Characterization of Cytosolic Glutathione S-Transferases Involved in the Metabolism of the Aromatase Inhibitor, Exemestane

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ABSTRACT

Exemestane (EXE) is a hormonal therapy used to treat estrogen receptor–positive breast cancer by inhibiting the final step of estrogen biosynthesis catalyzed by the enzyme aromatase. Cytochrome P450 3A4 (CYP3A4) metabolism is the major metabolic pathway for EXE. The present study was to identify cytosolic hepatic GSTs active in the GST-mediated metabolism of EXE and 17β-DHE. Twelve recombinant cytosolic hepatic GSTs were screened for their activity against EXE and 17β-DHE, and glutathionylated EXE and 17β-DHE conjugates were detected by ultraperformance liquid chromatography tandem mass spectrometry. GST α (GSTA) isoform 1, GST μ (GSTM) isoform 3 and isoform 1 were active against EXE, whereas only GSTA1 exhibited activity against 17β-DHE. GSTM1 exhibited the highest affinity against EXE with a Michaelis-Menten constant (KM) value that was 3.8- and 7.1-fold lower than that observed for GSTA1 and GSTM3, respectively. Of the three GSTs, GSTM3 exhibited the highest intrinsic clearance against EXE (intrinic clearance = 0.14 nl·min⁻¹·mg⁻¹). The KM values observed for human liver cytosol against EXE (46 μM) and 17β-DHE (77 μM) were similar to those observed for recombinant GSTA1 (53 and 30 μM, respectively). Western blot analysis revealed that GSTA1 and GSTM1 composed 4.3% and 0.57%, respectively, of total protein in human liver cytosol; GSTM3 was not detected. These data suggest that GSTA1 is the major hepatic cytosolic enzyme involved in the clearance of EXE and its major active metabolite, 17β-DHE.

SIGNIFICANCE STATEMENT

Most previous studies related to the metabolism of the aromatase inhibitor exemestane (EXE) have focused mainly on phase I metabolic pathways and the glucuronidation phase II metabolic pathway. However, recent studies have indicated that glutathionylation is the major metabolic pathway for EXE. The present study is the first to characterize hepatic glutathione S-transferase (GST) activity against EXE and 17β-dihydro-EXE and to identify GST α 1 and GST μ 1 as the major cytosolic GSTs involved in the hepatic metabolism of EXE.

Introduction

Breast cancer is the most commonly diagnosed cancer in women and, despite an overall improvement in breast cancer therapy, continues to be their second leading cause of death (American Cancer Society, 2021). More than 75% of diagnosed breast cancers are found to be expressing estrogen receptors (ERs) with estrogen contributing to tumor growth and proliferation (Howlader et al., 1975–2013; Osborne and Schif, 2011). Hormone therapy is most commonly prescribed for early-stage, ER-positive breast cancer in postmenopausal women, including treatments with selective estrogen receptor modulators or aromatase inhibitors [Uhnch and Thomssen, 2010; Early Breast Cancer Trialists’ Collaborative Group (EBCTCG), 2015]. The mechanism of action of selective estrogen receptor modulators, including tamoxifen (TAM), is manifested through blocking the ER to prevent the binding of estrogen, whereas aromatase inhibitors, including exemestane (EXE), act through suicide inhibition of the enzyme aromatase and disrupt androgen conversion to estrogen in the final step of estrogen biosynthesis (Miller, 1999; Campos, 2004; Eisen et al., 2008; Patel and Bihan, 2018). When compared with tamoxifen, EXE demonstrates a higher clinical efficacy and safety profile (Kiebach et al., 2010; Goss et al., 2011). Moreover, long-term use of EXE demonstrated a 65% reduction in the incidence of invasive breast cancer among high-risk but healthy postmenopausal women (Goss et al., 2011). In addition, unlike that observed for TAM, EXE has not been associated with higher risk for thromboembolism or gynecologic events, such as endometrial cancers, polyps, and fibroids (Coombes et al., 2007; Goss et al., 2011). However, although EXE demonstrates improved treatment efficacy as compared with TAM, the overall response rate of 46% is still relatively low (Paridaens et al., 2003; Paridaens et al., 2008). Additionally, compared with TAM, EXE has
been associated with a higher incidence of hot flashes, musculoskeletal pain, and lower bone mineral density (Coombes et al., 2007).

EXE is extensively metabolized in patients with <1% and <10% remaining as unmetabolized EXE in urine and plasma, respectively (Pfizer, 2018). A major route of EXE metabolism is the formation of 17β-dihydroxyestrane (DHE), an active metabolite catalyzed by cytochrome P450s, aldoketoreductases, and carbonyl reductases (Kamdem et al., 2011; Platt et al., 2016; Peterson et al., 2017). 17β-DHE is further conjugated through the glucuronidation pathway to form the inactive 17β-DHE-glucuronide (Gluc) by UDP-glucuronosyltransferase (UGT) 2B17 (Sun et al., 2010; Luo et al., 2017).

Recently, two novel cysteine (Cys) conjugates of EXE and 17β-DHE were identified: 6x-EXE-Cys and 6x-17β-DHE-Cys, which combined composed 77% and 35% of the total urinary and plasma EXE metabolites, respectively, in subjects taking EXE (Luo et al., 2018). Cysteine conjugates are formed through a three-step metabolic pathway, in which the first step involves conjugation with the tripeptide glutathione (GSH; γ-Glu-Cys-Gly) catalyzed by the glutathione-S-transferase (GST) family of enzymes (Hinchman and Ballatori, 1994; Hayes et al., 2005). The glutathione conjugates are subsequently metabolized by γ-glutamyl transpeptidase to remove the glutamyl moiety and by dipeptidase to remove the glycyl moiety, which ultimately forms the cysteine conjugate that is rapidly excreted. As the first step in this conjugation pathway, GST-mediated glutathionylation is a likely key step in EXE and 17β-DHE metabolism and excretion (Luo et al., 2018; Hanna and Anders, 2019). The ultimate cysteine conjugates render EXE and DHE more water-soluble and more easily excreted; although it is assumed that these conjugates also render EXE and DHE less active, this has not yet been directly tested.

GSTs are a multifunctional superfamily of enzymes involved in both catalytic and signaling processes. Cytosolic GSTs compose the largest subfamily of GSTs and are traditionally recognized as the major GSTs involved in phase II metabolism (Habig et al., 1974b; Hayes et al., 2005; Jancova et al., 2010). They are largely expressed in human liver, but are also expressed in many other tissues, including environmental pollutants, carcinogens, many drugs, and chemotherapeutic agents (Dostalek and Stark, 2012; Hanna and Anders, 2019). GSTs are also highly polymorphic and have been associated with an increased risk for a variety of cancers, variability in drug toxicity, cancer resistance, and altered drug metabolism (Perera et al., 2011; Platt et al., 2016; Peterson et al., 2017). 17β-DHE was subsequently centrifuged at 16,100 × g for 10 minutes at 4°C for 24 hours. Water (10 ml) was added to the reaction mixture, which was then washed with dichloromethane (3 × 8 ml). The pH of the water phase was adjusted to ~3 with 2 N HCl and it was then stored in a refrigerator overnight. The aqueous sample was loaded onto conditioned Oasis HLB 1 cc cartridges (14 aliquots), which was then followed by sequential elution with water (1.5 ml) and methanol (1.5 ml). The collected methanol solutions were combined, concentrated, and dried to afford S-(Androst-4-ene-1,4-diene-3,17-dion-6x-ylmethyl)-γ-glutathione (DEH-GS) (10.6 mg, Y = 45%) as a white solid. 1H NMR (D2O) δ 7.33 (d, J = 10.1 Hz, 1 H), 6.19 (dd, J1 = 10.1, J2 = 1.8 Hz, 1 H), 6.00 (bs, 1 H), 4.50 (dd, J1 = 8.8 Hz, J2 = 5.1 Hz, 1 H), 3.83 (s, 2 H), 3.69 (dd, J1 = 6.4 Hz, 1 H), 3.23 (s, 1 H), 3.00 (dd, J1 = 14.2 Hz, J2 = 5.1 Hz, 1 H), 2.87 (dd, J1 = 12.8 Hz, J2 = 6.3 Hz, 1 H), 2.81 (dd, J1 = 14.2 Hz, J2 = 8.8 Hz, 1 H), 2.69 (m, 1 H), 2.60 (dd, J1 = 12.8 Hz, J2 = 6.9 Hz, 1 H), 2.45 (m, 3 H), 2.16–2.20 (m, 1 H), 2.00–2.09 (m, 3 H), 2.18–2.20 (m, 2 H), 1.54–1.75 (m, 4 H), 1.07–1.26 (m, 2 H), 1.19 (s, 3 H), 0.90–0.94 (m, 1 H), 0.86 (s, 3 H), 0.74 (dd, J1 = 24.4 Hz, J2 = 12.3 Hz, 1 H). 13C NMR (D2O) δ 228.1, 188.9, 174.8, 173.8, 173.6, 172.5, 161.5, 125.2, 120.1, 53.8, 53.4, 53.2, 49.6, 48.8, 48.4, 45.0, 41.7, 39.3, 38.5, 35.7, 34.3, 33.8, 31.3, 30.6, 26.1, 22.0, 21.4, 17.7, 13.2. HRMS (EI) mass-to-charge ratio (m/z) calculated for C24H27N2O2S [M+Na]+ 466.2687; found 466.2693; purity > 95%.

Synthesis of S-[(Androst-4-ene-1,4-diene-3,17-dion-6-ylmethyl)-γ-glutathione (DEH-GS) was synthesized as described above for EXE-GES using 17β-DHE (10.6 mg, 0.036 mmol) and γ-glutathione (37.3 mg, 0.112 mmol) as the starting materials. DHE-GS (2.5 mg, Y = 11%) was purified as a white solid. 1H NMR (D2O) δ 7.35 (d, J = 10.2 Hz, 1 H), 6.20 (d, J = 10.2 Hz, 1 H), 5.90 (s, 4.49) (d, J1 = 8.8 Hz, J2 = 5.2 Hz, 1 H), 3.81 (s, 2 H), 3.68 (dd, J1 = 6.4 Hz, 1 H), 3.49 (dd, J1 = 8.5 Hz, 1 H), 2.99 (dd, J1 = 14.1 Hz, J2 = 5.0 Hz, 1 H), 2.78–2.88 (m, 2 H), 2.55–2.68 (m, 2 H), 2.44 (m, 2 H), 2.06 (m, 3 H), 1.89 (m, 1 H), 1.62–1.77 (m, 4 H), 1.21–1.49 (m, 3 H), 1.18 (s, 3 H), 0.74–0.96 (m, 3 H), 0.69 (s, 3 H), 0.61 (dd, J1 = 24.4 Hz, J2 = 12.2 Hz, 1 H). 13C NMR (D2O) δ 188.9, 175.5, 174.7, 174.0, 173.6, 172.4, 162.1, 125.1, 119.9, 81.1, 53.9, 53.8, 53.2, 49.4, 45.2, 42.7, 41.9, 39.5, 39.4, 35.4, 34.8, 33.9, 31.3, 28.7, 26.1, 22.9, 22.4, 17.8, 10.6. HRMS (EI) m/z calculated C24H27N2O2S [M+Na]+ 606.2844, found 606.2900; purity = 94%.

Biosynthesis of S-(DEX-GS and 17β-DHE-GS. S-(DEX-GS and 17β-DHE-GS, internal standards for LC-MS analysis of glutathione conjugates of EXE and 17β-DHE, were generated in an enzymatic reaction containing pooled HLC (200 μg), 100 mM potassium phosphate (KH2PO4) at pH 7.4, and 100 ppm D3-EXE or 100 ppm D3-17β-DHE in a total volume of 200 μl. The reaction was incubated at 37°C for 3 minutes before the addition of 5 nM GSH (Lash et al., 1999; Zarth et al., 2015; Shi et al., 2016). Final mixtures were incubated for 2 hours at 37°C and stopped with 200 μl cold acetonitrile. Mixtures were subsequently centrifuged at 16,100 × g for 10 minutes at 4°C. Supernatants
were collected, and aliquots of 50 μl were injected onto the ACQUITY UPLC BEH C18 column (2.1 × 100 mm; Waters). The ultra-pressure liquid chromatography (UPLC) conditions used were as described below. Fractions containing EXE-GS conjugates were collected at UPLC retention times of 1.2–2 minutes, whereas DHE-GS conjugates were collected at 0.8–1.8 minutes.

**Recombinant Protein Production.** The Human Protein Atlas was queried (April 19, 2018), and 12 cytosolic human GSTs were identified to be heptatically expressed: GSTA1, GSTA2, GSTA4, GSTK1, GSTM1, GSTM2, GSTM3, GSTM4, GST ο (GSTO) 1, GST ι (GSTI) 1, and GST θ (GSTT) 1. GSTA1, GSTA4, GSTK1, GSTM2, GSTM4, GSTM1, GSTM3, and GSTA2 were purchased commercially; GSTT1, GSTP1, GSTZ1, and GSTO1 were not found to be commercially available and were cloned as described below.

In addition to the noncommercially available GSTs (GSTT1, GSTP1, GSTZ1, and GSTO1), the GSTs that exhibited initial activity against EXE and 17β-DHE (GSTA1, GSTM1, and GSTM3) were also cloned and expressed as codon-optimized, recombinant proteins. All GSTs were cloned with a C-terminal His-tag. Codon-optimized plasmids encoding wild-type human GSTA1, GSTM3, GSTT1, GSTZ1, GSTP1, and GSTO1 were commercially synthesized by GenScript (Piscataway, NJ). Selected bacterial colonies were grown overnight in 10 ml of LB supplemented with 100 μg/ml of ampicillin at 37°C in a tabletop shaker (250 rpm). A total of 90 ml of fresh LB medium containing 100 μg/ml of ampicillin was inoculated with the overnight culture and grown an additional 2.5 hours to reach an optical density value of 0.60. The expression of GST protein was induced by the addition of isopropyl-1-thio-β-D-galactopyranoside at a final concentration of 0.5 mM. After induction, cells were grown for an additional 4 hours at 37°C and then harvested by centrifugation. The cytosolic fraction was collected after cell lysis with 150 μl B-PER Complete Bacterial Protein Extraction Reagent and centrifugation per the manufacturer’s protocols.

His-tagged GST proteins were purified from the cytosol by nickel affinity chromatography. Ni-NTA resin spin columns were equilibrated with binding buffer containing 50 mM sodium phosphate (pH 8.0), 300 mM NaCl, and 10 mM imidazole. Each cytosolic lysate was mixed with an equal volume of binding buffer, loaded onto the column, and incubated for 20 minutes at 4°C for maximal binding. After incubation, the columns were centrifuged at 700 x g for 2 minutes, and the flow through was discarded. Columns were subsequently washed with 20, 60, and 100 mM of imidazole in PBS (pH 7.4), and each of the elutions were collected; GSTP1 His-tagged protein was washed with 20, 60, 100, 150, and 200 mM of imidazole. Using dextran desalting columns, the imidazole was removed, and purified proteins were subsequently stored in PBS (pH 7.4) buffer. A total of 125 μg of protein for each fraction was loaded onto an SDS-PAGE gel, and all bands were found to be greater than 90% pure by silver staining (Supplemental Fig. 1). As performed for commercially purchased recombinant GST proteins, the activity of purified recombinant proteins was verified using the CDNB assay described below. Pure recombinant enzymes were stored in 200 μl aliquots in 25% glycerol at −20°C.

**GST Activity Assays.** The enzymatic activities of recombinant GSTs were verified using a spectrophotometric assay against CDNB, a known substrate for GSTs. Inhibition analysis was performed by preincubation at 30°C with CDNB and 1 mM GSH in 100 mM sodium phosphate buffer at 30°C containing 50 mM sodium phosphate (pH 8.0), 300 mM NaCl, and 10 mM imidazole. GSTs were loaded onto the column, and incubated for 20 minutes at 4°C.

The reaction was preincubated at 37°C for 3 minutes prior to the addition of 5 mM GSH to start the incubation (1 hour, 37°C). Incubations were terminated by adding an aliquot (2.5 μl) to ice-cold acetonitrile (5 μl) spiked with 2.5 μl of D2-EXE-GS or D2-17β-DHE-GS internal standard. After vortexing and centrifuging at 16,100 x g for 10 minutes at 4°C, supernatants (10 μl) were transferred to a glass sample vial containing 10 μl water. Reactions containing HLC were performed as a positive control, and reactions without enzyme were performed as a negative control.

For enzyme kinetic analysis, EXE-GS formation was examined as described above in reactions incubated for 1 hour at 37°C using 2.5–8.0 ng/μl of purified recombinant GSTA1, GSTM1, or GSTM3 protein and varying concentrations of EXE (2–250 μM). Similar kinetic assays were also performed with pooled HLC (1 μg/μl). 17β-DHE-GS conjugate formation was examined using recombinant GSTA1 (5 ng/μl) or pooled HLC protein (2 μg/μl) as described above for EXE, using 17β-DHE (2–250 μM) as the substrate. Reaction mixtures were processed as described above and loaded onto the ultra-pressure liquid chromatography–mass spectrometry (UPLC/MS) to monitor glutathione (GS) conjugate formation. EXE-GS and 17β-DHE-GS concentrations were quantified using a standard curve generated from a serial dilution of known amounts of chemically synthesized EXE-GS or 17β-DHE-GS (synthesis described above).

**UPLC/MS Analysis of GS Conjugates.** EXE-GS and 17β-DHE-GS conjugate formation was monitored in individual reactions using a UPLC/MS system (Waters) consisting of an Acquity UPLC, Acquity UPLC BEH C18 column (2.1 × 100 mm), and Xevo G2-S QToF mass spectrometer. The UPLC flow rate was 0.4 μl/min with a column temperature of 35°C. UPLC conditions for EXE-GS separation were as follows: 0.5 minutes at 25%:75% of mobile phase B (100% acetonitrile); mobile phase A (5 mM ammonium formate and 0.1% formic acid), a linear gradient to 100% B in 4 minutes, and 1.5 minutes at 100% B, which was followed by re-equilibrium with 25% B for 2 minutes. The UPLC conditions for DHE-GS separation were 2 minutes at 20% mobile phase B, a linear gradient to 100% B in 4 minutes, and 1.5 minutes at 100% B, which was followed by re-equilibrium with 20% B for 2 minutes. The Waters Xevo G2-S QToF MS operated in tandem mass spectrometry mode, and the ESI probe operated in the positive-ion mode with a capillary voltage at 0.6 kV. Nitrogen was used as both the cone and desolvation gases with flow rates maintained at 50 and 800 l/h, respectively. The collision energy for EXE-GS and DHE-GS detection was optimized at 25 V with a cone voltage of 30 V. Glutathione conjugate formation was detected using the following mass transitions (m/z): 604.2692 → 297.184, 607.281 → 300.203, 606.2849 → 299.2, and 609.3037 → 302.203 to monitor EXE-GS, D2-EXE-GS, 17β-DHE-GS, and D2-17β-DHE-GS, respectively.

**Recombinant GSTA1, GSTM1, and GSTM3 Quantification in HLC.** Western blot analysis was performed to quantify the amount of GSTA1, GSTM1, and GSTM3 protein present in commercial-pooled HLC. Serial dilutions of HLC (25–6.25 μg of total protein) and purified recombinant protein (GSTA1 = 1–0.125 μg, GSTM1 = 0.25–0.03 μg, or GSTM3 = 1–0.03 μg) were loaded on three separate 15% SDS-polyacrylamide gels and, after electrophoresis, were transferred to polyvinylidene fluoride membranes using an iBlot system (Thermo Fisher Scientific). The membranes were blocked overnight at 4°C in blocking buffer (5% nonfat dry milk in Tris-buffered saline containing 50 mM Tris-Cl, pH 7.6; 0.9% NaCl, 0.1% Tween 20), and subsequently washed three times (10 minutes each) with Tris-buffered saline/Tween 20. For GSTA1, GSTM1, and GSTM3, membranes were probed with mouse monoclonal GSTA1 antibody (1:400 dilution), mouse monoclonal GSTM1 antibody (1:1,000 dilution), and mouse polyclonal GSTM3 antibody (1:250), respectively, for 2 hours in blocking buffer, which was followed by a goat anti-mouse secondary antibody (1:10,000 dilution) in blocking buffer for 1 hour. Bands on the membranes probed with anti-GSTM1 and anti-GSTA1 were visualized with the Novex ECL Chemiluminescent Kit, whereas the membrane probed with anti-GSTM3 was visualized with SuperSignal Femto Maximum Sensitivity Substrate. The densitometry analysis of images at 400-second exposure time were performed using Image J software (National Institutes of Health, Bethesda, MD). Western blot experiments were performed in triplicate.

**Enzyme kinetic analysis.** Kinetic parameters were determined utilizing the Michaelis-Menten equation using GraphPad Prism software (version 6.01). V_max values were calculated as nmol/min/μg of pure recombinant protein. All reported results were values of three independent experiments.

**Results**

**Identification of EXE-GS and DHE-GS Conjugates.** Chemically synthesized standard EXE-GS and 17β-DHE-GS at 10 ppm were used to confirm the identity of EXE-GS and 17β-DHE-GS conjugates in the
Fig. 1. UV and UPLC/MS chromatograms of EXE-GS and DHE-GS conjugates. (A) EXE-GS standard with the parent ion spectrum (insert) for the peak at 1.20 minutes; (B) EXE-GS conjugate formation by HLC with the parent ion spectrum (insert) for the peak at 1.20 minutes; (C) EXE-GS conjugate formation with no enzyme added; (D) 17β-DHE-GS standard with the parent ion spectrum (insert) for the peak at 0.80 minutes; (E) 17β-DHE-GS conjugate formation by HLC with the parent ion spectrum (insert) for the peak at 0.90 minute; (F) 17β-DHE-GS conjugate formation with no enzyme added.

Representative Michaelis-Menten plots of EXE-GS and 17β-DHE-GS formation are shown in Fig. 3. Kinetic analysis of EXE-GS formation by recombinant GSTA1, GSTM1, and GSTM3 enzymes demonstrated that GSTM1 exhibited the highest affinity for EXE [Michaelis-Menten constant (K_M) = 14 ± 4.1 μM] followed by GSTA1 (K_M = 53 ± 17 μM) and GSTM3 (K_M = 99 ± 6.0 μM; Table 1). The apparent K_M (46 ± 12 μM) for EXE-GS formation in HLC was similar to that observed for GSTA1. GSTM3 exhibited the highest rate of EXE-GS formation (V_max = 14 ± 1.4 nmol·min⁻¹·mg⁻¹), which was approximately 3- and 33-fold higher than that observed for GSTA1 and GSTM1 (V_max = 4.7 ± 2.9 nmol·min⁻¹·mg⁻¹) and GSTM1 (V_max = 0.43 ± 0.29 nmol·min⁻¹·mg⁻¹), respectively. Overall, recombinant GSTM3 exhibited a marginally higher intrinsic clearance (CL_INT) of EXE (CL_INT = 0.14 ± 0.092 nl·min⁻¹·mg⁻¹) compared with GSTA1 (CL_INT = 0.085 ± 0.043 nl·min⁻¹·mg⁻¹) but exhibited a CL_INT that was 4.4-fold higher than that observed for GSTM1 (CL_INT = 0.032 ± 0.017 nl·min⁻¹·mg⁻¹). Similar to that observed for EXE-GS formation, the K_M observed for 17β-DHE in HLC (51 ± 14 μM) was similar to that observed for GSTA1 (32 ± 12 μM).

Relative Expression of GSTA1, GSTM1, and GSTM3 in Pooled HLC. Quantitative Western blot analysis was performed to determine the relative amounts of each active GST present in pooled HLC. Commercial antibodies for GSTA1, GSTM1, and GSTM3 were first verified for specificity and cross-reactivity (Supplemental Fig. 3). Western blots containing serial dilutions of HLC and purified recombinant GSTA1, GSTM1, and GSTM3 proteins were then probed with each specific antibody (representative images shown in Fig. 4). Densitometry analysis of three independent experiments, each containing pure recombinant protein as a standard, estimated that GSTA1 and GSTM1 composed 0.043 ± 0.0051 and 0.0057 ± 0.00043 μg of GST per microgram of HLC, respectively (Table 2). No GSTM3 proteins were detected in HLC by Western blot analysis.
Glutathionylation is an important step in the xenobiotic detoxification pathway of many compounds and might play an important role in the rate of excretion and elimination of EXE, thereby contributing to the variation observed in EXE treatment efficacy and side effects (Jancova et al., 2010). As shown in previous studies, cysteine conjugates of EXE compose 77% of total urinary metabolites, whereas in plasma, cysteine conjugate levels are similar to another major metabolite, 17β-DHE-Gluc (Luo et al., 2018). These data suggest that the formation of cysteine conjugates is a major route of metabolism of EXE. Cysteine conjugates are formed through a three-step pathway similar to that observed in the mercapturic acid synthesis pathway with the first step, GSH conjugation, catalyzed by the GST family of enzymes (Hanna and Anders, 2019). Glutathione conjugates are typically inactive, less toxic, more water soluble, and more readily excreted than parent unconjugated compound (Allocati et al., 2018). Subsequently, the glutamyl moiety is removed by γ-glutamyltransferases, the glycyl moiety is removed by

![Fig. 2.](https://example.com/fig2.png) Cytosolic GST activities against EXE and 17β-DHE. (A) EXE-GS formation by recombinant GSTs; (B) 17β-DHE-GS formation by recombinant GSTs. The GSTs were screened by incubating GSH with EXE (250 μM) using 2.5 ng/μl of purified recombinant protein. GS conjugates of EXE and DHE were detected using a Waters Xevo G2-S QTof mass spectrometer and expressed in ppm as described in Materials and Methods. Asterisks represent those GST enzymes exhibiting glutathionylation activities against EXE or 17β-DHE that were >3x the mock control.

![Fig. 3.](https://example.com/fig3.png) Representative Michaelis-Menten curves of recombinant GSTs and HLC for the conjugation of EXE to EXE-GS (A) and DHE to DHE-GS (B). For EXE conjugation, experiments were performed using 1 μg/μl of HLC protein, 2.5 ng/μl of purified recombinant GSTA1, or 8 ng/μl of purified recombinant GSTM1 or GSTM3 with varying concentrations (2–250 μM) of EXE. For 17β-DHE conjugation, experiments were performed using 2 μg/μl of HLC protein or 5 ng/μl purified recombinant GSTA1 with varying concentrations (2–250 μM) of 17β-DHE.
dipeptidases, and cysteine conjugates are excreted in the urine (Hanna and Anders, 2019). This three-step pathway has been verified for EXE through in vitro biosynthesis, in which the resulting enzymatically synthesized cysteine conjugate of EXE matches both chemically synthesized EXE-Cys, and through ex vivo analysis of urinary EXE-Cys detected in subjects taking EXE (Luo et al., 2018). In the present study, we demonstrate that GSTA1, GSTM1, and GSTM3 are the major enzymes forming the EXE-GS conjugate and that GSTA1 is the primary GST leading to the formation of 17β-DHE-GS (see Fig. 5). The χ class of GSTs is the major form of the enzyme expressed in hepatocytes, and they play a critical role in cellular defense against oxidative stress by catalyzing glutathione peroxidase reactions (e.g., fatty acid hydroperoxides and phospholipid hydroperoxides) and detoxification of xenobiotics, such as environmental carcinogens (e.g., polycyclic aromatic hydrocarbons) and therapeutic drugs (busulfan, cyclophosphamide, and chlorambucil) (Czerwinski et al., 1996; Coles and Kadlubar, 2005; Bertholee et al., 2018). These data further suggest that cysteine conjugate formation through GS conjugation of EXE is the primary route of elimination of a metabolite of EXE, is found at comparable levels to EXE-Cys in plasma but was 4.2-fold lower in urine in patients taking EXE (Luo et al., 2018). 17β-DHE-Gluc, another major metabolite of EXE, is found at comparable levels to EXE-Cys in plasma but was 4.2-fold lower in urine in patients taking EXE (Luo et al., 2018). These data further suggest that cysteine conjugate formation through GS conjugation of EXE is the primary route of elimination of EXE via phase II metabolism.

Consistent with other GST isoforms, GSTM1 catalyzes the glutathionylation of a variety of different electrophilic compounds including carcinogens, environmental toxins, therapeutic drugs [busulfan, acetaminophen, azathioprine, cisplatin, etc. (Czerwinski et al., 1996; Peters et al., 2000; Arakawa et al., 2012)], and products of oxidative stress (Marinković et al., 2013). Similar to that observed for GSTA1, GSTM1 is also involved in the mitogen-activated protein kinase signal transduction pathway through complexes with apoptosis signal-regulating kinase 1 and repression of apoptotic cell death (Cho et al., 2001), which supports its important role in multiple cellular processes. The data from the

### TABLE 1

|          | EXE-GS | 17β-DHE-GS |
|----------|--------|------------|
|          | K_M  | V_max | CL_INT | K_M  | V_max | CL_INT |
| HLC     | 46 ± 12 | 0.044 ± 0.0067 | 0.0018 ± 0.00010 | 51 ± 14 | 0.0020 ± 0.00084 | 0.000037 ± 0.0000082 |
| GSTA1   | 53 ± 17 | 4.7 ± 2.9 | 0.085 ± 0.043 | 32 ± 12 | 0.48 ± 0.13 | 0.017 ± 0.0067 |
| GSTM3   | 99 ± 6.0 | 14 ± 1.4 | 0.14 ± 0.092 | Not active | Not active | Not active |
| GSTM1   | 14 ± 4.1 | 0.43 ± 0.29 | 0.032 ± 0.017 | Not active | Not active | Not active |

*Data are expressed as milligrams of total cytosolic protein.*

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**Fig. 4.** Western blot quantification of GSTA1, GSTM3, and GSTM1 in HLC. (A) Serial dilution of HLC (25–6.25 μg of total protein) and purified recombinant GSTA1 (1–0.125 μg) used as standard, probed with a GSTA1-specific antibody; (B) serial dilution of HLC (25–6.25 μg of total protein) and purified recombinant GSTM1 (0.25–0.03 μg) used as standard, probed with a GSTM1-specific antibody; (C) serial dilution of HLC (25–6.25 μg of total protein) and purified recombinant GSTM3 (1–0.03 μg) used as standard, probed with a GSTM3-specific antibody. Western blots were conducted as described in Materials and Methods. rGST, recombinant GST.
present study suggest that GSTM1 also plays an important role in the hepatic clearance of EXE. GSTM1 exhibited the highest affinity of any GST enzyme for EXE with a $K_M$ value of 14 $\mu$M, which is 3.7-fold lower than GSTA1 ($K_M = 53 \pm 17 \mu$M). However, GSTM1 composed only 0.57% of all hepatic cytosolic protein as determined by quantitative Western blot analysis, a level that was >7.5-fold lower than that observed for GSTA1 in the same experiments, suggesting that its role in hepatic EXE metabolism may be secondary to GSTA1.

The third isoform, GSTM3, shows the highest intrinsic clearance values for EXE in vitro (0.14 nl·min$^{-1}$·mg$^{-1}$) among the three GSTs. However, it likely plays a minimal role in the hepatic clearance of EXE since it was not detected in HLC. These data are consistent with that observed in the Human Protein Atlas database, which showed that GSTM3 mRNA levels are 169-fold less abundant than GSTA1 and 29-fold less abundant than GSTM1 in liver [http://www.proteinatlas.org; queried on July 10, 2021; (Uhlén et al., 2015)]. GSTM3 might, however, contribute to the first-pass metabolism of EXE since its expression is about 2-fold higher than GSTM1 in the small intestine (http://www.proteinatlas.org; queried on July 10, 2021).

EXE reduction to 17β-DHE during phase I metabolism and the subsequent glucuronidation of 17β-DHE by UGT2B17 has been extensively studied (Sun et al., 2010; Kamdem et al., 2011; Platt et al., 2016; Peterson et al., 2017). Deletion of UGT2B17 was associated only with decreased 17β-DHE-Gluc metabolite levels and increased levels of 17β-DHE (Luo et al., 2017). Recent studies examining the potential correlation between the UGT2B17 deletion and commonly reported side effects (fatigue, hot flashes, and joint pain) in postmenopausal women taking EXE found that the UGT2B17 gene deletion is associated with a higher risk of severe fatigue, hot flashes, and joint pain (Ho et al., 2020). Interestingly, common functional polymorphisms also exist for several GSTs including GSTA1 and GSTM1. GSTA1 has three linked, functional single-nucleotide polymorphisms in the promoter region resulting in two allelic variants, GSTA1*A and GSTA1*B, with the GSTA1*B minor allele frequency at 0.43–0.49 in the Caucasian population (Mikstacki et al., 2016; Michaud et al., 2019). The promoter single-nucleotide polymorphism in position −52 (G>A) has functional importance since it impairs the binding of the specificity protein 1 transcription factor, reduces promoter activity, and is associated with altered hepatic GSTA1 expression and increased risk for a variety of cancers (Coles et al., 2001; Coles and Kalu, 2005) The GSTA1*B genotype was also associated with interindividual variability in busulfan clearance in children undergoing hematopoietic stem cell transplantation, which led to the higher incidence of hematopoietic stem cell transplantation–related toxicities such as sinusoidal obstruction syndrome, acute graft-versus-host disease, and other treatment-related toxicities (Ansari et al., 2017). In addition, GSTM1 has a whole-gene deletion polymorphism that is highly prevalent (minor allele frequency = 48%–57%) in the Caucasian population and has been associated with increased risk for a variety of cancers (Geisler and Olshan, 2001). The GSTM1 null genotype has also been linked with alterations in drug metabolism and clinical efficacy. For example, the GSTM1 null genotype has been associated with lower efficacy in patients taking azathioprine as an immunosuppressant during inflammatory bowel disease (Lucáfo et al., 2019). These GST functional variants may therefore contribute to the variability in hepatic EXE metabolism in the population.

In conclusion, in vitro studies suggest that GSTA1 is the major isoform responsible for the hepatic metabolism of EXE and 17β-DHE. GSTM1 contributes to the hepatic clearance of EXE but not 17β-DHE. Although GSTM3 is active against EXE, it does not contribute significantly to hepatic clearance, given its negligible expression in the liver. Further studies examining the

| Table 2: Mean levels of GSTA1, GSTM1, and GSTM3 in human liver cytosols |
|----------------|----------------|----------------|
| GSTA1 | GSTM1 | GSTM3 |
| 0.043 ± 0.0051$^a$ | 0.0057 ± 0.00043$^a$ | Not detected |

$^a$Data are expressed as micrograms of GST per micrograms of liver cytosolic protein.
role of functional polymorphisms in GSTA1 and GSTM1 on EXE metabolism should be performed to better evaluate the role of these enzymes on individual differences in EXE efficacy, side effects, and overall treatment outcomes.

Authorship Contributions

Participated in research design: Teslenko, Lazarus.
Conducted experiments: Teslenko.
Contributed new reagents or analytic tools: Xia.
Performed data analysis: Teslenko, Chen, Lazarus.
Wrote or contributed to the writing of the manuscript: Teslenko, Watson, Xia, Chen, Lazarus.

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