbolonSpray® probe and Analyst version 1.4.2 software (AB Sciex, Framingham, MA) that was operated in multiple reaction monitoring mode. Ion spray voltage was -4250 V, and the source temperature was set to 400 °C. The mass transitions in negative ion mode for monitoring DCF, OH-DCF, DCF-AG, and indomethacin were m/z 294.0→249.9, 309.9→265.9, 470.1→192.9, and 356.0→311.8, respectively. The retention times of diclofenac, 4′-hydroxy diclofenac, diclofenac acyl glucuronide, and indomethacin were 3.25, 2.84, 2.69, and 3.20 min, respectively. Concentrations of analytes in the samples were determined by comparing the peak area ratios (analyte/internal standard) to those in the standard curve using a linear regression model. The dynamic range was 10 to 5,000 ng/mL for bile, liver homogenate, and plasma.
samples. The criterion of acceptance for standards was defined to be ±20% of nominal concentration.

**Immunohistochemistry.** Slides for immunohistochemistry were deparaffinized by xylene, and the xylene was removed by sequentially decreasing concentrations of ethanol followed by hydration in water. After a 30 min heat induced epitope retrieval in sodium citrate buffer, endogenous peroxidase activity was blocked with 3% hydrogen peroxide for 15 min. Slides were subsequently treated with an Avidin/Biotin Blocking Kit (Vector Laboratories Incorporated, Burlingame, CA) as per the manufacturer recommendations and incubated with a Dako Serum-free Protein Block (Dako Incorporated, Carpinteria, CA) for 30 min. A rabbit polyclonal primary antibody against DCF at a 1:5000 dilution was applied for 60 min at room temperature after which slides were incubated for 30 min with a 1:300 dilution of a Dako biotinylated swine anti-rabbit secondary antibody. The slides were then exposed to streptavidin-horseradish peroxidase (BD Biosciences, San Jose, CA) for 30 min. To develop the chromagen, a 30 min treatment with a Vector® NovaRED™ Substrate Kit was utilized, and slides were counterstained with Mayer’s Hematoxylin (Life Technologies, Grand Island, NY). Finally, slides were dehydrated with ethanol and xylene and cover-slipped using Histomount Mounting Solution (Life Technologies). For negative controls, samples from the vehicle-only groups were treated in the same manner as subjects dosed with DCF.

**Clinical Chemistry.** Plasma samples from the toxicodynamic study were analyzed for alanine transaminase (ALT) and blood urea nitrogen (BUN) using kits purchased from Thermo Fisher Scientific Incorporated (Waltham, MA) as per the manufacturer’s recommendations. Positive and negative controls were utilized to assess assay functionality. A BioTek UV/Vis microplate
spectrophotometer (BioTek Instruments Incorporated, Winooski, VT) was used to measure assay endpoints.

**Histopathology. Liver & Kidney.** Liver and kidney samples were fixed in 10% neutral-buffered zinc formalin prior to processing and paraffin embedding. Tissue sections (5 μm) were stained with hematoxylin and eosin. Sections were examined by light microscopy for the presence and severity of necrosis and degeneration using an established grading system (Manautou et al., 1994).

**Gastrointestinal Tract.** The gastrointestinal tract was examined histologically with multiple transverse sections of the stomach and large intestine and Swiss Roll sections of the small intestine (Moolenbeek and Ruitenberg, 1981). Histological examination used a scoring system adapted from a method described by Krieglstein et al. (2007). Briefly, 3 independent parameters were measured for a combined semi quantitative injury score; the degree of villus/crypt damage, the severity of inflammation (none, minimal, mild, moderate, marked, and severe), and the depth of injury (mucosa with epithelium and lamina propria, submucosa, muscularis, and serosa).

**Statistical Analysis.** Data are expressed as mean ± standard error of the mean. *P* values ≤ 0.05 were considered as statistically significant. GraphPad Prism version 6.0 (GraphPad Software Incorporated, La Jolla, CA) was used for statistical analysis of data. Two groups were compared by Student *t* test. Multiple groups were compared by an analysis of variance followed by Newman-Keuls *post hoc* test.
Results

Toxicokinetic Study. In animals that remained anesthetized for surgical exposure of the abdominal cavity and bile duct cannulation, the maximal tolerated dose without morbidity was 75 mg/kg. Plasma concentrations for 75 mg/kg DCF (Figure 1A) were significantly higher in KO compared to WT, and the increases were generally less than 40%. Conversely, OH-DCF concentrations in plasma (Figure 1B) were significantly higher in WT with a 90% increase observed at 37.5 min. There was a dramatic disparity in plasma concentrations between WT and KO for DCF-AG (Figure 1C) with WT having nearly 9-fold higher concentrations in plasma compared to KO. A summary of pertinent toxicokinetic parameters is presented in Table 1. Both genotypes had similar estimated DCF plasma concentrations at time zero (C₀). Though there was a difference in the DCF elimination half-life (t₁/₂) between the 2 genotypes, the DCF plasma exposure (AUC₀-tlast) for WT and KO was comparable.

To determine whether the loss of Mrp3 affected the biliary disposition of DCF and the two metabolites under consideration, the biliary excretion of DCF and its metabolites were quantified. There was no difference in bile flow between WT and KO (data not shown). The biliary excretion of DCF and its metabolites were comparable between the two genotypes (Figure 1D, E, and F). Of the three analytes, DCF-AG was most predominant in bile constituting nearly 10% of the total DCF dose for each genotype, whereas DCF and OH-DCF biliary concentrations accounted for 0.2 and 0.1% of total DCF dose, respectively, irrespective of genotype. The limited availability of KO mice permitted assessing hepatic concentrations of DCF and its metabolites only at the terminal time point of 90 min post-administration. The KO livers had more DCF though the difference was not statistically significant. OH-DCF and DCF-AG concentrations in KO livers were statistically lower compared to WT (Figure 2). In contrast
to bile for which the major detected analyte was DCF-AG, unchanged DCF in both genotypes was most abundant compared to OH-DCF and DCF-AG.

**Clinical Chemistry.** Having established a role for Mrp3 to modulate systemic exposure of DCF-AG *in vivo*, the next objective was to evaluate to susceptibility of KO to DCF-induced injury. For these studies, the DCF dose was increased to 90 mg/kg as that was the maximal non-lethal dose in animals that were non-surgerized and freely moving. Rather than oral gavage, intraperitoneal administration was used to maximize dose absorption and delivery of DCF via portal circulation for immediate uptake into the liver. ALT concentrations (Figure 3A) were not significantly different between WT and KO suggesting no injuries in the liver. Furthermore, ALT values in all vehicle control and DCF-treated groups were less than 30 U/L, which is the upper limit of normal range for ALT. BUN levels (Figure 3B) were statistically higher in KO mice compared to WT, however the lack of difference between vehicle and DCF treated groups in KO mice suggest there was no DCF-induced renal injury.

**Histopathology.** Histopathological examination of liver and kidneys showed no obvious injuries at the administered dose confirming the clinical chemistry results (data not shown). The small intestines were also examined and scored according to three categories of injury. WT which received DCF showed a trend of higher injury compared to vehicle treated subjects (Figure 4), though these differences were not statistically significant. In addition, KO dosed with DCF had significantly greater incidence and severity of erosions and ulcers compared to treatment-matched WT mice. For both WT and KO, ulcers were observed in the jejunal and ileal but not duodenal regions of the small intestine. Thus, the data suggest that the loss of Mrp3 increased the susceptibility to intestinal injury from an acute dose of DCF.
Immunohistochemistry. Sections of livers, kidneys, and small intestines were subjected to immunohistochemistry in order to determine the extent of DCF adduction. The rationale for conducting this assay was that reactive intermediates or metabolites of DCF are known to covalently bind to proteins. Thus the goal was to establish possible links between covalent binding of reactive DCF products and tissue injury. Kidneys were entirely devoid of DCF adduct staining implying that reactive DCF metabolites were not likely to be generated or accumulated by transit in kidneys (data not shown). In contrast, WT and KO livers showed strong evidence of DCF adduction after DCF administration compared to vehicle controls. The staining was robust and was observed in centrilobular, midzonal, and periportal regions. Vehicle controls did not exhibit staining suggesting that the primary antibody was specific for diclofenac adducts (Figure 5A). Interestingly, the livers showed intense staining for DCF adduct yet this organ did not manifest any apparent signs of injury either through clinical chemistry or histopathology. Lastly, compared to small intestines from vehicle controls which were unremarkable (Figure 5D), the small intestines from WT and KO also exhibited positive staining of DCF adducts (Figure 5E-5F). The level of adduct staining in the small intestine was notably weaker than that observed in the liver as qualitatively assessed by chromagen intensity and the degree of scatter. Adduct formation was detected along the brush border of villi and extended inwards towards the basement membrane. In terms of regiospecificity, staining was scattered throughout the small intestine and did not appear to be confined to any particular location.
Discussion

This work explores the role of Mrp3 on the disposition and acute toxicity of DCF. DCF has high passive permeability, therefore its uptake into tissues should not be limited by active transport processes (Huang et al., 2010). The elevated DCF and lower OH-DCF plasma concentrations in KO compared to WT (Figure 1A-B) may indicate metabolic saturation. In vitro studies using mouse hepatic S9 fraction did not show differences in DCF metabolism as the WT and KO Km values were comparable (data not shown). Further evidence of metabolic saturation comes from the OH-DCF plasma concentration-time profile which was relatively flat at 75 mg/kg DCF whereas at lower doses plasma OH-DCF was initially high before decreasing by first-order kinetics (Supplement Figure 1).

The present DCF-AG data are consistent with low dose studies and demonstrate Mrp3-mediated DCF-AG efflux (Figure 1C). Our data confirm the observation reported by Lagas et al. (2010) that DCF-AG is an in vivo substrate of mouse Mrp3. KO had DCF-AG plasma concentrations that were nearly 90% lower compared to WT. Plasma concentrations of several glucuronide metabolites have been reported to be lower in Mrp3 KO compared to WT mice (Manautou et al., 2005; Zamek-Gliszczynski et al., 2006). As KO mice were comparable to WT in terms of overall transporter expression except for Mrp3, the results indicate that Mrp3 mediates DCF-AG basolateral efflux in vivo.

DCF, OH-DCF, and DCF-AG biliary excretion showed no evident distinction between WT and KO. Because Mrp3 acts as a basolateral efflux pump for bile acids (Zelcer et al., 2003), the bile flow in WT and KO was measured and found to be equal suggesting that Mrp3 deletion and DCF treatment did not affect bile flow. That DCF-AG biliary excretion was similar between WT and KO was unexpected considering the pronounced plasma differences. Other studies in
KO reported that low plasma or perfusate concentrations of glucuronides were inversely correlated with increased glucuronide biliary concentrations compared to WT (Manautou et al., 2005; Zamek-Gliszczynski et al., 2006). Similar to rats, canalicular DCF-AG excretion would likely have been mediated by Mrp2 given the 88% protein sequence homology between mouse and rat Mrp2 (Altschul et al., 2005). Another canalicular transporter, breast cancer resistance protein (Bcrp/Abcg2), has been also demonstrated to transport DCF (Lagas et al., 2009). However, exploratory studies in our laboratory with Bcrp-KO mice resulted in equivalent DCF-AG biliary excretion compared to WT (data not shown).

To account for other possible DCF metabolites, bile fractions were pooled and infused onto the LC/MS/MS for qualitative metabolite profiling. Peaks corresponding to DCF taurine conjugate and diclofenac acyl glucuronide (OH-DCF-AG) were detected (data not shown). Identification of these metabolites is consistent with their formation in rodents (Kenny et al., 2004; Sarda et al., 2012). Nonetheless, the OH-DCF-AG signal in KO bile would not have wholly accounted for the DCF-AG fraction that was diverted from entering the blood. Despite the DCF-AG mass balance inequity between WT and KO, there are instances in which Mrp3 ablation affects basolateral but not canalicular efflux. Zelcer et al. (2006) noted that hyodeoxycholate glucuronide perfusate concentrations were 4-fold greater in WT compared to KO while bile concentrations were similar between genotypes. Moreover, fexofenadine plasma concentrations decreased 50% in Mrp3-KO mice relative to WT, yet biliary and hepatic fexofenadine concentrations between the genotypes were the same (Tian et al., 2008). Thus, Mrp3 deletion solely affected DCF-AG basolateral efflux.

The other aim of this study was to assess the susceptibility of Mrp3-null subjects to DCF-induced injury. Initial studies in FVB 129/Ola mice at a 90 mg/kg DCF dose resulted in KO, but
not WT, exhibiting greater intestinal injury (data not shown). As FVB 129/Ola KO were unavailable, further studies were conducted in C57BL/6 KO. Neither the liver nor kidneys showed any evidence of damage by serum biomarker analysis (Figure 3). DCF has been shown to induce nephrotoxicity in ICR mice evidenced by a 2.5-fold increase in BUN concentrations 24 hours following an oral 100 mg/kg dose (Hickey et al., 2001). The finding in ICR mice likely reflects that strain’s higher sensitivity to renal injury since C57BL/6 mice (Figure 3B) had no changes in BUN concentrations compared to vehicle treatment 24 hours after 90 mg/kg intraperitoneal administration. Regarding the liver, Lagas et al. (2010) reported that a 25 mg/kg intraperitoneal DCF injection caused ALT concentrations to increase 2-fold compared to WT leading the authors to conclude that slight liver toxicity occurred. However, the mice used in that study were triple knockouts for Bcrp, Mrp2, and Mrp3 making it difficult to ascribe which transporter was truly responsible for enhancing the toxic effect. Additionally, ALT, bilirubin, liver weights, and triglycerides were also slightly elevated in the triple KO versus WT suggesting that the mice may be more susceptible to challenge by a toxicant (Vlaming et al., 2009). Though liver and kidney were devoid of injury for the present study, the small intestines in both genotypes exhibited damage with KO sustaining greater injury (Figure 4). The intestinal injury is consistent with published reports on DCF ulcerogenicity (Atchison et al., 2000; Ramirez-Alcantara et al., 2009).

Reactive DCF metabolites form adducts with a number of hepatic proteins (Seitz et al., 1998; Sallustio and Holbrook, 2001; Kenny et al., 2004). Immunohistochemistry revealed widespread covalent binding in the liver and small intestine but not in kidneys of both WT and KO (Figure 5). Qualitative assessment of the extent of staining did not provide meaningful distinction between the two genotypes (data not shown). DCF adduct staining was most intense
in the liver, yet this organ did not appear to have any obvious histopathological damage. DCF-AG synthesis would be high in the liver, and it is plausible that DCF-AG adducted albumin, which is synthesized in the liver, and/or sequestered by thiols (protein and non-protein) that are not critical cellular targets. Though staining in small intestines was less robust, histopathology revealed significant damage (Figure 4). DCF-AG adduction to enterocytes potentially compromised enterocyte function and viability and possibly induced an immune-mediated response. Modulation of the immune function within 24 hours of toxicant exposure has previously been demonstrated for drugs such as acetaminophen (APAP). Administration of a toxic APAP dose activates hepatic macrophages (i.e., Kupffer cells) to release proinflammatory cytokines (Blazka et al., 1995). This in turn stimulates the migration and infiltration of immune cells into the liver, influencing the ultimate toxic outcome. The role of the immune system in intestinal toxicity following DCF administration was beyond the scope of the present work and will be a focus of future studies.

DCF-AG could adduct enterocyte proteins on the extracellular surface or alternatively adduct from within after uptake by various transporters. Glucuronide conjugates can be transported by organic anion transporting polypeptides (OATPs) of which OATP2B1 is the predominant isoform in the human intestine (Ishiguro et al., 2008; Drozdzik et al., 2014). It is likely through the mouse Oatp2b1 orthologue, which is also expressed in the intestines, that DCF-AG uptake occurs (Cheng et al., 2005). Nonetheless, the fact that the liver had intense adduct formation without apparent injury compared to the intestine which had extensive damage but moderate adduction may indicate that protein adducts of DCF metabolite(s) do not necessarily contribute to or cause toxicity.
DCF administration resulted in two diverse outcomes: 1) rapid generation of DCF-AG that was excreted into bile or plasma and 2) COX inhibition that decreased local and/or systemic prostaglandins that protect the GI mucosa. Based on the data, we propose the following series of events to occur in our model of DCF-induced toxicity. DCF-AG is taken up and covalently binds to targets (plasma membrane, intracellular proteins, etc.) compromising the integrity of the enterocyte. In KO, the DCF-AG basolateral efflux is attenuated potentially leading to higher accumulation of intracellular DCF-AG within enterocytes compared to WT. Meanwhile, intestinal mucosal protection is weakened due to DCF’s pharmacological inhibition of both COX-1 and COX-2 (Menasse et al., 1978) causing a decrease in protective prostaglandins. Simultaneously, the highly permeable DCF enters enterocytes and exerts further injury through mitochondrial dysfunction leading to apoptosis (Gomez-Lechon et al., 2003; Lim et al., 2006). Unbound DCF-AG may also dissociate into DCF and glucuronic acid intensifying diclofenac-induced mitochondrial dysfunction. Mrp2, which normally confers a measure of protection via DCF-AG efflux, could be affected as Mrp2 translocates intracellularly from its apical membrane localization during oxidative stress (Sekine et al., 2006). The proposed events would breakdown the overall intactness of the GI tract.

There are several issues that remain to be addressed: (1) the relationship between DCF-AG exposure and developing injury is unclear, (2) determining the DCF-AG concentrations in the small intestine that can cause damage, and (3) assessing why the small intestines but not liver or kidneys were affected. It will be necessary to devise experiments wherein the mechanism of injury by DCF-AG can be studied with minimal interference from its parent or hydroxylated metabolites. The degree of intestinal COX inhibition also warrants examination as a contributing cause for the GI injury observed following DCF administration.
In conclusion, the present work demonstrates that (1) Mrp3 is responsible for DCF-AG basolateral efflux, (2) canalicular efflux is not perturbed by Mrp3 deletion, (3) KO mice have greater gastrointestinal damage compared to WT, and (4) appearance of adducts does not necessarily signify the occurrence of injury as certain organs are more sensitive to injury than others.
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Authorship Contributions

Participated in research design: Csanaky, Manautou, and Scialis

Conducted experiments: Csanaky and Scialis

Performed data analysis: Goedken and Scialis

Wrote or contributed to the writing of the manuscript: Csanaky, Manautou, and Scialis

Conflict of Interest

The authors state no conflict of interests.
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Figure Legends

**Figure 1.** Toxicokinetics of DCF and its metabolites in FVB wild-type (WT, ●) and FVB Mrp3-null (KO, ○) mice after a single intraarterial dose of 75 mg/kg DCF. (A-C) Plasma concentration profiles for (A) DCF, (B) OH-DCF, and (C) DCF-AG at discrete time points. (D-F) Biliary excretion profiles for (D) DCF, (E) OH-DCF, and (F) DCF-AG. Time points represent accumulation of biliary flow during successive 15 min intervals (0-15, 15-30, 30-45, 45-60, 60-75, and 75-90 min). All data are expressed as mean ± standard error of the mean for 10-12 subjects/group. * P < 0.05; ** P < 0.01; *** P < 0.001 versus WT.

**Figure 2.** Hepatic concentrations of DCF, OH-DCF, and DCF-AG in FVB wild-type (WT, ■) and FVB Mrp3-null (KO, □) mice. Mice were injected with 75 mg/kg DCF. Livers were harvested 90 min following administration of vehicle or DCF. Data are expressed as mean ± standard error of the mean for 10-12 subjects/group. * P < 0.05; ** P < 0.01 versus WT.

**Figure 3.** Clinical chemistry of C57 wild-type (WT) and C57 Mrp3-null (KO) mice 24 hours after a single dose of 90 mg/kg DCF. (A) Plasma alanine aminotransferase (ALT). (B) Plasma blood urea nitrogen (BUN). Results are expressed as mean ± standard error of the mean for 3-7 subjects/group. ** P < 0.01 versus WT.

**Figure 4.** Summary of histopathology of small intestines from C57 wild-type (WT) and C57 Mrp3-null (KO) mice 24 hours after administration of vehicle or 90 mg/kg DCF. Results are expressed as mean ± standard error of the mean for 3-7 subjects/group. The overall grade was based on the following scheme: 0 = none, 1 = minimal, 2 = mild, 3 = moderate, 4 = marked, and
5 = severe. Ulcers and erosions reflect the number of findings that were indentified on an entire tissue section. ** *P < 0.01; *** *P < 0.001 versus treatment-matched WT.

**Figure 5.** Immunohistochemistry of tissues taken from C57 wild-type (WT) and C57 Mrp3-null (KO) mice treated with vehicle or 90 mg/kg DCF (immunoperoxidase with hematoxylin counterstain). Tissues were harvested 24 hours after administration. (A-C) Liver sections at 4× magnification. (A) Representative liver section from vehicle treated subject. (B) WT liver after 90 mg/kg. (C) KO liver after 90 mg/kg. (D-F) Small intestine sections at 15× magnification. (D) Representative small intestine from vehicle treated subject. (E) WT small intestine after 90 mg/kg. (F) KO small intestine after 90 mg/kg. The presence of DCF adducts is visualized by the presence of red/brown staining.
Table 1. Summary of DCF toxicokinetic parameters in plasma of FVB wild-type (WT) and FVB Mrp3-null (KO) after a single 75 mg/kg DCF dose. C₀ indicates the estimated DCF plasma concentration at time zero, t₁/₂ is the DCF elimination half-life, and AUC₀₋₉last is the area under the plasma concentration versus time curve for DCF from time zero to the last collected time point. Data are expressed as mean ± standard error of the mean for 10-12 subjects/group.

<table>
<thead>
<tr>
<th>Group</th>
<th>C₀ (µM)</th>
<th>t₁/₂ (min)</th>
<th>AUC₀₋₉last (µM × min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>699 ± 31</td>
<td>74.1 ± 12.8</td>
<td>34,600 ± 2,100</td>
</tr>
<tr>
<td>KO</td>
<td>701 ± 38</td>
<td>108 ± 10</td>
<td>35,900 ± 2,500</td>
</tr>
</tbody>
</table>
FIGURE 3

A: ALT

- WT Vehicle
- WT 90 mg/kg
- KO Vehicle
- KO 90 mg/kg

B: BUN

- WT Vehicle
- WT 90 mg/kg
- KO Vehicle
- KO 90 mg/kg

**
FIGURE 4

Histology

Overall Grade

# Ulcers

# Erosions

Grade or Number

WT Vehicle

WT 90 mg/kg

KO Vehicle

KO 90 mg/kg

***

**

WT 90 mg/kg:

KO 90 mg/kg:

KO Vehicle:

WT Vehicle: