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### Species Differences of Bile Acid Redox Metabolism: Tertiary Oxidation of Deoxycholate is Conserved in Preclinical Animals

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Species Differences of Bile Acid Redox Metabolism

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### Abbreviations

CA, 3 $\alpha$ , 7 $\alpha$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
3-dehydroCA, 3-oxo, 7 $\alpha$ , 12 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
isoCA, 3 $\beta$ , 7 $\alpha$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
7-oxoDCA, 3 $\alpha$ , 7-oxo, 12 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
UCA, 3 $\alpha$ , 7 $\beta$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
isoUCA, 3 $\beta$ , 7 $\beta$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
12-epiCA, 3 $\alpha$ , 7 $\alpha$ , 12 $\beta$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA, 3 $\alpha$ , 12 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
isoDCA, 3 $\beta$ , 12 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
12-oxoLCA, 3 $\alpha$ , 12-oxo-hydroxy-5 $\beta$ -cholan-24-oic acid  
12-epiDCA, 3 $\alpha$ , 12 $\beta$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
3-dehydroDCA, 3-oxo, 12 $\alpha$ -hydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-1 $\beta$ -ol, 1 $\beta$ , 3 $\alpha$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-5 $\beta$ -ol, 3 $\alpha$ , 5 $\beta$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-6 $\alpha$ -ol, 3 $\alpha$ , 6 $\alpha$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-6 $\beta$ -ol, 3 $\alpha$ , 6 $\beta$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-4 $\beta$ -ol, 3 $\alpha$ , 4 $\beta$ , 12 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
DCA-19-ol, 3 $\alpha$ , 12 $\alpha$ , 19-trihydroxy-5 $\beta$ -cholan-24-oic acid  
CDCA, 3 $\alpha$ , 7 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
7-oxoLCA, 3 $\alpha$ , 7-oxo-hydroxy-5 $\beta$ -cholan-24-oic acid  
UDCA, 3 $\alpha$ , 7 $\beta$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
isoUDCA, 3 $\beta$ , 7 $\beta$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
LCA, 3 $\alpha$ -hydroxy-5 $\beta$ -cholan-24-oic acid  
isoLCA, 3 $\beta$ -hydroxy-5 $\beta$ -cholan-24-oic acid  
MDCA, 3 $\alpha$ , 6 $\beta$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
6-oxoLCA, 3 $\alpha$ , 6-oxo-hydroxy-5 $\beta$ -cholan-24-oic acid  
HDCA, 3 $\alpha$ , 6 $\alpha$ -dihydroxy-5 $\beta$ -cholan-24-oic acid  
 $\alpha$ MCA, 3 $\alpha$ , 6 $\beta$ , 7 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
 $\beta$ MCA, 3 $\alpha$ , 6 $\beta$ , 7 $\beta$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
 $\alpha$ HCA, 3 $\alpha$ , 6 $\alpha$ , 7 $\alpha$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
 $\beta$ HCA, 3 $\alpha$ , 6 $\alpha$ , 7 $\beta$ -trihydroxy-5 $\beta$ -cholan-24-oic acid  
NA, not applicable

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ND, not detected

$S_{50}$ , substrate concentration occupying half of the binding sites

$V_{\max}$ , maximal velocity

$CL_{\text{int}}$ , intrinsic clearance

LC-MS/MS, liquid chromatography with tandem mass spectrometry

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### Abstract

It was recently disclosed that CYP3A is responsible for the tertiary stereoselective oxidations of deoxycholic acid (DCA), which becomes a continuum mechanism of the host-gut microbial co-metabolism of bile acids (BAs) in human. This work aims to investigate the species difference of BA redox metabolism and clarify whether the tertiary metabolism of DCA is a conserved pathway in preclinical animals. With quantitative determination of the total unconjugated BAs in urine and fecal samples of human, dogs, rats and mice, it was confirmed that the tertiary oxidized metabolites of DCA were found in all tested animals while DCA and its oxidized metabolites disappeared in germ-free mice. The *in vitro* metabolism data of DCA and the other unconjugated BAs in liver microsomes of human, monkeys, dogs, rats and mice showed consistencies with the BA profiling data, confirming that the tertiary oxidation of DCA is a conserved pathway. In liver microsomes of all tested animals, however, the oxidation activities toward DCA were far below the murine-specific 6 $\beta$ -oxidation activities toward chenodeoxycholic acid (CDCA), ursodeoxycholic acid (UDCA) and lithocholic acid (LCA), and 7-oxidation activities toward murideoxycholic acid (MDCA) and hyodeoxycholic acid (HDCA) came from the 6-hydroxylation of LCA. These findings provided further explanations for why murine animals have significantly enhanced downstream metabolism of CDCA compared to human. In conclusion, the species differences of BA redox metabolism disclosed in this work will be useful for the inter-species extrapolation of BA biology and toxicology in translational researches.

### Keywords

Primary bile acids; secondary bile acids; tertiary bile acids; species difference; deoxycholate.

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### **Significance Statement**

It's important to understand the species difference of bile acids metabolism when deciphering biological and hepatotoxicology findings from preclinical studies. However, the species difference of tertiary bile acids is poorly understood compared to primary and secondary bile acids. This work confirmed that the tertiary oxidation of deoxycholic acid is conserved among preclinical animals and provided deeper understanding of how and why the downstream metabolism of chenodeoxycholic acid dominates that of cholic acid in murine animals compared to human.

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### Introduction

Bile acids (BAs) are amphipathic steroids produced almost exclusively by the liver from cholesterol. Most BAs are trapped in the bile acid pool by the process of enterohepatic circulation driven by a series of host-gut microbial metabolism and transport mechanisms (Russell, 2003; Halilbasic et al., 2013; Dawson and Karpen, 2015). As shown in **Figure 1**, this co-metabolism involves metabolic pathways from primary to secondary BAs and from secondary to tertiary BAs, in which the nomenclature of BAs in our work follows Hofmann's proposal (Hofmann et al., 1992). During the enterohepatic circulation of BAs, BA-mediated host-gut microbial crosstalk is important for maintaining a healthy gut microbiota (Theriot et al., 2014; Buffie et al., 2015), balanced lipid and carbohydrate metabolism (de Aguiar Vallim et al., 2013; Wahlstrom et al., 2016), insulin sensitivity (Maruyama et al., 2002; Kawamata et al., 2003), and innate immunity (Inagaki et al., 2006; Vavassori et al., 2009). Drug induced disturbance of BA homeostasis may result in cholestasis and induces hepatic and extrahepatic toxicities, known as drug induced liver injury (DILI). Because there are significant species differences along the host-gut microbiota co-metabolism axis of BAs, DILI is often a poorly predicted adverse event during preclinical studies, and sometimes is unaware until later clinical trials (Chen et al., 2014). As such, it's of great importance to seriously take into account the species difference when deciphering biological and toxicological findings from preclinical animal species.

The species difference of primary BA comes firstly from oxidative on the steroid nucleus and secondly from conjugation with glycine, taurine, sulfate and/or glucuronic acid. Cholic acid (CA) and chenodeoxycholic acid (CDCA) are the primary BAs for most mammals (Hofmann et al., 2010). CDCA may be partly 6 $\alpha$ -hydroxylated into  $\alpha$ -hyocholic acid ( $\alpha$ HCA) by CYP3A (Deo and Bandiera, 2008). Due to the presence of the hepatic 6 $\beta$ -hydroxylase, murine animals have additional primary BAs, known as muricholic acids ( $\alpha$ MCA and  $\beta$ MCA) (Hsla et al., 1957; Mahowald et al., 1957a). The murine 6 $\beta$ -hydroxylase was recently identified as CYP2C22 in rats and Cyp2c70 in mice, whose homologous enzyme in human, CYP2C9, is a drug-metabolizing enzyme without BA oxidation activities (Takahashi et al., 2016). Ursodeoxycholic acid (UDCA) is also a primary BA of mice (Sayin et al., 2013) since mice Cyp2c70 is also able to transform CDCA into UDCA (Takahashi et al., 2016). The BAs in humans, minipigs, and hamsters conjugate mainly with glycine, while taurine amidation is predominant in mice, rat and dogs. It has been also discovered that less sulfation occurs in rat and mice compared to human and chimpanzee (Thakare et al., 2018b; Thakare et al., 2018a).

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The reactions of secondary BAs metabolism greatly enlarge the structural diversity. The major pathway for secondary BAs metabolism is the deconjugation of the amidated primary BAs by bacteria with bile salt hydrolase (BSH) activity (Huijghebaert and Hofmann, 1986; Gopal-Srivastava and Hylemon, 1988) and the subsequent 7-dehydroxylation of the unconjugated forms by bacteria that carry bile acid inducible (Bai) genes (Stellwag and Hylemon, 1979; Hirano et al., 1981; Batta et al., 1990). CA and CDCA are 7-dehydroxylated into deoxycholic acid (DCA) and lithocholic acid (LCA), respectively. UDCA is dehydroxylated into LCA at a similar fashion. The murine-specific BAs,  $\alpha$ MCA and  $\beta$ MCA, are 7-dehydroxylated into murideoxycholic acid (MDCA) (Zhang et al., 2012). Another type of reactions of secondary BAs metabolism is epimerization of hydroxyl groups catalyzed by hydroxysteroid dehydrogenases (HSDHs) (Macdonald et al., 1976; MacDonald et al., 1977). CDCA and CA are epimerized into UDCA and ursocholic acid (UCA) and subsequently into isoursodeoxycholic acid (isoUDCA) and isourschocholic acid (isoUCA), respectively (Zhu et al., 2018). CA and DCA are epimerized into 12-epicholic acid (12-epicCA) and 12-epideoxycholic acid (12-epicDCA), respectively (Zhu et al., 2018). To the best of our knowledge, evidences are not yet available for 6-HSDH that may catalyze epimerization between  $\beta$ MCA and  $\beta$ -hyocholic acid ( $\beta$ HCA, also termed  $\omega$ MCA in literatures) in murine animals (Ridlon et al., 2006; Ridlon et al., 2016). Some of the secondary BAs can be reabsorbed into the liver, where they undergo N-acylamidation metabolism.

Tertiary BAs are redox metabolites of the reabsorbed secondary BAs catalyzed by host enzymes. The term of “tertiary BA” was proposed for the first time based on the identified 7 $\beta$ -oxidation pathway from hyodeoxycholic acid (HDCA) to  $\beta$ HCA after oral administration of HDCA to germ-free rats (Madsen et al., 1975). As a matter of fact, earlier studies have provided evidences for the tertiary BA metabolism by administrating the radiolabeled secondary BAs to bile fistula rats. CDCA, MDCA,  $\alpha$ MCA and  $\beta$ MCA were identified as metabolites of LCA (Thomas et al., 1964), MDCA and  $\beta$ HCA were identified as metabolites of HDCA (Matschiner et al., 1957; Matschiner et al., 1958),  $\beta$ MCA was identified as a major metabolite of MDCA (Thomas et al., 1965), CA and DCA-6 $\beta$ -ol were identified as metabolites of DCA (Mahowald et al., 1957b; Ratliff et al., 1961). The murine-specific 7 $\alpha$ -hydroxylase, which catalyzes the conversion of DCA and LCA to CA and CDCA in taurine-conjugated forms, respectively, was recently identified as Cyp2a12 in mice (Honda et al., 2020). However, it is much more challenging to study tertiary BA metabolism in larger animals, particularly in human, due to lack of germ-free models and ethnic problems of radiolabeled interventions. Although several BAs with unusual oxidation sites have been



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identified in humans in the last century (Sjövall et al., 2010), only two CYP3A-catalyzed pathways, 6 $\alpha$ -hydroxylation of LCA to HDCA (Trulzsch et al., 1974; Araya and Wikvall, 1999; Deo and Bandiera, 2009) and 1 $\beta$ -hydroxylation of DCA to DCA-1 $\beta$ -ol (Gustafsson et al., 1985; Bodin et al., 2005; Hayes et al., 2016), have been confirmed. The species difference of tertiary BAs is still poorly understood compared to primary and secondary BAs.

We have recently extended the scope of tertiary BA metabolism in human based on BA metabolome analysis in combination with *in vitro* metabolism assays. As shown in **Figure 1**, a series of tertiary oxidation reactions of DCA, glycodeoxycholic acid (GDCA) and taurodeoxycholic acid (TDCA) regioselectively at C-3 $\beta$ , C-1 $\beta$ , C-5 $\beta$ , C-6 $\alpha$ , C19, C-4 $\beta$  and C-6 $\beta$  were characterized to be exclusively catalyzed by CYP3A4 and CYP3A7 (Zhang et al., 2019). The 19-hydroxylation of DCA, GDCA and TDCA was identified as a novel *in vitro* marker of CYP3A7 activity (Chen et al., 2019). Following this observation, we confirmed in this work that the tertiary metabolism of DCA is a conserved pathway in commonly used preclinical animal models. A series of murine-specific metabolic pathways that may be responsible for the predominance of downstream metabolism of CDCA in murine animals compared to human were identified and illustrated in **Figure 1**.

## Materials and Methods

### *Materials and Reagents*

Authentic standards of 25 unconjugated BAs and 4 stable isotope-labeled internal standards were obtained from Steraloids (Newport, RI), TRC (Toronto, Canada), Santa Cruz (Dallas, TX, USA) or Sigma-Aldrich (St. Louis, MO) as previously described (Zhu et al., 2018). Six DCA metabolites, DCA-1 $\beta$ -ol, DCA-4 $\beta$ -ol, DCA-5 $\beta$ -ol, DCA-6 $\beta$ -ol, DCA-6 $\alpha$ -ol and DCA-19-ol, were synthesized as described in our recent report (Zhang et al., 2019). Sulfatase from *Helix pomatia* Type H-1,  $\beta$ -glucuronidase from *Helix pomatia* Type H-1 and choloylglycine hydrolase from *Clostridium perfringens* were purchased from Sigma-Aldrich. Human liver microsomes from 150 (76 female and 74 male) mixed gender pooled donors, dogs liver microsomes from 7 (3 female and 4 male) mixed gender pooled donors, rats liver microsomes from 181 (21 female and 160 male) mixed gender pooled donors, mice liver microsomes from 170 (150 female and 20 male) mixed gender pooled donors, NADPH regenerating system solution A (NADPH-A, containing 26 mM NADP<sup>+</sup>, 66 mM glucose-6-phosphate and 66 mM MgCl<sub>2</sub> in water), NADPH regenerating system solution B (NADPH-B, containing 40 U/mL glucose-6-phosphate dehydrogenase in 5 mM sodium citrate) and 0.5 M pH 7.4 PBS were purchased from Corning (Tewksbury, MA, USA). Cynomolgus monkeys

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liver microsomes from 10 (7 female and 3 male) mixed gender pooled donors were purchased from Research Institute for Liver Diseases (Shanghai, China). Sodium acetate, glacial acetic acid, ammonium hydroxide, and LC-MS grade methanol, acetonitrile and formic acid were purchased from Sigma-Aldrich. DMSO was purchased from Thermo Fisher Scientific (Waltham, MA, USA). Ultra-pure water was obtained by using a Milli-Q system (Bedford, MA, USA).

### ***Fecal and Urine Samples***

Human fecal and urine samples were collected from healthy volunteers (n=6, 5 female and 1 male) in our laboratory who have signed informed consents. Fecal and urine samples of Beagle dogs (n=6, 3 male and 3 female), Sprague-Dawley rats (n=6, 3 male and 3 female) and C57BL/6 mice (n=8, 4 male and 4 female) were gifted from West China-Frontier PharmaTech (Chengdu, China). Fecal and urine samples of Germ-free C57BL/6 mice (n=3, male) were gifted from Shanghai SLAC Laboratory Animal Co., Ltd (Shanghai, China). The collected samples were stored at -80 °C until analysis.

### ***Sample Preparation for BA Profile Analysis***

Quantitative analysis of BA profile was performed using the enzyme digestion techniques (Zhu et al., 2018). In brief, urine and fecal samples were thawed on ice bath. All urine samples were centrifuged at 4°C at 12,000 g for 5 min and 100 µL supernatants from the same species were mixed into a pooled urine sample. Each 50 mg fecal sample was homogenized with 500 µL 0.1% (v/v) ammonium hydroxide solution. The homogenized samples were frozen at -40°C for 10 min for protein precipitation. The processed samples were centrifuged at 4°C at 12,000 g for 20 min, and 100 µL supernatants from the same species were mixed into a pooled fecal sample. An aliquot (50 µL) of the pooled urine or fecal samples was transferred to 700 µL round well 96-well plate in triplicate. A volume of 150 µL sodium acetate buffer (pH 5.0) containing 50 U of sulfatase, 500 U of β-glucuronidase and 100 U of choloylglycine hydrolase was added to digest the conjugated BAs. The plate was incubated at 37°C for 6 h and subsequently lyophilized. Then, 200 µL of acetonitrile containing 1% formic acid and 100 nM internal standards (LCA-2,2,4,4-D4, DCA-2,2,4,4-D4, UDCA-2,2,4,4-D4 and CA-2,2,4,4-D4) was added in each well. The plate was mixed by vortexing at 1,500 rpm for 30 min at 10°C and then centrifuged at 3,000 g for 20 min at 4°C. The 200 µL supernatant were transferred to another plate and vacuum-evaporated at 30°C. The residue was reconstituted with 50 µL of acetonitrile and 50 µL of

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water and then mixed by vortexing at 900 rpm for 20 min at 10°C. After centrifugation, the plate was placed into an autosampler for analysis.

### *In Vitro Oxidation Metabolism Assay*

*In vitro* metabolism was performed using the protocol described in our recent report (Chen et al., 2019; Zhang et al., 2019). In brief, stock solutions of unconjugated BAs were prepared in DMSO. Incubations with an initial substrate concentration of 1.0, 5.0, 25, 50, 100, 200, 300, 500, 750, 1000, 3000, and 5000  $\mu\text{M}$  for DCA were performed in 96-well plates in a shaking incubator at 37°C. Incubations for the other unconjugated BAs were performed with an initial substrate concentration of 50  $\mu\text{M}$ . The 100  $\mu\text{L}$  incubation solution contained 0.1 M PBS (pH 7.4), 5.0  $\mu\text{L}$  NADPH-A, 1.0  $\mu\text{L}$  NADPH-B, 0.5  $\mu\text{L}$  DCA working solution, 0.5  $\mu\text{L}$  blank solvent, and 2.5  $\mu\text{L}$  liver microsomes (protein concentration of 20 mg/mL). The final protein concentration in the incubation media was 0.5 mg/mL. All incubations were performed in triplicate and the DMSO concentration in all incubations was 1% (v/v). The reactions were initiated after 5 min preincubation at 37°C by adding liver microsomes and stopped at a pre-set time point by adding 300  $\mu\text{L}$  of ice-cold acetonitrile containing 0.1% formic acid and 50  $\mu\text{M}$  CA-2,2,4,4-D4 as an internal standard. The reaction mixture was then centrifuged at 4°C at 4000 g for 20 minutes. The supernatant (50  $\mu\text{L}$ ) was diluted with 50  $\mu\text{L}$  water and subjected to LC-MS/MS analysis.

### *Quantitative LC-MS/MS Analysis*

Quantitative analysis of unconjugated BAs was performed on ACQUITY ultra-performance liquid chromatography coupled to a Xevo TQ-S mass spectrometer (Waters, Milford, MA, USA) (Yin et al., 2017; Zhu et al., 2018). The mobile phases consisted of 0.01% formic acid in water (mobile phase A) and acetonitrile (mobile phase B). The 5  $\mu\text{L}$  of each sample was injected onto an ACQUITY BEH C18 column (1.7  $\mu\text{m}$ , 100 mm  $\times$  2.1 mm) (Waters, Milford, MA). The flow rate was 0.45 mL/min with the following mobile phase gradient: 0.0-0.5 min (95% A), 0.5-1.0 min (95-64% A), 1.0-2.0 min (64-74% A), 2.0-4.0 min (74-70% A), 4.0-6.0 min (70% A), 6.0-7.0 min (70-62% A), 7.0-9.0 min (62-55% A), 9.0-12.5 min (55-30% A), 12.5-13.0 min (30-0% A), 13.0-14.0 min (0% A), 14.0-14.1 (0-95% A) and 14.1-15.0 min (95% A). The mass spectrometer was operated in the negative mode with a 3.0 kV capillary voltage. Selected ion recording for quantification and identification of unconjugated BAs was described in our previous reports (Yin et al., 2017; Zhu et al., 2018; Zhang et al., 2019). The source and desolvation temperatures were set at 150 and 550 °C, respectively. The collision energy was set at 27 V. Nitrogen and argon were used as cone and

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collision gases, respectively. The cone gas flow and desolvation gas flow were set at 150 and 950 L/h, respectively.

### *Data processing*

The LC-MS/MS raw data was processed by UNIFI (V1.8, Waters, Milford, MA, USA). The metabolite formations as a function of substrate concentrations were fit to Hill (sigmoidal) equation and hyperbolic (Michaelis-Menten) equation using GraphPad Prism software (version 7.0, GraphPad Software, LaJolla, CA).

## Results

### *Tertiary oxidations of deoxycholate is a conserved pathway among the tested animals*

In this work, we utilized a pooled-sample strategy to attenuate the intra-species difference and highlight the inter-species difference of the BA profile. Serum or plasma samples were not included in this study due to the known limited exposure of BAs in circulation. A total of 31 unconjugated BAs was quantitated in the pooled urine and fecal samples collected from human, dogs, rats, SPF mice and germ-free mice. These BA metabolites were classified into secondary or tertiary metabolites for the downstream of CA or CDCA (**Figure 2**), based on the known host-gut microbial co-metabolism network of BAs. It was clear that BAs are excreted mainly via feces and minorly via urine. The phenomenon was more significantly observed in murine animals than in human and dogs. The primary BAs, CA and CDCA, and the corresponding secondary BAs, DCA and LCA, respectively, were prevalent in mice, rats, dogs and human.  $\alpha$ MCA and  $\beta$ MCA, the 6 $\beta$ -hydroxylated metabolites of CDCA and UDCA, were almost exclusively detected in murine animals, except that  $\alpha$ MCA was detected to a much lesser extent in dogs.  $\beta$ MCA, the 6-hydroxyl epimer of  $\beta$ MCA, was exclusively detected in rats and mice.  $\alpha$ HCA, a CYP3A-catalyzed 6 $\alpha$ -oxidized metabolite of CDCA (Deo and Bandiera, 2008), was detected in human and mice. Comparison between SPF and germ-free mice confirmed that CA, CDCA, UDCA,  $\alpha$ MCA and  $\beta$ MCA are the primary BAs of mice, while the other BAs detected in mice are more or less associated with the modification of primary BAs by the host, the secondary metabolism of primary BAs by the gut microbes and/or the tertiary metabolism of reabsorbed secondary BAs by the host.

We have recently characterized both *in vitro* and *in vivo* the tertiary oxidations of DCA, GDCA and TDCA regioselectively at C-1 $\beta$ , C-3 $\beta$ , C-4 $\beta$ , C-5 $\beta$ , C-6 $\alpha$ , C-6 $\beta$  and C-19, in which the 3 $\beta$ -hydroxylated metabolite rapidly dehydrates into 3-dehydroDCA (Zhang et al., 2019). This finding was also confirmed in this study that 3-dehydroDCA, DCA-5 $\beta$ -ol, DCA-

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6 $\alpha$ -ol, DCA-4 $\beta$ -ol and DCA-6 $\beta$ -ol were also detected in the feces of dogs, rats and mice (**Figure 2**). DCA-1 $\beta$ -ol was detected in dogs but not in rats and mice. Similar as our recent BA profiling data of human urine, DCA-19-ol, the human CYP3A7-specific tertiary BA metabolite characterized *in vitro*, was not detected in human feces and absent in dogs, rats and mice. Comparison between SPF and germ-free mice showed that both DCA and its downstream tertiary metabolites were absent in germ-free mice. The same pattern was also observed for both LCA and its downstream tertiary metabolites, HDCA and MDCA. Our data has provided a preliminary *in vivo* evidence that the tertiary metabolism of LCA and DCA can be catalyzed by host enzymes.

*In vitro* metabolite screening of DCA and the other unconjugated monohydroxy or dihydroxy BAs were performed in liver microsomes of dogs, rats, mice, monkeys and human to confirm whether these tertiary BAs found in animals were metabolites uniquely from DCA. Similar to our recent observations in human liver microsomes (Zhang et al., 2019), these tertiary BAs were identified to be neither the di-oxidized metabolites of LCA nor the mono-oxidized metabolites of the other unconjugated dihydroxy BAs (data not shown). As shown in **Figure 3**, a total of 8 oxidized metabolites were continuously produced within 0-720 min after an incubation of 50  $\mu$ M DCA in liver microsomes of the test species. The DCA oxidations at C-3 $\beta$ , C-1 $\beta$ , C-5 $\beta$ , C-6 $\alpha$ , C-4 $\beta$  and C-6 $\beta$  were detected in all the test species, whereas the human CYP3A7-specific metabolite, DCA-19-ol, was not found at a substrate level of 50  $\mu$ M in the test species. Moreover, rats preferred 7 $\beta$ -oxidation from DCA to UCA, which was commonly considered as the epimerized metabolite of CA mediated by gut microbes. In brief, these results have made it clear that the tertiary oxidation of DCA is a conserved pathway in human, monkeys, dogs, rats and mice.

### ***Species difference of the regioselective oxidation activities of DCA in liver microsomes***

**Figure 4** showed the apparent kinetic plots of DCA oxidation activities in the liver microsomes of human, monkeys, dogs, rats and mice. Consistent with previous results observed from the recombinant human CYP3A enzymes, oxidation activities gradually reduced to zero for all the species when the concentration of substrates were above 300  $\mu$ M. The activity loss was probably caused by the protein denaturation of enzymes and/or the formation of multimer and micelle of DCA molecules (Chen et al., 2019). The Hill equation (Supplemental **Table S1**) provides a better fit than the hyperbolic equation (Supplemental **Table S2**) for most kinetic plots within the concentration range from 1 to 300  $\mu$ M for DCA. The  $R^2$  coefficient for most fittings was  $>0.99$ , but lower than that for the none or less productive reactions.

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**Figure 5** illustrated the  $V_{\max}$ ,  $S_{50}$  and  $CL_{\text{int}}$  data obtained from the best curve fitting. Data were calculated predominately using the Hill equation, except that the results for 6 $\beta$ -oxidation in dogs, 3 $\beta$ -oxidation in mice, and 4 $\beta$ -oxidation in mice were calculated using the hyperbolic equation because the Hill-fitting was not applicable. The fitting threshold (300  $\mu\text{M}$ ) and critical micelle concentration (CMC, about 1500  $\mu\text{M}$ ) of DCA in the incubation media were marked on the  $S_{50}$  plot, indicating that all reactions may not achieve the maximum productivity due to the activity loss at substrate levels higher than 300  $\mu\text{M}$ . Anyway, the *in vitro*  $CL_{\text{int}}$  data represented the intrinsic hepatic metabolic clearance toward DCA under physiological levels. As shown in **Figure 5**, the total clearance of DCA decreased in turn in the liver microsomes of human, monkeys, rats, mice, dogs. In the liver microsomes of the test animals, C-3 $\beta$ , C-1 $\beta$  and C-7 $\beta$  are the major oxidation sites of DCA, while oxidations at the other sites have minor or minimum contribution to the total clearance. A trace activity toward the 19-oxidation of DCA, a human CYP3A7-specific reaction, was detected only in monkeys. The 7 $\beta$ -oxidation of DCA was a rat-specific reaction, which explained well why UCA was found with the highest level in the rat fecal sample. Murine animals showed none or only a trace activity toward the 1 $\beta$ -oxidation of DCA compared to human, monkeys and dogs, which was consistent with that DCA-1 $\beta$ -ol was not detected in rats and mice.

### *In vitro reactions responsible for the murine-specific downstream metabolism of CDCA*

It was recently discovered that rat CYP2C22 and mouse Cyp2c70 are responsible for the murine-specific 6 $\beta$ -oxidation from CDCA to  $\alpha\text{MCA}$  and UDCA to  $\beta\text{MCA}$  (Takahashi et al., 2016). Cyp2a12 was recently reported to be responsible for the 7 $\alpha$ -oxidation from TDCA to TCA and TLCA to TCDCA (Honda et al., 2020). Thus, the species difference of BA metabolism between murine and the others observed in our study may also indicate that CDCA metabolism appears to be superior to CA metabolism in murine animals. We therefore investigated the oxidation metabolism of the downstream metabolites of CDCA, including CDCA, UDCA, LCA, HDCA and MDCA (50  $\mu\text{M}$ ), in liver microsomes of murine animals in contrast to the other species. In this way, a series of murine-specific metabolic reactions were identified. As shown in **Figure 6**, these reactions revealed not only the known 6 $\beta$ -oxidation from CDCA to  $\alpha\text{MCA}$  and UDCA to  $\beta\text{MCA}$ , but also the 6 $\beta$ -oxidation from LCA to MDCA, the 7 $\alpha$ -oxidation from MDCA to  $\alpha\text{MCA}$ , and the rat-specific 7 $\beta$ -oxidation from MDCA to  $\beta\text{MCA}$  and HDCA to  $\beta\text{HCA}$ . These murine-specific oxidation activities were much higher than their activities toward DCA oxidations (**Figure 2**). The 7 $\alpha$ -oxidation from DCA to CA and LCA to CDCA was not detected, which is consistent with that conjugated BAs are much better substrates for Cyp2a12 than unconjugated BAs in mice (Honda et al., 2020).

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### Discussion

By using BA profiling technique in combination with the *in vitro* metabolism assays, this work has confirmed that tertiary oxidation of DCA is a conserved pathway in human, monkeys, dogs, rats and mice. The BA profiling data between SPF mice and germ-free mice has provided preliminary *in vivo* evidence that the host liver is responsible for the tertiary metabolism of DCA. Future works addressing dispositions of oral DCA in germ-free mice may provide direct evidences to identify how the host eliminates DCA without colonization of gut microbiota. Species differences in the oxidation regioselectivity of DCA were shown by the apparent oxidation kinetics of DCA in the pooled liver microsomes of animals. Most of the *in vitro* kinetic data was consistent with the BA profiling data, in which all conjugated forms (N-amidated forms, sulfated forms and glucuronidated forms) were detected as unconjugated forms by using the enzyme-digestion techniques in the present work. Some *in vitro* - *in vivo* data inconsistency may be associated with the N-acylamidation metabolism of BAs, which has been shown to have an impact on the activity and regioselectivity of DCA oxidation in human (Zhang et al., 2019). Deeper understanding of the species difference relies on development of the next-generation BA profiling techniques including not only N-amidated forms but also sulfated forms and glucuronidated forms of BAs.

Our previous work has demonstrated that renal clearance of the tertiary metabolites of DCA is significantly higher than that of DCA and CA, indicating that tertiary BA metabolism facilitates, at least in part, the renal excretion of DCA (Zhang et al., 2019). Similarly, 12-epiDCA, a epimerized microbial metabolite of DCA, was also inclined to be excreted in urine, where it was detected mainly as amidated forms (Zhu et al., 2018). In this work, a total of 9 downstream metabolites of DCA was detected in human urine and feces, including 3 microbial metabolites (isoDCA, 12-epiDCA and 12-oxoLCA) and 6 tertiary metabolites (3-dehydroDCA, DCA-6 $\beta$ -ol, DCA-5 $\beta$ -ol, DCA-6 $\alpha$ -ol, DCA-1 $\beta$ -ol, and DCA-4 $\beta$ -ol). Two microbial metabolites of DCA, 12-epiDCA and 12-oxoLCA, were detected in both urine and feces, while isoDCA was only found in feces. Consistent with our previous data, all these tertiary metabolites of DCA were detected in urine except for 3-dehydroDCA, which was detected with much higher level in feces than the other tertiary metabolites. Nevertheless, the microbial metabolites of DCA had higher levels than the tertiary metabolites in urine and particularly feces. Therefore, DCA appeared to be disposed mainly by microbial metabolism and fecal excretion and complementally by hepatic tertiary metabolism and renal excretion in human. As illustrated in **Figure 2**, the disposition pathways of DCA are relatively conserved

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in the tested animals, which might have explained why a slight decrease of TDCA was observed without significance in the liver and gallbladder of Cyp3a knock out (KO) mice compared to the wild-type littermate controls (Wahlstrom et al., 2017).

This work also has provided deeper understanding of how and why the species difference of BA metabolism between murine and the other animals occurs more in the downstream metabolism of CDCA than that of CA. As shown in **Figure 2**, CA metabolism prevails over CDCA metabolism in human and dogs while CDCA metabolism is significantly enhanced in murine animals, particularly in rats. The underlying mechanism is clearly shown by that the murine animals have strong 6 $\beta$ -hydroxylation activities toward the downstream metabolites of CDCA. In liver microsomes of all tested animals, the oxidation activities toward DCA (**Figure 3**) are far below the murine-specific oxidation activities toward CDCA, UDCA and LCA (**Figure 6**). Therefore, the 6 $\beta$ -oxidation of CDCA and UDCA constitute the major pathway to synthesis of  $\alpha$ MCA and  $\beta$ MCA. Moreover, murine animals also have a specific tertiary pathway for the 6 $\beta$ -oxidation from LCA to MDCA, and the 7 $\alpha$ - and 7 $\beta$ -oxidation from MDCA to  $\alpha$ MCA and  $\beta$ MCA, which furnish an alternative pathway to synthesis  $\alpha$ MCA and  $\beta$ MCA. In these ways, CDCA, UDCA and LCA in murine animals are almost completely transformed into the more polar 6 $\beta$ -hydroxylated BAs,  $\alpha$ MCA,  $\beta$ MCA and MDCA. In contrast, due to the lack of 6 $\beta$ -oxidation activities, human and dogs have evolved the BA metabolism patterns dominated by the downstream metabolism of CA and DCA.

However, the host-responsible *in vitro* reactions carried out in this work did not well explain the murine-specific synthesis of  $\beta$ HCA. Although rats liver microsomes were able to oxidize HDCA at C-7 $\beta$  into  $\beta$ HCA, both rats and mice had limited activities toward the 6 $\alpha$ -oxidation from LCA to HDCA. A recent study also found no significant differences of  $\beta$ HCA and T $\beta$ HCA in Cyp3a KO mice compared to the wild-type controls (Wahlstrom et al., 2017). Therefore, we deduced that tertiary metabolism of LCA contribute less to the production of HDCA and  $\beta$ HCA compared to the microbial modifications of  $\alpha$ MCA and  $\beta$ MCA (Eyssen et al., 1999). Our deduction was consistent with that from a recent study of BA metabolism in Cyp2a12 KO, Cyp2c70 KO, and Cyp2a12/Cyp2c70 double KO mice (Honda et al., 2020). Future studies are required to characterize the microbial 6-HSDHs that are potentially responsible for the 6-epimerization reactions between  $\beta$ MCA and  $\beta$ HCA in murine animals.

In conclusion, this work demonstrated that the tertiary oxidation of DCA is a conserved BA metabolism pathway in preclinical animals. The orthologous genes of human CYP3A are believed to be responsible for the tertiary oxidation of DCA in animals. In the tested animals, the majority of DCA synthesized by microbes in lower gut is disposed by microbial



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metabolism and undergoes fecal excretion, while the tertiary metabolism of DCA might have physiologically constituted a complementary disposition mechanism of DCA. The conclusion was consistent with that Cyp3a KO did not significantly alter the major BA composition in mice (Wahlstrom et al., 2017). Compared to human and dogs, murine animals favored the downstream metabolism of CDCA, mainly due to the presence of the strong hepatic 6 $\beta$ -oxidation activities towards CDCA, UDCA, LCA and 7-oxidation activities towards MDCA and HDCA, the 6-hydroxylated metabolites of LCA. The murine-specific 6 $\beta$ -hydroxylase was identified as CYP2C22 in rats and Cyp2c70 in mice (Takahashi et al., 2016). The mouse-specific 7 $\alpha$ -hydroxylase responsible for hydroxylating TDCA into TCA and TLCA into TCDCA was identified as Cyp2a12 (Honda et al., 2020). These P450s are believed to produce a murine-specific hydrophilic BA composition, which partly explains why murine animals are relatively resistant to hepatobiliary toxicities caused by accumulation of hydrophobic BAs. Cyp2c70 KO, Cyp2a12 KO, and Cyp2c70/Cyp2a12 double KO mice have been characterized to produce more human-like hydrophobic BA composition (de Boer et al., 2019; Honda et al., 2020). Although the tertiary BAs were not studied in these works, the expression and activity of Cyp3a11 was found to be complementarily induced in Cyp2c70/Cyp2a12 double KO mice via activation of pregnane X receptor and/or constitutive androstane receptor. Collectively based on these evidences, the genetic modified murine animal models that knock out murine-specific BA metabolizing P450 genes are believed to be promising interspecies scaling tools for future studies of BA associated signaling, metabolism, drug metabolism and toxicology.

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## Authorship Contributions

Participated in research design: Lan.

Conducted experiments: Lin, Tan, Wang, Zeng, Gui, Su, Lan.

Contributed metabolite synthesis: Xu.

Performed data analysis: Lan, Lin, Tan.

Wrote or contributed to the writing of the manuscript: Lan, Su, Jia, Liu, Lin, Tan.

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## **Footnotes**

\* Q.-H. L. and X.-W. T. contributed equally to this work.

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### Figure Legends

**Figure 1.** Metabolic scheme of the primary BAs to secondary BAs to tertiary BAs pathways. The abbreviated nomenclature of unconjugated bile acids follows Hofmann's proposal (Hofmann et al., 1992). The structures of conjugated forms and oxo- or keto- intermediates were not shown.

**Figure 2.** Quantitative profiles of the total unconjugated BAs in the pooled urine and fecal samples of human (n=6), dogs (n=6), rats (n=6), SPF mice (n=8) and germ-free mice (n=3). The unconjugated BAs were quantitatively determined by treating samples with cholylglycine hydrolase, sulfatase and  $\beta$ -glucuronidase as the method described previously. Data was shown as mean  $\pm$ SD for triplicate analysis of the pooled samples.

**Figure 3.** Time-dependent metabolite formation after incubation of DCA (50  $\mu$ M) in the liver microsomes (protein level 0.5 mg/mL) of human, monkeys, dogs, rats and mice. Data was shown as mean  $\pm$  SD (n=3).

**Figure 4.** Kinetic plots of DCA oxidations in the liver microsomes (protein level 0.5 mg/mL) of human, monkeys, dogs, rats and mice. The dotted extrapolations of Hill curves demonstrate a violation of enzyme kinetics at higher substrate levels (>300  $\mu$ M). Data was shown as mean  $\pm$  SD (n=3).

**Figure 5.** Apparent Hill parameters of DCA oxidation in the liver microsomes (protein level 0.5 mg/mL) of human, monkeys, dogs, rats and mice fitted with Hill equation (1-300  $\mu$ M).

**Figure 6.** Metabolite formation after incubation of LCA, CDCA, UDCA, HDCA and MDCA (50  $\mu$ M) in the liver microsomes (protein level 0.5 mg/mL) of human, monkeys, dogs, rats and mice for 60 min. Data was shown as mean  $\pm$  SD (n=3) in pmol/min/mg protein.

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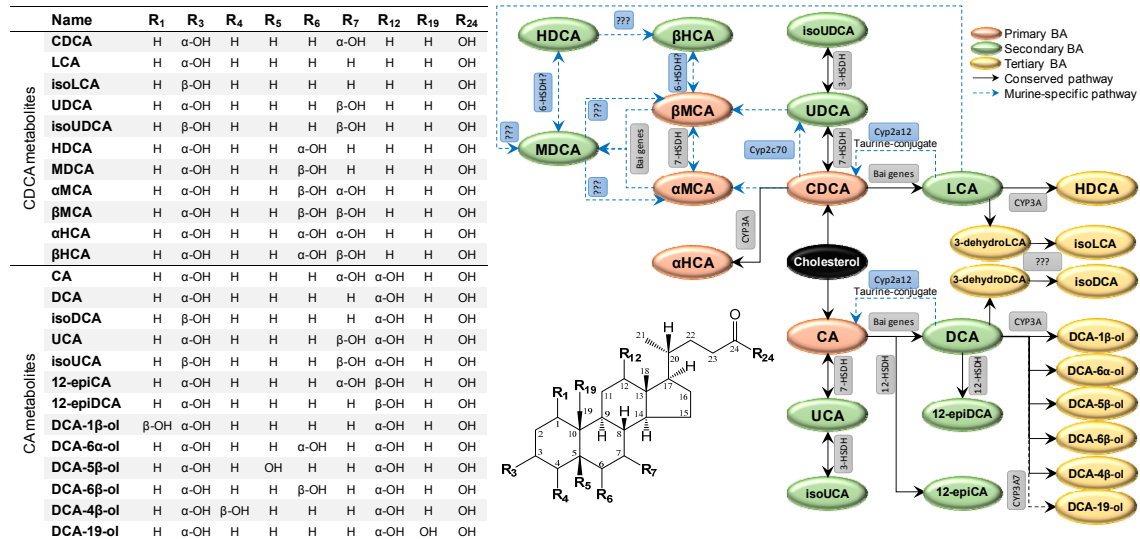


Figure 1

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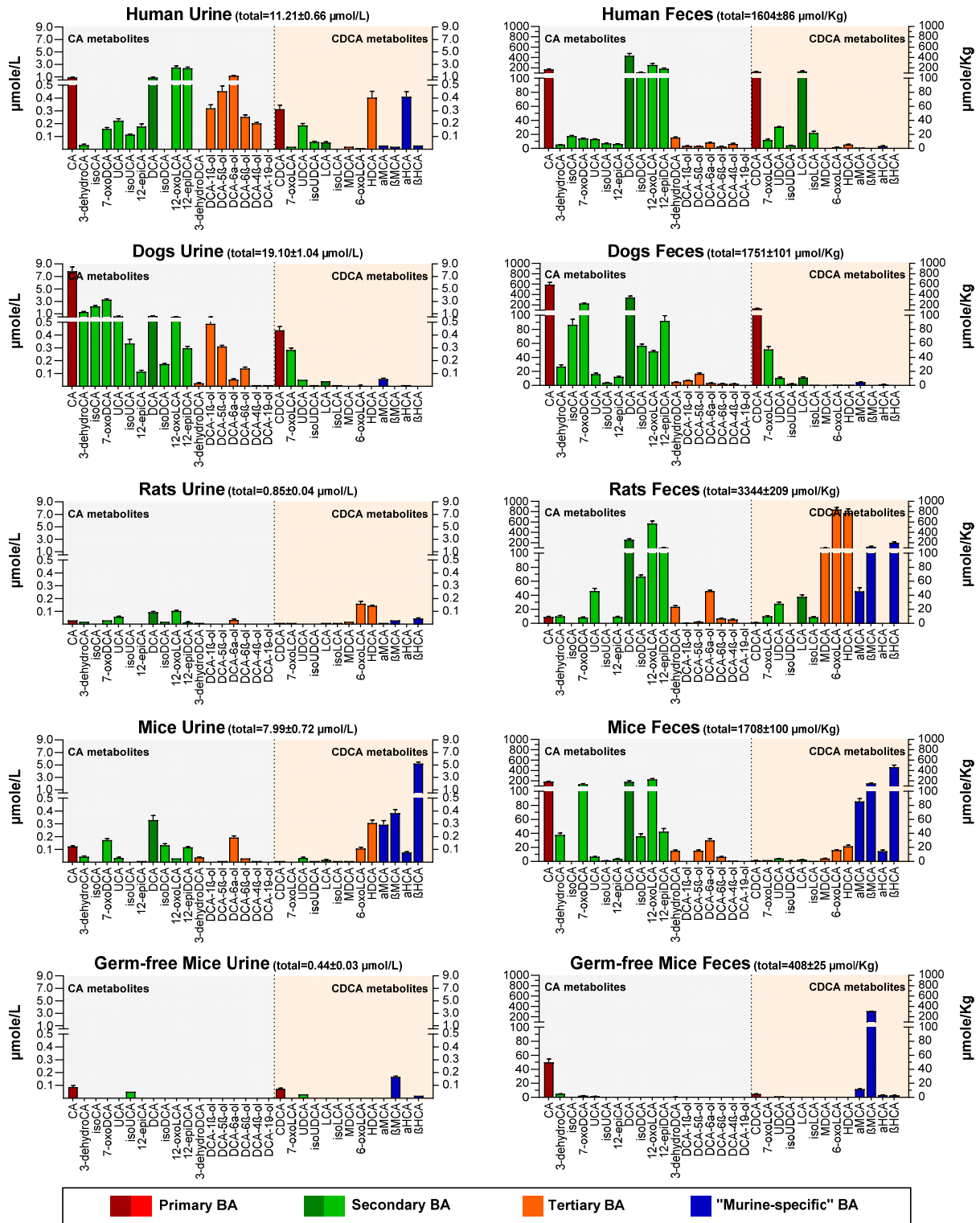


Figure 2



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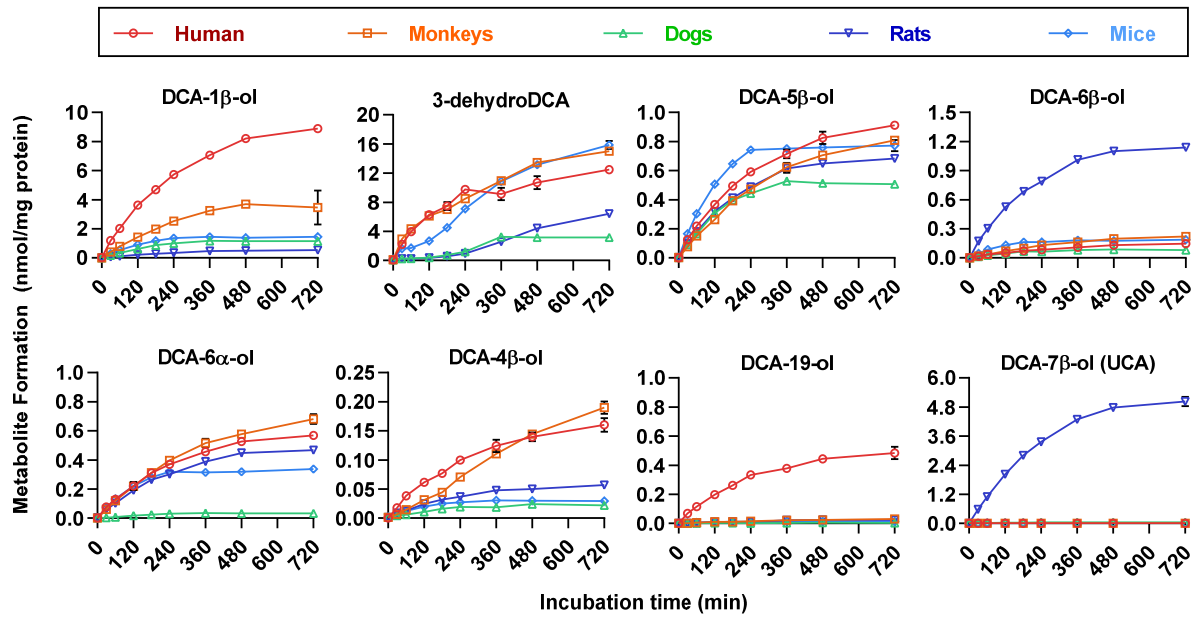


Figure 3

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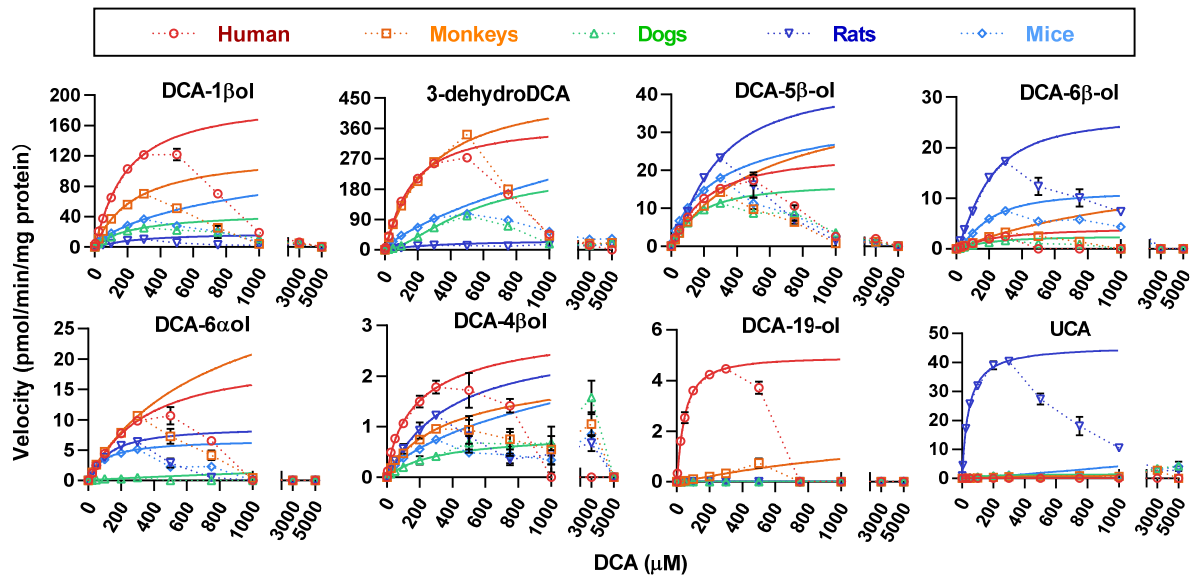


Figure 4

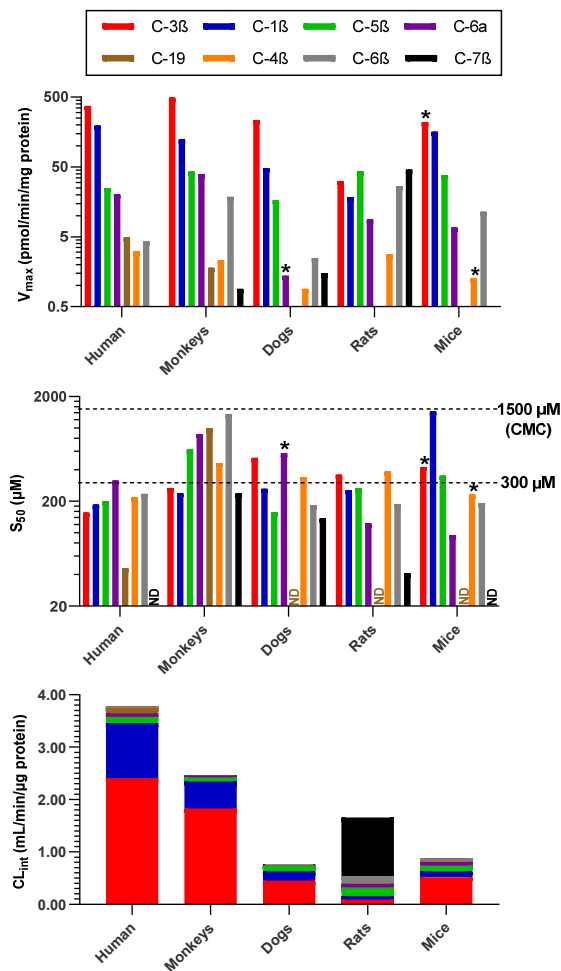


Figure 5

DMD # 090464

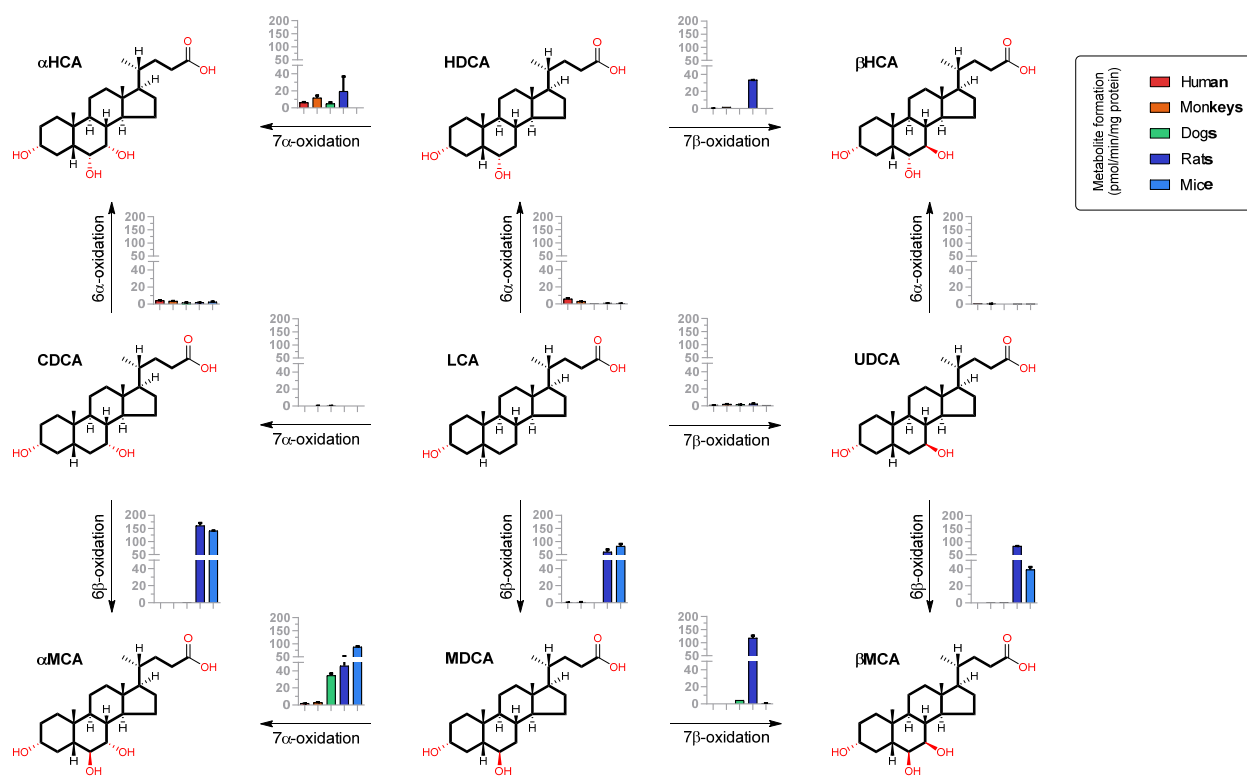


Figure 6

## Supplemental Material

### **Species Differences of Bile Acid Redox Metabolism: Tertiary Oxidation of Deoxycholate is Conserved in Preclinical Animals**

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**Table S1.** Hill kinetic parameters for DCA oxidations measured in the pooled liver microsomes within the 1-300  $\mu\text{M}$  substrate concentration range.

Parameters	Species	Oxidation site								Total
		C-3 $\beta$	C-1 $\beta$	C-5 $\beta$	C-6 $\alpha$	C-19	C-4 $\beta$	C-6 $\beta$	C-7 $\beta$	
<b><math>V_{max}</math></b> (pmol/min/ mg protein)	Human	374.9	195.1	24.9	20.3	4.9	3.1	4.3	ND	
	Monkeys	489.6	125.0	43.0	39.2	1.8	2.3	18.7	0.9	
	Dogs	234.0	47.8	16.8	NA	ND	0.9	2.5	1.5	
	Rats	31.5	18.5	43.4	8.9	ND	2.8	26.5	45.8	
	Mice	NA	160.0	38.3	6.8	ND	NA	11.4	NA	
<b><math>S_{50}</math></b> ( $\mu\text{M}$ )	Human	156	186	200	316	46	218	236	NA	
	Monkeys	268	240	625	877	993	463	1365	238	
	Dogs	520	264	157	NA	NA	342	184	138	
	Rats	360	256	266	123	NA	385	189	41	
	Mice	NA	1449	352	95	NA	NA	192	NA	
<b><math>CL_{int}</math></b> (mL/min/ $\mu\text{g}$ protein)	Human	2.41	1.05	0.12	0.06	0.11	0.01	0.02	NA	3.79
	Monkeys	1.83	0.52	0.07	0.04	0.00	0.00	0.01	0.00	2.49
	Dogs	0.45	0.18	0.11	NA	NA	0.00	0.01	0.01	0.77
	Rats	0.09	0.07	0.16	0.07	NA	0.01	0.14	1.12	1.66
	Mice	NA	0.11	0.11	0.07	NA	NA	0.06	NA	0.35
<b>Hill coefficient</b>	Human	1.14	1.08	1.13	1.08	1.22	0.80	1.17	NA	
	Monkeys	1.04	1.02	0.96	0.92	1.25	0.86	1.02	1.77	
	Dogs	1.67	0.93	1.16	0.79	NA	0.96	1.30	1.17	
	Rats	1.00	1.12	1.30	1.11	NA	1.02	1.39	1.04	
	Mice	NA	0.77	0.81	0.95	NA	0.69	1.48	1.14	
<b>Goodness of Fit (<math>R^2</math>)</b>	Human	0.9992	0.9992	0.9980	0.9977	0.9961	0.9884	0.9974	NA	
	Monkeys	0.9978	0.9986	0.9975	0.9982	0.9658	0.9910	0.9891	0.9820	
	Dogs	0.9968	0.9962	0.9969	0.7739	NA	0.9445	0.9954	0.9871	
	Rats	0.9936	0.9955	0.9982	0.9872	NA	0.9789	0.9973	0.9976	
	Mice	0.9959	0.9955	0.9818	0.9818	NA	0.9819	0.9959	0.9830	

NA, not applicable; ND, not detected

**Table S2.** Hyperbolic (Michaelis-Menten) kinetic parameters for DCA oxidations measured in the pooled liver microsomes within the 1-300  $\mu\text{M}$  substrate concentration range.

Parameters	Species	Oxidation site								
		C-3 $\beta$	C-1 $\beta$	C-5 $\beta$	C-6 $\alpha$	C-19	C-4 $\beta$	C-6 $\beta$	C-7 $\beta$	
$V_{max}$ (pmol/min/ mg protein)	Human	449.5	218.8	30.61	24.49	5.406	2.386	5.880	NA	
	Monkeys	528.2	130.3	37.52	28.40	NA	1.664	21.98	NA	
	Dogs	NA	42.41	20.68	1.390	NA	0.8167	4.109	1.836	
	Rats	31.35	23.73	97.44	9.880	NA	2.967	52.97	46.51	
	Mice	219.7	68.58	26.97	6.547	NA	1.284	29.83	NA	
$S_{50}$ ( $\mu\text{M}$ )	Human	224.5	234.3	298.2	442.3	56.15	111.6	418.1	NA	
	Monkeys	310.0	260.5	494.0	505.5	NA	231.3	1706	NA	
	Dogs	NA	203.7	236.5	575.5	NA	288.3	433.6	202.4	
	Rats	356.2	402.0	935.3	155.7	NA	431.5	599.6	42.50	
	Mice	425.0	271.3	157.5	85.61	NA	233.7	867.3	NA	
$CL_{int}$ (mL/min/ $\mu\text{g}$ protein)	Human	2.00	0.93	0.10	0.06	0.10	0.02	0.01	NA	3.23
	Monkeys	1.70	0.50	0.08	0.06	NA	0.01	0.01	NA	2.36
	Dogs	NA	0.21	0.09	0.00	NA	0.00	0.01	0.01	0.32
	Rats	0.09	0.06	0.10	0.06	NA	0.01	0.09	1.09	1.50
	Mice	0.52	0.25	0.17	0.08	NA	0.01	0.03	NA	1.06
<b>Goodness of Fit (<math>R^2</math>)</b>	Human	0.9986	0.9989	0.9975	0.9975	0.9940	0.9861	0.9966	NA	
	Monkeys	0.9977	0.9986	0.9974	0.9980	NA	0.9901	0.9891	NA	
	Dogs	NA	0.9959	0.9961	0.7703	NA	0.9445	0.9930	0.9860	
	Rats	0.9936	0.9950	0.9960	0.9867	NA	0.9789	0.9935	0.9975	
	Mice	0.9941	0.9932	0.9939	0.9816	NA	0.9771	0.9909	NA	