

# The Human UGT2B7 Nanodisc

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## ABSTRACT

The 20 uridine diphosphate glycosyl-transferases (UGTs) encoded in the human genome form an essential homeostatic network of overlapping catalytic functions that surveil and regulate the activity and clearance of scores of small molecule metabolites. Biochemical and biophysical UGT studies have been hampered by the inability to purify these membrane-bound proteins. Here, using cell-free expression and nanodisc technology, we assemble and purify to homogeneity the first UGT nanodisc—the human UGT2B7•nanodisc. The complex is readily isolated in milligram quantities. It is stable and its initial-rate parameters are identical within error to those associated with UGT2B7 in microsomal preparations (i.e., Supersomes). The high purity of the nanodisc preparation simplifies UGT assays, which allows complexities traditionally associated with microsomal assays (latency and the albumin effect) to be circumvented. Each

nanodisc is shown to harbor a single UGT2B7 monomer. The methods described herein should be widely applicable to UGTs, and these findings are expected to set the stage for experimentalists to more freely explore the structure, function, and biology of this important area of phase II metabolism.

## SIGNIFICANCE STATEMENT

Lack of access to pure, catalytically competent human uridine diphosphate glucuronosyl-transferases (UGTs) has long been an impediment to biochemical and biophysical studies of this disease-relevant enzyme family. Here, we demonstrate this barrier can be removed using nanodisc technology—a human UGT2B7•nanodisc is assembled, purified to homogeneity, and shown to have activity comparable to microsomal UGT2B7.

## Introduction

Collectively, the 20 uridine diphosphate glucuronosyl-transferase (UGT) isoforms encoded in the human genome regulate the activity, solubility, transport, and clearance of scores of xenobiotics and endogenous metabolites. In so doing, they defend against the toxicities of environmental chemicals and maintain the homeostatic balance of numerous metabolic processes. UGTs regulate the receptor binding and terminal half-lives of steroids (Hum et al., 1999; Sten et al., 2009), thyroid hormones (Visser et al., 1993; Richardson and Klaassen, 2010), and neurotransmitters (Antonio et al., 2003); they limit volatility and hence “shape” olfaction (Lazard et al., 1991; Jedlitschky et al., 1999; Sneitz et al., 2009); glucuronidation potently activates morphine and controls its blood-brain-barrier transport (Pasternak et al., 1987; Francés et al., 1990; Osborne et al., 1990; Wu et al., 1997; Zelcer et al., 2005); finally, coincident upregulation of UGTs and multiple-drug-resistance transporters confers chemo-resistance in cancer cells (Bock et al., 2000; Meijerman et al., 2008; Tolson and Wang, 2010). Despite their importance, the fundamental structure/function information needed to predict, interpret, and control the molecular behavior of UGTs is largely absent from the field due primarily to the challenges associated with purifying these membrane-bound enzymes.

The catalytic domains of UGTs are tethered to the luminal side of the smooth endoplasmic reticulum by a single-pass, C-terminal trans-membrane helix and cannot be separated from the membrane without significant loss of activity (Mackenzie, 1987; Meech and Mackenzie, 1997, 1998; Kurkela et al., 2003). Consequently, *in vitro* UGT experiments are typically performed using microsomes (membraneous preparations isolated from cells by differential centrifugation) and hepatocytes. Although such systems have led to extensive insights into UGT selectivity, tissue expression, and metabolism (Rowland et al., 2013; Oda et al., 2015; Lv et al., 2019; Meech et al., 2019), they do not provide opportunity to study the pure enzyme. Nanodiscs are widely used in the purification of membrane-bound proteins. These lipid discs are ringed by amphipathic membrane scaffolding proteins (MSPs), and their dimensions (10–16 nm) are well suited to incorporating single- and multiple-pass membrane proteins (Civjan et al., 2003; Denisov et al., 2004). Here, using cell-free expression techniques, we assemble, purify, and characterize a nanodisc that harbors the human UGT2B7—the isoform that glucuronidates numerous endogenous steroids (Cheng et al., 1998; Coffman et al., 1998; Girard et al., 2003) and plays pivotal roles in morphine activation (Stone et al., 2003) and the inactivation of AZT (Barbier et al., 2000). We anticipate that the cell-free nanodisc technology will be applicable to numerous UGT isoforms and will provide experimentalists with ready access to a wide variety of pure, active UGTs nanodiscs.

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**ABBREVIATIONS:** AZT, azidothymidine; GSH, glutathione; HIS, histidine; HPLC, High Pressure Liquid Chromatography; KCl, potassium chloride; KOH, potassium hydroxide; LiCl, lithium chloride; MBP, maltose binding protein; NTP, ribonucleoside triphosphate; 4-MU, 4-methylumbelliferone; BSA, bovine serum albumin; DTT, dithiothreitol; GST, glutathione S-transferase; MSP, membrane scaffold protein; MWCO, molecular weight cut off; PMSF, phenylmethylsulfonyl fluoride; POPC, 1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine; SULT, sulfotransferase; TCE, 2,2,2-trichloroethanol; UDPGA, uridine diphosphate glucuronic acid; UGT, uridine diphosphate glucuronosyl-transferase.

## Materials and Methods

The materials and sources used in this study are as follows: Dithiothreitol (DTT), EDTA, formic acid, L-glutathione (reduced), imidazole, isopropyl-thio- $\beta$ -D-galactopyranoside, lysozyme broth (LB), lysozyme, morphine, morphine-3- $\beta$ -D-glucuronide, morphine-6- $\beta$ -D-glucuronide, pepstatin A, polyvinyl sulfonic acid, potassium phosphate, tetrabutylammonium hydrogen sulfate, 2,2,2-trichloroethanol (TCE), and uridine diphosphate glucuronic acid (UDPGA) were the highest grade available from Sigma. Ampicillin, acetonitrile, BSA, HEPES, potassium acetate, KCl, KOH, LiCl, magnesium acetate,  $MgCl_2$ , NaCl, NaAc,  $NAD^+$ , NADH, phenylmethylsulfonyl fluoride (PMSF), saccharolactone, sodium cholate, TRIS, Tube-O-Dialyzer (MWCO 2000 Da), uranyl formate, and Whatman filter paper were purchased from Fisher Scientific. Creatine phosphate was purchased from Tokyo Chemical Industry Co., Ltd. Supersomes (microsomes isolated from sf9 insect cells expressing UGT2B7) were purchased from Corning. Hexokinase (yeast) was purchased from Roche Applied Science. Human SULT1E1, SULT2A1, PreScission Protease and GST4A were synthesized as described previously (Zhang et al., 1998; Cook et al., 2019). TnT T7 Insect Cell Extract Protein Expression System was purchased from Promega. Gibson Assembly kit, T7 RNA polymerase, and rNTPs were purchased from New England Biolabs. 4-methylumbelliferone (4-MU), and palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine (POPC) were purchased from Santa Cruz Biotechnology. Glutathione- and nickel-chelating resins, and Superdex 200 Increase 10/300 GL columns were obtained from GE Life Sciences. The PEPP column (Ultra PEPP 150  $\times$  4.6 mm, 3  $\mu$ m) was obtained from Restek. Cardiolipins were purchased from Avanti Polar Lipids. Electron microscopy grids were purchased from Electron Microscope Sciences. Competent *Escherichia coli* [BL21(DE3)] was purchased from Novagen. MidiPrep DNA Extraction Kits were purchased from Qiagen. XL1 Blue competent cells and XL-10 Gold ultracompetent cells were obtained from Agilent. Gibson Assembly Kits and DpnI were purchased from New England Biolabs. The UGT2B7 coding region described in *Construction of Expression Vectors* was purchased from transOMIC Technologies Inc. MSP1D1 in the p28a vector (Hagn et al., 2013) was purchased from Addgene.

## Construction of Expression Vectors

**UGT2B7.** The open reading frame of mature UGT2B7 [residues 25–525 (Meech and Mackenzie, 1998; Ouzzine et al., 1999)] was inserted into the Nde I site of pSKB4 (Andreassi and Leyh, 2004), which attaches a PreScission-Protease cleavable, HIS/GST-tag to the N terminus of the UGT coding region. Using Gibson assembly (Gibson et al., 2009), the HIS/GST-fusion protein sequence was inserted into the insect expression vector, pF25A (Ezure et al., 2006). Plasmid was purified [MidiPrep DNA Extraction Kit (Qiagen)] from BL21 *E. coli* grown in LB medium (Ezure et al., 2006). To prevent toxicity in *E. coli*, UGT2B7 expression was suppressed with glucose (2.0%) (Zhang et al., 2003).

**MSP1D1.** The MSP1D1 coding region in p28a was purchased from Addgene. Using Gibson assembly (Gibson et al., 2009), the coding region was transferred from p28a to pGEX-6P (Cook et al., 2017, 2019), which attaches a PreScission-Protease cleavable, MBP/GST/HIS-tag to the MSP1D1 amino terminus.

**RNA Synthesis with T-7 RNA Polymerase.** RNA was synthesized by adding 10  $\mu$ g of UGT2B7-pU25 to a 200  $\mu$ l (final volume) reaction mixture containing 2.0 U of T7 RNA polymerase, 4.0 mM of each rNTP, polyvinyl sulfonic acid (10  $\mu$ g/ml),  $MgCl_2$  (20 mM), and the T7 NEB buffer reaction mix. Reactions were incubated for 4 hours at 37°C. RNA was precipitated by addition of 20  $\mu$ l of NaAc (3.0 M) followed by 200  $\mu$ l of isopropanol (4°C). The sample was incubated overnight at –20°C. The RNA was then pelleted at 15,000g for

1.0 hour. The supernatant was decanted, and the pellet was washed with 200  $\mu$ l of 70% ethanol (ambient temperature) and spun at 15,000g for 15 min. Ethanol was removed and the pellet was air-dried for 5 min on ice before resuspension in 30  $\mu$ l of RNase free water. RNA degradation was assessed using agarose gels. RNA was quantitated at 260 nm, and the 260/280 ratio was used to estimate its purity.

**MSP1D1 Expression and Purification.** *E. coli* [BL21(DE3)] containing MSP1D1 expression vector were grown at 37°C in LB medium (Cook et al., 2017). At  $OD_{600} \sim 0.6$ , the culture was cooled in an ice/water bath. Upon reaching 17°C, isopropyl-thio- $\beta$ -D-galactopyranoside was added (0.30 mM final) and the culture was incubated at 17°C for 16 hours. Cells were then pelleted and resuspended in lysis buffer [PMSF (290  $\mu$ M), pepstatin A (1.5  $\mu$ M), lysozyme (0.10 mg/ml), EDTA (2.0 mM), KCl (400 mM),  $K_2PO_4$  (50 mM), pH 7.5]. The suspension was sonicated and then centrifuged (10,000g, 1.0 hour, 4°C).  $MgCl_2$  (5.0 mM) was added to chelate EDTA before passing the solution through a Chelating Sepharose Fast Flow column charged with  $Ni^{2+}$ . The column was washed [imidazole (10 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5], enzyme was eluted [imidazole (250 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5] and loaded directly onto a Glutathione Sepharose column. The GST column was washed [DTT (2.0 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5] before eluting the tagged enzyme [reduced glutathione (10 mM), DTT (2.0 mM), KCl (400 mM), and Tris (100 mM), pH 8.0]. The fusion protein was digested overnight at 4°C using PreScission Protease and passed through a GST column to remove the tag and excess protease. A dipeptide (GlyGln-) remains at the N terminus of the protein following cleavage. The protein was  $\geq 95\%$  pure as judged by SDS-PAGE, and its concentration was determined by UV absorbance [ $\epsilon_{280} = 18.2 \text{ mM}^{-1} \text{ cm}^{-1}$  (Civjan et al., 2003; Denisov et al., 2004)]. The protein was then concentrated, flash frozen, and stored at –80°C.

**Expression and Purification of UGT2B7•Nanodiscs.** UGT2B7 was expressed using the TnT T7 Insect Cell Extract Protein Expression System (Promega). The extract was supplemented with POPC (6.0 mM), sodium cholate (12 mM), and purified MSP1D1 (100  $\mu$ M). Expression was initiated by addition of UGT2B7 mRNA (~500  $\mu$ g) to a final volume of 1.0 ml in a Tube-O-Dialyzer, MWCO 2000 kDa. The reaction was dialyzed against 20 ml of HEPES (40 mM), potassium acetate (100 mM), magnesium acetate (2.0 mM), cardiolipins (6.0 mM), sodium cholate (12 mM), ATP (0.50 mM), GTP (0.25 mM), creatine phosphate (20 mM), 20 amino acids (100  $\mu$ M each), DTT (2.0 mM), EDTA (0.25 mM), and PMSF (0.50 mM), pH 7.9. The reaction was run at 15°C. Dialysis buffer was replaced every 48 h. Expression was monitored using SDS-PAGE and the reaction reached completion after 4 days.

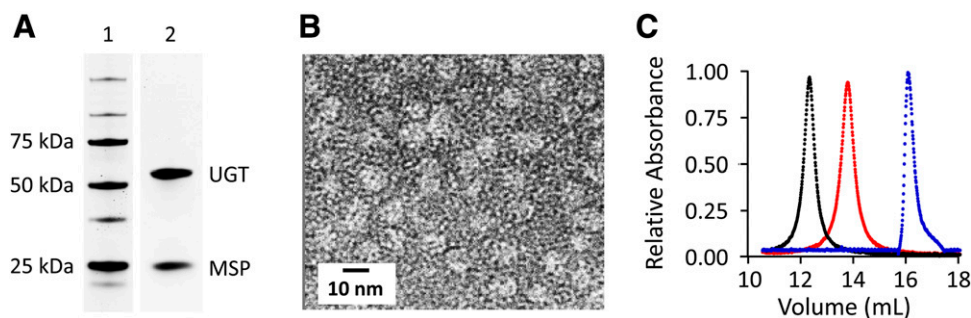
Unless specified otherwise, buffers were equilibrated and manipulations were performed at 4°C. Following UGT expression, the extract was dialyzed three times over 24 h against 1.0 l of HEPES (40 mM), KCl (100 mM), pH 7.9. Extract was then centrifuged (15,000g, 10.0 minute) and the supernatant was incubated in a spin cup for 8 h with 100  $\mu$ l of Chelating Sepharose Fast Flow resin charged with  $Ni^{2+}$  and equilibrated in dialysis buffer (Radchenko et al., 2010). The cup was then spun (100g, 1.0 minute) and the resin was suspended and spun three times in 300  $\mu$ l of His wash buffer [HEPES (40 mM), imidazole (25 mM), KCl (100 mM), pH 7.9]. UGT2B7 nanodiscs were then eluted with His elution buffer [imidazole (250 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5]. Nanodiscs were then incubated for 4 h with 50  $\mu$ l of Glutathione Sepharose resin equilibrated with GSH wash buffer [DTT (2.0 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5]. The resin was then spun (100g, 1.0 minute) and washed and spun three times with 100  $\mu$ l of GSH wash buffer. Nanodiscs were eluted using 100  $\mu$ l GSH elution buffer [reduced glutathione (10 mM), DTT (2.0 mM), KCl (400 mM), and  $KPO_4$  (50 mM), pH 7.5]. The purified fusion protein was then digested during overnight dialysis using PreScission Protease (0.4  $\mu$ M). A GlnGly-dipeptide remains at the N terminus of the coding region following cleavage. Dialysis was repeated three times against 1.0 l of phosphate buffer [ $KPO_4$  40 mM, KCl (100 mM), pH 7.5]. PreScission Protease and the fusion tag were removed by passing the proteolyzate over ~100  $\mu$ l of GST resin equilibrated with phosphate buffer. Finally, to remove aggregates and nanodisc stacks, the solution was passed through a size exclusion column (Superdex 200 Increase 10/300) equilibrated at ambient temperature in phosphate buffer. UGT2B7 was quantitated by comparing its fluorescence to that of purified standards (MSP1D1, SULT2A1, SULT1E1, Hexokinase, and GST4A) in TCE-treated SDS-PAGE gels (Chopra et al., 2019). The purity of the final UGT2B7 preparation was estimated, using SDS PAGE, at ~95%. The protocol yielded 1.2 mg of UGT2B7 per ml of cell-free extract. The purified UGT2B7 nanodiscs were flash frozen in liquid nitrogen and stored in

TABLE 1

Nanodisc and microsomal UGT2B7 initial-rate parameters

Substrate	$K_m$ ( $\mu$ M)	$k_{cat}$ ( $s^{-1}$ )	$K_i$ ( $\mu$ M)	$k_{cat}^{inh}$ ( $s^{-1}$ )
Nanodisc				
UDPGA	260 (17) <sup>d</sup>	2.2 (0.2)	—	—
4-MU	170 (15)	2.2 (0.3)	1100 (30)	0.96 (0.05)
Microsome				
UDPGA	300 (23) <sup>d</sup>	1.8 (0.2)		
4-MU	200 (12)	1.9 (0.2)		

<sup>d</sup>Parentheses enclose one S.D. unit.



**Fig. 1.** Purity and homogeneity of the UGT2B7•nanodisc. (A) SDS-PAGE analysis. Lane 1, molecular weight standards; lane 2, purified UGT2B7•nanodiscs (1.0  $\mu$ g). Proteins were visualized via protein fluorescence in TCE-infused gels (see *Results and Discussion*). (B) Negative stain, EM image of the purified UGT2B7•nanodisc (original magnification, 50,000 $\times$ ). (C) Size-exclusion chromatography. Each color-coded peak represents the chromatographic profile of a purified component: UGT2B7•nanodisc (0.14 mg, black), empty nanodisc (0.11 mg, red), and free MSP1D1 (0.11 mg, blue). Protein was monitored at 280 nm, and the peaks were normalized to the highest measured absorbance.

aliquots at  $-80^{\circ}\text{C}$ . The samples showed no loss of activity over 6 months at  $-80^{\circ}\text{C}$ , they are stable for more than 3 days at  $4^{\circ}\text{C}$ , and their activity begins to deteriorate after three freeze/thaw cycles.

**Negative Staining.** Four microliters of purified UGT•nanodiscs (0.55 mg/ml) was layered onto carbon-coated 400-mesh electron-microscope grids. Excess liquid was removed from the grids by blotting from the side with Whatman paper #1. The grids were then washed two times with distilled water, stained twice with 1% uranyl formate solution, and UV-irradiated for 5.0 minute before imaging using a TVIPS F416 camera at 50,000 $\times$  magnification (Tan et al., 2006).

**4-MU Binding to BSA.** The binding of 4-MU was monitored via ligand-induced decrease in the intrinsic fluorescence of BSA ( $\lambda_{\text{ex}} = 285 \text{ nm}$ ,  $\lambda_{\text{em}} = 330 \text{ nm}$ ). BSA fluorescence decreased 33% at saturation. 4-MU (10  $\mu\text{M}$  to 10 mM) was titrated into a solution containing BSA (1.0%),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^{\circ}\text{C}$ . Titrations were performed in duplicate. Data were averaged and least-squares fit using the quadratic equation to a model that assumes a single binding site per subunit.  $K_d$  for 4-MU, BSA interaction was  $380 \pm 21 \mu\text{M}$ .

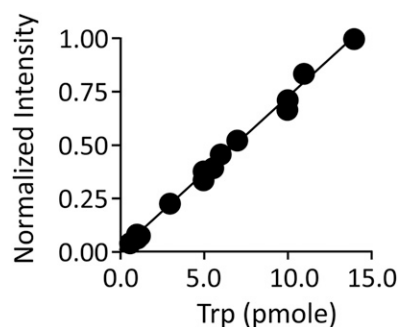
**Initial-Rate Studies.** Reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ) (Uchaipichat et al., 2004). Rate measurements were performed at a fixed-saturating concentration of one substrate and varied the other from 0.20  $K_m$  to 5.0  $K_m$  in equal increments in double-reciprocal space. For experiments involving BSA, the total 4-MU concentration required to achieve the intended free 4-MU concentration was calculated using the  $K_d$  for 4-MU binding to BSA. At  $[4\text{-MU}]_{\text{free}}$  ranging from 0.20 to 5.0  $\times K_m$ , BSA-bound 4-MU ranged from 5% to 17% of the total 4-MU added. Supersome studies involved incubating fresh Supersomes (5.0 mg/ml) with alamethicin (25  $\mu\text{M}$ ) and saccharolactone (5.0 mM) for 60 min in an ice-water bath ( $\sim 0^{\circ}\text{C}$ ) prior to reaction. Reaction conditions were as follows: UGT2B7 (100 nM, active site) or UGT2B7 supersomes (50  $\mu\text{g}$ ), BSA (0 or 1.0% wt/vol), alamethicin (25 nM, Supersomes only), saccharolactone

(5.0  $\mu\text{M}$ , Supersomes only),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^{\circ}\text{C}$ . The fixed-saturating concentrations of UDPGA and 4-MU were 5.0 mM ( $21 \times K_m$ ) and 3.5 mM ( $20 \times K_m$ ), respectively. Reactions were initiated by adding UDPGA to a final volume of 500  $\mu\text{l}$ , and reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ). In all cases, less than 5% of the concentration-limiting substrate consumed at the reaction end point was converted to product during the measurement. Initial-rate constants were estimated using a weighted-least-squares fit to a simple Michaelis-Menten model using *sequeno* (Cleland, 1979).

**Partial Substrate Inhibition.** 4-MU partial-substrate inhibition was evaluated under the following conditions: UGT2B7 (100 nM, active site), 4-MU (0.16–11 mM,  $0.15\text{--}10 \times K_i$ ), UDPGA (5.0 mM,  $21 \times K_m$ ),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^{\circ}\text{C}$ . Reaction progress was monitored via the decrease of fluorescence associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ). Initial-rate kinetic parameters were obtained by least-squares fitting to an uncompetitive, partial-inhibition model (Yoshino and Murakami, 2015; Wang et al., 2016) using *solver* (Excel 2007, Microsoft). Fitting was initiated using initial-rate parameters obtained from *Initial-Rate Studies* ( $k_{\text{cat}}$ ,  $K_m$ ) and graphical analysis of the data ( $k_{\text{cat, inh}}$ ,  $K_i$ ). The parameters are reported in Table 1.

**Albumin-Effect Assays.** UGT2B7 Supersomes were incubated prior to reaction with alamethicin and saccharolactone as described above (see *Initial-Rate Studies*). Reaction conditions were as follows: UGT2B7 [nanodisc (50 nM), or microsomes (25  $\mu\text{g}$ )], BSA (0 or 1.0%), 4-MU (20  $\mu\text{M}$ ,  $0.12 \times K_m$ ), UDPGA (5.0 mM,  $21 \times K_m$ ), alamethicin (12.5 nM, Supersomes only), saccharolactone (2.5  $\mu\text{M}$ , Supersomes only),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  buffer (50 mM), pH 7.5,  $25^{\circ}\text{C}$ . Reactions were initiated by addition of UDPGA to a final volume of 500  $\mu\text{l}$ . Reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ).

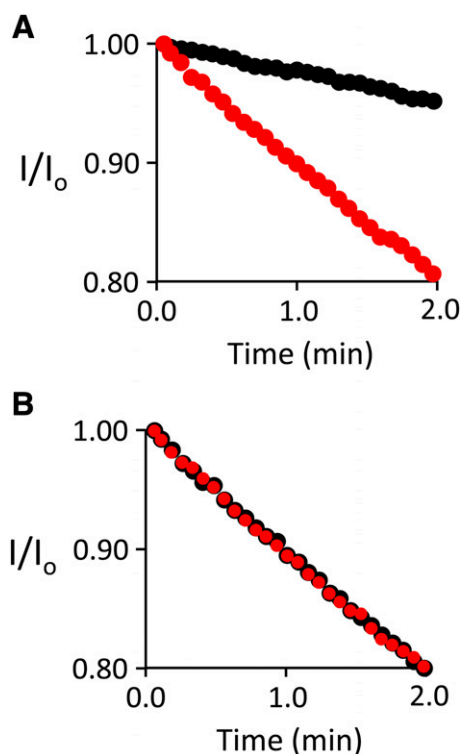
**Rate Studies Using Morphine.** Reaction conditions were as follows: UGT2B7 nanodisc (100 nM, UGT active site) or UGT2B7 Supersomes (100  $\mu\text{g ml}^{-1}$ ), morphine (100  $\mu\text{M}$ ), UDPGA (5.0 mM,  $21 \times K_m$ ), BSA (1.0% wt/vol, Supersomes only), alamethicin (25 nM, Supersomes only), saccharolactone (5.0  $\mu\text{M}$ , Supersomes only),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^{\circ}\text{C}$ . Reactions were initiated by addition of UDPGA. To ensure initial rates were measured, less than 5% of the morphine consumed at the end point of the reaction was formed during the measurement. Reactions were quenched by addition of 1.0 N NaOH (final concentration, 0.10 N) and neutralized 5 min later by addition of 1.0 N HCl. Eppendorf tubes containing 100  $\mu\text{l}$  reaction aliquots were placed in a boiling water bath (5 min) and then spun at 15,000g (5 min). The supernatant was diluted (1/20 v/v) in water/formic acid (0.10% v/v), loaded onto an Ultra PEPP HPLC column, and reactants were separated using an acetonitrile gradient (Suominen et al., 2013). Supersomes (5.0 mg/ml) were incubated with alamethicin (25  $\mu\text{M}$ ) and saccharolactone (5.0 mM) for 60 min in an ice-water bath ( $\sim 0^{\circ}\text{C}$ ) prior to reaction.



**Fig. 2.** Standard curve to determine UGT2B7:nanodisc stoichiometry. The normalized fluorescent intensity of protein-standard bands in TCE-infused SDS-PAGE gels is plotted vs. picomole of Trp calculated from known amino acid compositions and extinction coefficients. Intensities are normalized relative to the maximum measured intensity. The standard curve was constructed using five purified proteins [MSP1D1 (synthetic), SULT2A1 (human), SULT1E1 (human), hexokinase (yeast), and GST4A (human)], each of which was loaded at three different concentrations. Fluorescence intensity ( $\lambda_{\text{ex}} = 310 \text{ nm}$ ,  $\lambda_{\text{em}} \geq 500 \text{ nm}$ ) was quantitated using Image Laboratory Software.

## Results and Discussion

**Assembly and Purification of UGT2B7•MSP1D1 Nanodiscs.** An expression plasmid that attaches a PreScission-Protease removable, HIS/GST-dual tag to the N terminus of the mature form of UGT2B7 [which lacks 25 N-terminal amino acids (Meech and Mackenzie, 1998)] was



**Fig. 3.** Albumin effects on nanodisc and microsomal UGT2B7 turnover. (A) Microsomal UGT2B7. Supersomes (5.0 mg/ml) were incubated with alamethicin (25  $\mu$ M) and saccharolactone (5.0 mM) for 60 min in an ice-water bath ( $\sim 0^{\circ}\text{C}$ ) prior to reaction. Reaction conditions: Supersomes (25  $\mu$ g protein), BSA (0, black dots, or 1.0% wt/vol, red dots), 4-MU (20  $\mu$ M,  $0.12 \times K_m$ ), alamethicin (12.5 nM), saccharolactone (2.5  $\mu$ M), UDPGA (5.0 mM,  $20 \times K_m$ ),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  buffer (50 mM), pH 7.5,  $25^{\circ}\text{C}$ . Reactions were initiated by adding UDPGA to a final volume of 500  $\mu$ l, and reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370$  nm,  $\lambda_{\text{em}} = 451$  nm). (B) The UGT2B7•nanodisc. Assays were identical to (A) except that Supersomes were replaced with the UGT2B7•nanodisc (50 nM), and alamethicin and saccharolactone were absent.

constructed (see *Materials and Methods*) and used to test expression of the fusion protein in extracts from *E. coli*, *Saccharomyces cerevisiae*, wheat germ, and sf9 insect cells. Consistent with the UGT codon bias, expression is significantly (15–20-fold) greater in the insect cell extract. Expression is enhanced by continuous dialysis of the extract against buffer containing protein synthesis reagents (see *Materials and Methods*). Assembly of nanodiscs was accomplished by adding pure MSP (MSP1D1), phospholipids (POPC and cardiolipin), and bile acid (sodium cholate) to the insect extract. Nanodiscs form spontaneously and incorporate UGT2B7 as cholate is removed by dialysis (Civjan et al., 2003).

UGT2B7•nanodiscs were purified successively over His- and GST-affinity resins. Empty nanodiscs lack affinity tags and are thus not expected to bind these resins significantly. However, the empty discs can form aggregates, or “stacks,” with UGT2B7•nanodiscs (B Kumar et al., 2017). Stacks comprised  $\sim 10\%$  of the affinity purified UGT2B7•nanodiscs and were removed using size exclusion chromatography. SDS-PAGE analysis of the size exclusion chromatography-purified UGT2B7•nanodiscs (Fig. 1A) reveals that the preparation contains highly purified UGT2B7 and MSP1D1. Negative-staining electron microscopy of the nanodisc preparations (Fig. 1B) shows fields of discoidal structures whose dimensions ( $\sim 10$  nm) are consistent with those expected for MSP1D1 nanodiscs (Civjan et al., 2003; B Kumar et al., 2017). The homogeneity of the UGT2B7•nanodisc preparation was further assessed using size-exclusion chromatography. Chromatograms of

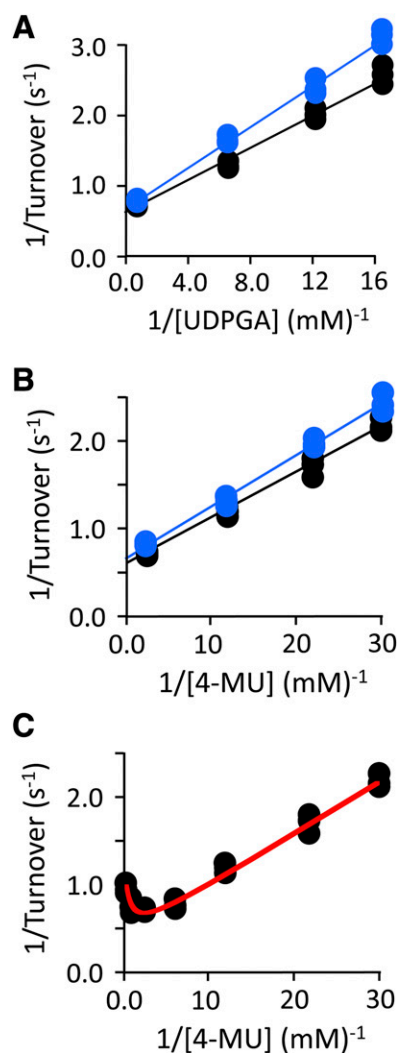
purified UGT2B7•nanodiscs (black), empty nanodiscs (red), and MSP1D1 protein (blue) are superposed in Fig. 1C. The UGT2B7•nanodisc peak is highly symmetric, suggesting a homogeneous preparation, and is well isolated from contaminants that would be transparent to the SDS-PAGE and negative staining methods.

**UGT2B7 Oligomerization.** The oligomerization status of UGTs remains an open question. Although most studies support that microsomal UGTs are dimeric (Meech and Mackenzie, 1997; Yuan et al., 2015), others suggest monomers (Peters et al., 1984; Vessey and Kempner, 1989). Given that nanodiscs harbor two MSPs (Civjan et al., 2003; B Kumar et al., 2017), the number of 2B7 molecules per nanodisc can be calculated from the 2B7:MSP ratio in pure, homogeneous complexes. The 2B7-to-MSP stoichiometry was obtained from the relative fluorescent intensities of the 2B7 and MSP protein bands in UV-exposed, SDS-PAGE gels infused with TCE. TCE undergoes UV-induced reactions with Trp and Tyr residues (Casas-Finet et al., 1992; Ladner et al., 2006) that allow them to be distinguished based on their fluorescence emission spectra (Chopra et al., 2019). The TCE reactions are covalent, highly efficient (Casas-Finet et al., 1992), and have been used to quantitate proteins in SDS-PAGE gels based on their Trp composition and fluorescent intensity relative to standards (Casas-Finet et al., 1992; Chopra et al., 2019).

To assess the linearity and precision of the TCE method, a standard curve was constructed (Fig. 2) using five highly purified proteins with gravimetrically determined extinction coefficients [human SULT2A1 (Wang et al., 2014), human SULT1E1 (Zhang et al., 1998), yeast hexokinase (Jacob et al., 1991), human GST4A (Mannervik, 1985), and synthetic MSP1D1 (Denisov et al., 2004)]. Notably, MSP1D1 (Denisov et al., 2004) purified from *E. coli* (see *Materials and Methods*) was one of the standards. The fluorescent intensities of the standards spanned the range of intensities used to determine the MSP:2B7 stoichiometry. The data demonstrate that the method is highly linear and precise ( $R^2 = 0.994$ ) over the proteins and range of intensities used in the study. The 2B7-to-MSP stoichiometry in the purified nanodisc, determined in triplicate, is  $1.02 (\pm 0.04)$ . This finding strongly suggests that UGT2B7 is a monomer in the nanodisc; however, the analysis does not withstand the possibility that the fluorescent intensity of UGT2B7 per Trp is aberrant such that it yields a well-defined stoichiometry.

**UGT2B7 Assays: Nanodiscs versus Microsomes.** Given the challenges traditionally associated with UGT purification, in vitro UGT studies are typically carried out using microsomes prepared from cell-lines that overexpress the isoform of interest. Such preparations are complex and pose certain experimental challenges (Zhou and Miners, 2014). For example, microsomes must be perforated, using membrane channel-forming peptides (Fox and Richards, 1982; Bánhegyi et al., 1993), to allow substrates to diffuse into the microsomal lumen and access UGT-active sites. Further, glucuronidase-catalyzed cleavage of the glycosidic bond formed in UGT reactions is often inhibited by addition of saccharolactone (D-glucaro-1,4-lactone), which can also inhibit turnover by direct interaction with UGTs (Robinson et al., 1991; Zhou and Miners, 2014; Argikar, 2018). Finally, endogenous long-chain fatty acids, which can isoform-specifically inhibit UGTs, are frequently “removed” in situ by adsorption using BSA (Rowland et al., 2007, 2008; Manevski et al., 2011). The use of BSA requires that BSA-binding of the UGT substrate be taken into consideration (Manevski et al., 2011). The multiple possible points-of-action of BSA and saccharolactone with components of the microsome assay suggest that the effects of the components should be characterized for each UGT isoform and substrate.

Given the well-known, complex effects of BSA on UGT catalysis in microsomes (Zhou and Miners, 2014), it was of interest to assess its effects on the activity of UGT2B7•nanodiscs and compare them to those on microsomal UGT2B7. The assays used 4-methylumbelliferone



**Fig. 4.** Initial-rate behavior of UGT2B7 in nanodiscs and microsomes. (A)  $1/\text{Turnover}$  vs.  $1/[\text{UDPGA}]$ . Reaction conditions: UGT2B7-nanodisc (100 nM active sites, black dots) or UGT2B7 Supersomes (110  $\mu\text{g}$ , blue dots), UDPGA (60–1250  $\mu\text{M}$ ,  $0.2\text{--}5 \times K_m$ ), 4-MU (3.5 mM free,  $20 \times K_m$ ), BSA (1.0% wt/vol, Supersome assay only),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^\circ\text{C}$ . Supersomes were incubated ( $0^\circ\text{C}$ , 60 min) with alamethicin (25  $\mu\text{M}$ ) and saccharolactone (5.0 mM) prior to assay. Reactions were initiated by addition of UDPGA to a final volume of 500  $\mu\text{l}$ . Reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ). (B)  $1/\text{Turnover}$  vs.  $1/[\text{4-MU}]$ . Assays were identical to (A) except [UDPGA] was fixed (5.0 mM,  $21 \times K_m$ ) and [4-MU] was varied from 35 to 900  $\mu\text{M}$  ( $0.2\text{--}5 \times K_m$ ). (C) 4-MU substrate inhibition. Assays were identical to (B) except [4-MU] was varied from 0.035 to 11 mM ( $0.03\text{--}10 \times K_i$ ). Initial-rate parameters were obtained by weighted-least-squares fitting to either a simple Michaelis-Menten (A and B) or a partial substrate inhibition model (C). Initial-rate parameters are compiled in Table 1.

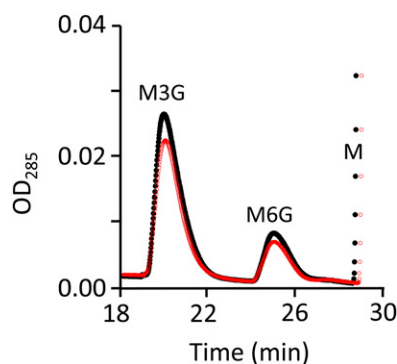
(4-MU) as the substrate acceptor, and reaction progress was monitored via the fluorescence decrease associated with 4-MU glucuronidation ( $\lambda_{\text{ex}} = 370 \text{ nm}$ ,  $\lambda_{\text{em}} = 451 \text{ nm}$ ) (Uchaipichat et al., 2004). UDPGA was saturating (5.0 mM,  $21 \times K_m$ ); 4-MU was subsaturating ( $0.12 \times K_m$ ) to allow  $k_{\text{cat}}$  and/or  $K_m$  effects to be detected. Preincubation with alamethicin, a pore-forming peptide, and saccharolactone was needed to optimize turnover of the microsomal preparation but had no effect on UGT2B7 nanodisc activity. BSA was set either at zero or 1.0% (wt/vol). Reactions were run at  $25^\circ\text{C}$  and were initiated by addition of UDPGA. Further details are given in *Materials and Methods*, subsection *Albumin-Effect Assays*. As is evident (Fig. 3A), the velocity of the 4-MU reaction is substantially (4.6-fold) faster in the presence (red dots) of BSA than in

its absence (black dots). In contrast, BSA has no detectable effect on turnover of the UGT2B7•nanodisc (Fig. 3B). Thus, several of the experimental challenges associated with assaying UGTs in microsomes are circumvented by the 2B7•nanodisc system.

**Initial-Rate Studies.** The initial-rate parameters of nanodisc- and microsomal-UGT2B7 toward UDPGA and 4-MU were determined. The experimental design holds the concentration of one substrate fixed and saturating while varying the other from  $0.2$  to  $5 \times K_m$  in equal increments in double reciprocal space; consequently, the constants are apparent rather than true kinetic constants. The microsome experiments used fresh Supersomes (i.e., commercial microsomes isolated from sf9 cells that overexpress recombinant UGTs). To correct the 4-MU concentration in the microsome studies for 4-MU binding to BSA,  $K_d$  for the interaction,  $380 \pm 21 \mu\text{M}$ , was determined via 4-MU induced changes in BSA intrinsic fluorescence (see *Materials and Methods*, subsection *BSA Binding to 4-MU*). The UGT2B7 concentration in Supersomes ( $925 \pm 126 \text{ pmol/mg}$  extract) (Fallon et al., 2013) was used to calculate 2B7 turnover in the microsomal studies.

The initial-rate-study  $1/v$ -versus- $1/[S]$  plots can be seen in Fig. 4. Black and blue dots (Fig. 4, A and B) reference the nanodisc and microsomal studies, respectively. Lines passing through the data represent the behavior predicted by initial-rate parameters obtained by weighted least-squares fitting (see *Materials and Methods*, subsection *Initial-Rate Studies*). The best-fit parameters are provided in Table 1. The data in Fig. 4, A and B reveal that the initial-rate parameters of UGT2B7 in the nanodisc and microsome are quite similar — they differ by less than one S.D. Extending the 4-MU concentration beyond  $5 \times K_m$  (Fig. 4C) reveals substrate inhibition, which has been reported for 4-MU with other UGT isoforms (Uchaipichat et al., 2004), Fig. 4C. The red line passing through the Fig. 4C data are the best-fit prediction obtained using an uncompetitive, partial-inhibition model (see *Materials and Methods*, subsection *Partial Substrate Inhibition*).

The catalytic integrity of the nanodisc complex was further examined using morphine, which exhibits high specificity for the 2B7 isoform (Court et al., 2003; Stone et al., 2003). Morphine is glucuronidated at the 3-OH by numerous isoforms, while glucuronidation at the 6-OH is highly specific for 2B7. The catalytic efficiency (i.e.,  $V/K$ ) of 2B7 toward the three- and six-positions varies such that at subsaturating morphine (i.e., where reaction rates are linear with  $V/K$ ) initial-rate measurements yield a product ratio of approximately 6-to-1 in favor of the three-position (Stone et al., 2003). The relative rates of reaction at the three- and six-positions provide a simultaneous measure of the partitioning between these two catalytic paths. At saturating UDPGA, the apparent  $K_m$  of morphine for the three- and six-conjugation reactions is reported to range from 0.5 to 1.0 mM (Court et al., 2003; Stone et al., 2003). To compare the partitioning of these reactions in the nanodisc and microsomes preparations, the rates of formation and distribution of the three- and six-conjugates were determined under subsaturating, initial-rate conditions (see *Materials and Methods*). Morphine reactants were separated using reverse-phase HPLC and quantitated using absorbance at 285 nm (Chan, 2017). 2B7 levels in the assays were concentration matched assuming 925 pmol UGT2B7 per mg Supersome extract (Fallon et al., 2013). The measurements were performed in triplicate, and representative nanodisc and Supersome HPLC profiles are superposed in Fig. 5. Statistical analysis of the peak areas reveals that the nanodisc and Supersome preparations produce conjugates at nearly identical rates ( $1.9 \pm 0.1$  and  $2.1 \pm 0.1 \mu\text{M min}^{-1}$ , respectively) and that their isomer distributions are also within error ( $6.2 \pm 0.1$  and  $6.0 \pm 0.2$ , respectively). The differences in the catalytic behavior of the two preparations are within the measurement error.



**Fig. 5.** Morphine glucuronides produced by nanodisc and microsomal UGT2B7. Reverse phase HPLC chromatograms of the morphine conjugates produced by the nanodisc (black dots) and microsomal (red dots) UGT2B7 are superposed. The 3- and 6-hydroxyl glucuronide peaks of morphine along with a partial peak of unconjugated morphine are labeled M3G, M6G and M, respectively. The concentrations of 2B7 in the nanodisc and Supersome assays were matched (see main text). Reaction conditions: UGT2B7 nanodisc (100 nM, UGT active site) or UGT2B7 Supersomes (100  $\mu\text{g ml}^{-1}$ ), morphine (100  $\mu\text{M}$ ), UDPGA (5.0 mM,  $21 \times K_m$ ), BSA (1.0% wt/vol, Supersomes only), alamethicin (25 nM, Supersomes only), saccharolactone (5.0  $\mu\text{M}$ , Supersomes only),  $\text{MgCl}_2$  (5.0 mM),  $\text{KPO}_4$  (50 mM), pH 7.5,  $25 \pm 2^\circ\text{C}$ . Reactions were initiated by addition of UDPGA. Less than 5% of the morphine consumed at the end point of the reaction was formed during the measurement. Reaction was quenched and chromatographically separated as described in *Materials and Methods*, subsection *Rate Studies Using Morphine*.

## Conclusions

The first UGT nanodisc, the human UGT2B7•nanodisc, has been assembled, purified, and characterized. The initial-rate parameters of the UGT2B7•nanodisc faithfully reproduce those of UGT2B7 in microsomes (i.e., Supersomes); hence, the catalytic integrity of UGT2B7 is neither enhanced nor compromised by its inclusion in nanodiscs. Further, the reactivity of UGT2B7 in nanodiscs and microsomes toward morphine is virtually indistinguishable. The purity of the nanodisc allows simplification of the UGT assay, circumventing the need to parameterize assays with respect to BSA, alamethicin, and saccharolactone. Their catalytic performance, stability, purity, and simplified assay recommend nanodiscs as an attractive alternative to the long-standing microsomal systems. We anticipate that the nanodisc technology can be used to purify many if not most human UGT isoforms, and that access to pure, stable, catalytically robust UGT nanodiscs will provide unprecedented opportunities to study this disease-relevant enzyme family.

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## Authorship Contributions

*Participated in research design:* Cook, Asenjo, Sosa, Leyh.

*Conducted experiments:* Cook, Asenjo.

*Performed data analysis:* Cook, Leyh.

*Wrote or contributed to the writing of the manuscript:* Cook, Leyh.

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