Disposion of Flavonoids via Enteric Recycling: Enzyme-Transporter Coupling Affects Metabolism of Biochanin A and Formononetin and Excretion of Their Phase II Conjugates

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ABSTRACT

The purpose of this study was to continue our effort to determine how enzyme-transporter coupling affect disposition of flavonoids. The rat intestinal perfusion and Caco-2 cell models were used together with relevant microsomes. In perfusion model, isoflavone (i.e., formononetin and biochanin A) absorption and subsequent excretion of its metabolites were always site-dependent. Maximal amounts of intestinal and biliary conjugates excreted per 30 min were 31 and 51 nmol for formononetin, more than that for pure biochanin A (12 and 20 nmol). When a standardized red clover extract (biochanin A/formononetin = 10:7) was used, the results indicated that more metabolites of biochanin A than formononetin were found in the perfusate (36.9 versus 22.8 nmol) and bile (78 versus 51 nmol). In metabolism studies, rat intestinal and liver microsomes always glucuronidated biochanin A faster (p < 0.05) than formononetin, whereas intestinal microsomes glucuronidated both isoflavones faster (p < 0.05) than liver microsomes. However, rapid metabolism in the microsomes did not translate into more efficient excretion in either the rat perfusion model as shown previously or in the Caco-2 model. In the Caco-2 model, both isoflavones were rapidly absorbed, efficiently conjugated, and the conjugates excreted apically and basolaterally. More formononetin conjugates were excreted than biochanin A when used alone, but much more biochanin A conjugates were found when using the isoflavone mixture. In conclusion, efficiency of enzyme-transporter coupling controls the amounts of metabolites excreted by the intestine and liver and determines the relative contribution of enteric and enterohepatic recycling to the in vivo disposition of isoflavones.

Red clover (Trifolium pratense L.) extracts are sold as dietary supplements in supermarkets and health food stores in both industrialized and developing countries. Several defined extracts of red clover are sold in the United States to treat women who suffer from menopausal-related symptoms (Rijke et al., 2001; Oleszek and Stochmal, 2002). The extracts are available as tablets (e.g., Promensil), capsules, tea, liquid preparations, and several other forms. Limited clinical studies have demonstrated the effectiveness of Promensil in the management of hot flashes (van de Weijer and Barentsen, 2002), although the efficacy of such products is not always consistent (Baber et al., 1999; St. Germain et al., 2001).

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ABBREVIATIONS: HBSS, Hanks’ balanced salt solution; HPLC, high-performance liquid chromatography; UGT, UDP-glucuronosyltransferase; ab, amounts of isoflavones absorbed; p-glu, amounts of conjugated isoflavones excreted into the intestinal lumen; b, amounts of conjugated isoflavones excreted via the bile; ANOVA, analysis of variance; total, total amounts of isoflavones absorbed from all four perfused segment.
Materials and Methods

Materials. Cloned Caco-2 cells, TC7, were a kind gift from Dr. Monique Rousset (Institut National de la Sante et de la Recherche Medicale U178, Villejuif, France). Biochanin A and formononetin were purchased from Indofine Chemicals (Somerville, NJ). A popular red clover product, Promensil tablets (lot no. 2L0449R3106), made by Novogen Ltd (Australia) were purchased from http://www.drugstore.com. β-Glucuronidase with sulfatase (catalog no. G1512) or β-Glucuronidase with sulfatase (catalog no. G1512) or β-Glucuronidase with sulfatase (catalog no. G1512) or β-Glucuronidase with sulfatase (catalog number. G1512) was used as described previously (Chen et al., 2003). Measurement of UGT Activities Using Microsomes. The incubation procedures for measuring UGT activities using microsomes were used as described previously (Chen et al., 2003).

Conversion of Biochanin A to Genistein Using Rat Liver Microsomes. The incubation procedures were as follows: 1) mix microsomes (0.4 mg protein/ml), magnesium chloride (0.88 mM), NADP, glucose-6-phosphate dehydrogenase, and glucose 6-phosphate; and different concentrations of substrates in a 100 mM potassium phosphate buffer, pH 7.4; 2) incubate the mixture (final volume = 200 μl) at 37°C for 30 min; and 3) stop the reaction by the addition of 50 μl of 94% acetonitrile/6% glacial acetic acid containing 100 μM testosterone as an internal standard.

Sample Extraction. To confirm the formation of a particular conjugate, we selectively extracted samples with methylene chloride to remove >90% of aglycones. The resulting sample was then divided into two parts, one of which was analyzed directly, whereas the other part was analyzed after glucuronidase or sulfatase hydrolysis. The difference in amount of aglycones found in these two samples was the amount of metabolites formed. The relationship between the peak areas of the metabolites before hydrolysis and the peak areas of aglycones after the hydrolysis was used to establish the conversion factor used to quantify the amounts of biochanin A and formononetin conjugates as described previously (Liu and Hu, 2002).
Red Clover Extraction. Promensil tablets were scraped to remove the coating and ground into powder. A 900-mg portion of the powder was extracted with 8 ml of ethanol, sonicated for 30 min, and centrifuged at 1000 rpm for 5 min. The concentrations of formononetin and biochanin A in the supernatant ethanol extract were 6 and 8.5 mM, respectively.

HPLC Analysis of Isoflavones and Their Conjugates. The conditions for analyzing biochanin A, formononetin, and their conjugates were as follows: system, Agilent 1090 with diode array detector and ChemStation (Agilent Technologies, Palo Alto, CA; column, Aqua (Phenomenex, Torrance, CA), 5 μm, 150 × 0.45 cm; mobile phase A, water (0.04% phosphoric acid and 0.09% triethylamine, pH 6.0); mobile phase B, 100% acetonitrile; gradient, 0 to 3 min, 15% B, 3 to 15 min, 15 to 19% B, 15 to 52, 19 to 41% B; wavelength, 254 nm (for formononetin, biochanin A, and the internal standard); and injection volume, 200 μl. There was a 4-min interval between the end of the run and the next injection to allow the column to be reequilibrated with 15% mobile phase B (Fig. 1). For biochanin A, two major metabolite peaks eluted earlier than the parent compound (designated as biochanin A-M1 and biochanin A-M2) (Fig. 1). On the other hand, there was only one glucuronidated metabolite for formononetin (designated as formononetin-M) (Fig. 1).

HPLC conditions for separating various phase I metabolites of biochanin A and formononetin from their parent compounds were published previously (Hu et al., 2003b).

Data Analysis. Permeability of the parent isoflavones were represented by $P_{eff}$, which was obtained as described previously (Hu et al., 1988, 1995; Liu and Hu, 2002). Amounts of isoflavones absorbed ($M_{abs}$), amounts of conjugated isoflavones excreted into the intestinal lumen ($M_{gut}$), amounts of conjugated isoflavones excreted via the bile ($M_{bile}$) and the percentage absorbed and percent metabolized values were calculated as described (Chen et al., 2003). Rates of metabolism in intestinal or liver microsomes were expressed as amounts of metabolites formed per min per mg protein (nanomoles per minute per milligram).

One-way ANOVA or an unpaired Student’s t test (Microsoft Excel, Microsoft, Redmond, WA) was used to analyze the data. The prior level of significance was set at 5% or $p < 0.05$.

Results

Regional Absorption and Metabolism of Pure Formononetin and Biochanin A. Absorption of formononetin and biochanin A (10 μM each) was rapid (Table 1), with
minimal effects on water flux (i.e., water flux < 0.5%/cm of perfused segment). However, there were differences between amounts absorbed for these two compounds in different regions of the intestine (Fig. 2). For formononetin, amounts absorbed was the highest in the colon (39.1 nmol/30 min or 67%, normalized to 10 cm of intestine for all perfusion results) and the lowest in the terminal ileum (13.5 nmol/30 min or 23%) \( (p < 0.05; \text{Fig. 2A}) \). For biochanin A, amounts absorbed in duodenum (47.7 nmol/30 min or 81% of perfused amounts) and colon (50.8 nmol/30 min or 89%) were higher \( (p < 0.05) \) than that in jejunum (31.5 nmol/30 min or 49%) and terminal ileum (30.5 nmol/30 min or 54%).

In the rat intestine and liver, biochanin A was metabolized into two glucuronidated metabolites, designated as biochanin A-M1 and biochanin A-M2. Both are glucuronides based on hydrolysis studies using sulfatase-free glucuronidases. On the other hand, formononetin was metabolized into a single glucuronic acid metabolite. Based on the structures of these two isoflavones and the fact that 7-OH group is most common site of glucuronidation, biochanin A-M1 and biochanin A-M2 are likely to be 7-OH glucuronic acid and 5-OH glucuronic acid, respectively. Alternatively, biochanin A-M2 would be biochanin A-5,7-diglucuronic acid, but this is unlikely since a much longer reaction time did not result in higher formation of biochanin A-M2 as would be expected from a secondary metabolite (see results presented under microsome studies). The formononetin metabolite is 7-OH-glucuronic acid since that is the only position available for glucuronidation and the peak is hydrolyzed by sulfatase-free glucuronidases.

There were also significant differences in excretion of conjugates. For example, larger amounts of formononetin conjugates were excreted \( (p < 0.05) \) than biochanin A conjugates in all regions of the intestine except for colon (Fig. 2B). In addition, for both compounds, excretion of conjugates was much higher in duodenum than that in jejunum, terminal ileum, and colon (Fig. 2B). The maximal differences in excretion were about 26-fold for biochanin A (32% of amounts absorbed or \( M_{ab} \) excreted as conjugates in duodenum versus 1.2% in colon). The differences may be even higher for formononetin (80% of \( M_{ab} \) excreted as conjugates in ileum, but none in colon). We also determined the amounts of formononetin and biochanin A absorbed during perfusion (10 \( \mu \)M each, \( M_{total} = 229 \text{ nmol} \) for all four segments every 30 min or 57 nmol for each 10-cm segment every 30 min) and found that \( M_{ab} \) was more rapid for biochanin A (total absorption from four segments combined: 89 nmol for formononetin and 160 nmol for biochanin A; \( p < 0.05 \)).

**Regional Absorption and Metabolism of Red Clover Isoflavones.** In the red clover extract, the main isoflavones were biochanin A and formononetin. In Promensil tablet extract, the ratio of formononetin/biochanin A was approximately 7:10. When the extract was used, absorption of the two isoflavones was also rapid and region-dependent (Table 1; Fig. 3). For example, for formononetin, \( M_{ab} \) was the highest in the colon (28.6 nmol/30 min or 77%) and the lowest in the terminal ileum (15.8 nmol/30 min or 42%) \( (p < 0.05; \text{Fig. 3A}) \). For biochanin A, \( M_{ab} \) was highest in the colon (46.3 nmol/30 min or 85% of perfused amounts, \( p < 0.05 \)), which were much higher than that in duodenum (36.2 nmol/30 min or 66%), jejunum (27.6 nmol/30 min or 50%), and terminal ileum (31.8 nmol/30 min or 58%). As for the conjugates excreted by the intestine, major metabolites of biochanin A and

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**Fig. 2.** Amounts of pure aglycones absorbed (A) and amounts of conjugated excreted (B) in a four-site rat intestinal perfusion model (number of replicates or \( n = 4 \)). Perfusate containing 10 \( \mu \)M formononetin (solid columns) or biochanin A (slashed columns) was used, and four segments of the intestine (i.e., duodenum, upper jejunum, terminal ileum, and colon) were perfused simultaneously at a flow rate of 0.191 ml/min. Amounts absorbed and conjugates excreted, normalized to 10-cm intestinal length, were calculated using eqs. 1 to 3. Each column represents the average of four determinations, and the error bar is the S.E.M. There were statistically significant differences \( (p < 0.05) \) between amount absorbed and conjugates excreted at different regions of the intestine for biochanin A and formononetin, according to one-way ANOVA analysis (a and b). In the same region of the intestine, amounts of absorption of biochanin A were higher than amounts of absorption of formononetin \( (p < 0.05, \text{arrows}) \) except in jejunum (A). In the same region of the intestine, amounts of formononetin conjugates excreted were significantly higher \( (p < 0.05, \text{arrows}) \) than amounts of biochanin A conjugates excreted except for colon (B).
formononetin were similarly excreted at all regions of the intestine (Fig. 3B). For both compounds, excretion of conjugates was much higher in duodenum than that in jejunum, terminal ileum, and colon (Fig. 3B). We also determined the amounts of formononetin and biochanin A absorbed during perfusion (9.7 μM biochanin A, M_total = 222 nmol for all four 10-cm segments every 30 min; 6.7 μM formononetin, M_total = 153 nmol for all four 10-cm segments every 30 min) and found that M_ab (81 nmol for formononetin, and 142 nmol for biochanin A; p < 0.05) was approximately equal to what we saw using pure isoflavones.

Intestinal versus Biliary Excretion of Phase II Conjugates of Pure Formononetin and Biochanin A. Intact aglycones were not found in the bile or plasma collected during the perfusion experiments, even though large percentages of aglycones were absorbed (Fig. 2). Therefore, we analyzed amounts of conjugates excreted in bile after their hydrolysis with β-glucuronidase + sulfatase (Fig. 4). The results indicated that for biochanin A amounts of conjugates excreted into the intestinal lumen or M_gut (10 nmol or 7% of M_ab on average and 29 nmol maximum per 30 min) were similar to that excreted into the bile or M_bile (20 nmol or 12% of M_ab on average and 27 nmol maximum) (p > 0.05) (Fig. 4B). In contrast, for formononetin, M_bile (48 nmol or 46% of M_ab on average and 51 nmol maximum) were much larger than M_gut (30 nmol or 29% of M_ab on average and 31 nmol maximum) (p < 0.05) (Fig. 4A). The highest observed conjugated formononetin concentration in bile was about 246 μM with an average steady-state concentration at approximately 190 μM, whereas the highest observed conjugated biochanin A concentration in bile was slightly more than 104 μM with an average of approximately 76 μM. The steady-state concentrations of formononetin and biochanin A conjugates in bile were significantly higher than the starting perfusate concentration of 10 μM.

Intestinal versus Biliary Excretion of Phase II Conjugates of Red Clover Isoflavones. For formononetin, M_bile (49 nmol or 50% of M_ab on average and 51 nmol maximum) was found to be much larger than M_gut (16 nmol or
20% of $M_{ab}$ on average and 23 nmol maximum per 30 min ($p < 0.05$) (Fig. 5A). For biochanin A, $M_{bile}$ (50 nmol or 35% of $M_{ab}$ on average and 78 nmol maximum) were also much larger than $M_{gut}$ (23 nmol or 16% of $M_{ab}$ on average and 37 nmol maximum) ($p < 0.05$) (Fig. 5B). The highest observed conjugated formononetin concentration in bile was about 119 $\mu$M with an average steady-state concentration at approximately 91 $\mu$M, whereas the highest observed conjugated biochanin A concentration in bile was slightly more than 184 $\mu$M with an average at approximately 110 $\mu$M. The steady-state concentrations of formononetin and biochanin A conjugates in bile were significantly higher than the starting perfusate concentration of 7 and 10 $\mu$M.

Glucuronidation of Pure Formononetin and Biochanin A in Intestinal Microsomes Prepared from Different Regions of the Intestine. The main conjugation reaction of formononetin and biochanin A was glucuronidation. Metabolism of formononetin and biochanin A (10 $\mu$M each) was determined using intestinal microsomes prepared from different regions of the rat intestine (i.e., duodenum, jejunum, ileum, and colon) (Fig. 6). The results indicated that there were significant differences in the metabolism of these two compounds using microsomes prepared from different regions of the rat intestine. Similar to what was observed in the perfusion studies, biochanin A was metabolized faster than formononetin. However, metabolism of these two compounds was always the highest in duodenum microsomes and occurred readily in the colon, even though very little or no metabolites were found in the colon perfusate. The difference in metabolism rate between duodenum and colon was 2.5-fold for biochanin A and 1.7-fold for formononetin. In contrast, the differences in amounts of metabolites excreted in duodenum versus colon were 37-fold for biochanin A, whereas no metabolite of formononetin was found in colon perfusate.

Kinetics of Glucuronidation of Pure Formononetin and Biochanin A by Microsomes. Metabolism of formononetin and biochanin A was determined using rat liver and intestinal microsomes at concentrations ranging from 0.625 to 50 $\mu$M. The results indicated that metabolism of both compounds was saturated in the intestinal microsomes and liver microsomes at the highest concentration tested (50 $\mu$M) (Fig. 7). We also determine the apparent kinetic parameters of the conjugation of formononetin and biochanin A using different microsomes. The results indicated that $K_{m}$ values were similar (5–8.4 $\mu$M) when using pure formononetin. They were more different ($K_{m}$ range 2.7–7 $\mu$M) when using pure biochanin A. The differences in $V_{max}$ values were also bigger for biochanin A than for formononetin. When we calculated the intrinsic clearance ($V_{max}/K_{m}$) of pure formononetin, we found that duodenum had the highest value (0.14 ml/min/mg), whereas the liver has the lowest value (0.041 ml/min/mg), a difference of 3 times. When we calculated the intrinsic clearance ($V_{max}/K_{m}$) of pure biochanin A using biochanin A-M1 formation, we found that duodenum had the highest value (0.40 ml/min/mg) whereas the liver has the lowest value (0.12 ml/min/mg), a difference of 3.3 times. Biochanin A-M2 formation had similar intrinsic clearance values for duodenum and ileum but smaller intrinsic clearance values for jejunum, colon, and liver. However, the $V_{max}$
values for biochanin A-M2 formation were very much smaller than that for biochanin-M1 formation (4–13 times smaller).

Glucuronidation of Red Clover Isoflavones in Liver and Jejunum Microsomes. Metabolism of red clover extract was determined using rat liver and jejunum microsomes at biochanin A concentrations ranging from 0.625 to 50 μM. The results indicated that metabolism of biochanin A was saturated in the jejunum microsomes at the highest concentration tested (50 μM) (Fig. 8). Metabolism of biochanin A in the liver microsomes was also saturated at 50 μM (Fig. 8), but metabolite of formononetin was not found. We also determined the metabolism of red clover isoflavones (containing 10 μM biochanin A) using rat liver microsomes from 0.5 to 12 h. The results indicated that formation of biochanin A-M1 increased rapidly between 0.5 and 4 h and became steady afterward. On the other hand, biochanin A-M2 increased slowly before 4 h, continued to increase until 6 h, but became steady after that, indicating that it is not a secondary metabolite of biochanin A-M1, which is expected to be biochanin A-5,7-diglucuronic acid and should form more rapidly after the formation of biochanin A-M1. Very small amounts of formononetin glucuronic acid were found at the beginning, and metabolism of formononetin increased slowly from 1 to 8 h (Fig. 9).

Conversion of Biochanin A to Genistein. Daidzein and genistein were found in bile after their hydrolysis with β-glucuronidase + sulfatase (Fig. 1). The bile concentration was about 19 μM for daidzein or 13 μM for genistein when pure
formononetin or biochanin A were used alone in the perfusion experiments. When red clover isoflavones were perfused, about 7 μM daidzein and 11 μM genistein were collected in the bile. To confirm the conversion of formononetin and biochanin A to daidzein and genistein as observed previously in human liver microsomes (Hu et al., 2003b), we incubated these two compounds individually with rat intestinal microsomes and found measurable conversion. Kinetic studies of conversion of biochanin A to genistein using rat liver microsomes generated a saturable kinetic profile with $V_{\text{max}}$ of $490 \pm 26$ pmol/min/mg protein and $K_m$ of $64.5 \pm 9.04$ μM (Fig. 10). The Eadie-Hofstee plot generated a curvilinear relationship.

### Absorption and Metabolism of Pure Biochanin A and Formononetin in the Caco-2 Model.
Significant amounts of formononetin and biochanin A (10 μM each at the donor side) were metabolized into glucuronidated metabolites during their transport across the Caco-2 cell monolayers. More formononetin was conjugated and excreted to the basolateral side than biochanin A, although similar amounts were excreted apically (Table 3). Amounts of formononetin glucuronic acid found in the basolateral and apical media were 1.6 times of biochanin A glucuronic acid, whereas the rate of excretion was 70% faster. A small amount of sulfated metabolites was also found in both apical and basolateral sides but are not reported here due to their very low concentrations.

### Absorption and Metabolism of Red Clover Isoflavones in the Caco-2 Model.
Significant amounts of biochanin A (10 μM at the donor side) were metabolized into glucuronidated metabolites during their transport across the Caco-2 cell monolayers, but no glucuronidated metabolite of formononetin was found (Table 3). Conjugated metabolites of biochanin A were excreted into both apical and basolateral sides (Table 3). Interestingly, the rate of apical excretion of biochanin A-M1 increased 77% ($p < 0.05$), but the rate of its basolateral excretion did not change, when given as a red clover isoflavone mixture. Additionally, we could not find the presence of sulfates in red clover incubation samples.

### Discussion
One of the main reasons why flavonoids have poor bioavailability is because they are extensively metabolized and participate in metabolic recycling processes, which are enabled by the coupling of efflux transporters and conjugating enzymes (or “enzyme-transporter coupling”) in gut and liver. The best known recycling process (i.e., enterohepatic recycling), which has been shown to be important for the dispo-

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![Fig. 10.](image-url) Demethylated metabolism of biochanin A as a function of concentrations by rat liver microsomes. Simple Michaelis-Menten equation was used to fit the data. The points are experimental values (Investigated), and curve (Estimated) is calculated number based on the fitted parameters (A). Genistein formation was saturated with a $K_m$ value of 64.5 ± 9.04 μM and a $V_{\text{max}}$ value of 490 ± 26 pmol/min/mg protein and $K_m$ of 64.5 ± 9.04 μM (Fig. 10). The Eadie-Hofstee plot generated a curvilinear relationship.
The excretion of isoflavones was found to change greatly and unexpectedly when given as a red clover mixture. We expected decreases in the excretion of both conjugates because of the expected competition for the same enzymes and efflux transporters. Interestingly, however, total amounts of biochanin A-M1 excreted (into the lumen) increased (~30%) in the small intestine, whereas that of the formononetin-M1 decreased about 30 to 50% (Figs. 2B and 3B). As a result, slightly more (p > 0.05) biochanin A conjugates were found in the perfusate than formononetin conjugates (Fig. 3B). Similarly, when formononetin and biochanin A were used alone in the Caco-2 cells, more formononetin-M was excreted than biochanin A-M (Table 3). When they were used together in the red clover mixture, however, only biochanin A-M1 was excreted. Moreover, apical biochanin A-M1 was increased when an isoflavone mixture was used in the Caco-2 study, similar to what we seen in rat luminal excretion (Fig. 5; Table 3).

To account for this unexpected change when isoflavone mixture was used, we examined two factors that will affect the intestinal excretion of conjugated isoflavones: conjugate formation and subsequent excretion of the conjugates. We performed microsomal metabolism studies to determine whether enzyme action could explain the difference. We found that microsomes, prepared from rat intestine and liver, always glucuronidated biochanin A faster than formononetin (p < 0.05), as evidenced by much larger intrinsic clearance values (2-4 times) for biochanin A (Table 2). When a red clover extract was used, glucuronidation of biochanin A by intestinal and liver microsomes decreased significantly (~33% decrease in intrinsic clearance), whereas glucuronidation of formononetin was severely limited (not measurable within 30 min) and much less than biochanin A-M formation in a long-term incubation study (Fig. 9). Therefore, these results suggest that the inhibition of enzyme action is most likely responsible for the difference seen when using a red clover isoflavone mixture.

Is the action of the conjugating enzyme always predictive of intestinal conjugate excretion, as shown above? The answer is no. This is based on our novel finding that a faster glucuronidation in the intestinal or liver microsomes (Table 2; Fig. 7) did not translate into a more extensive metabolite excretion in the intestine or the liver (Figs. 2 and 3). On the contrary, formononetin conjugates were excreted more rapidly than biochanin A conjugates when given alone, even though it has a much lower intrinsic clearance value in all

### Table 3

<table>
<thead>
<tr>
<th>Isoflavone: Pure or Mixture</th>
<th>Isoflavone Aglycone Permeability</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>10⁻⁶ cm/s</td>
</tr>
<tr>
<td>Pure formononetin</td>
<td>16.7 ± 0.22</td>
</tr>
<tr>
<td>Pure biochanin A</td>
<td>16.3 ± 0.10</td>
</tr>
<tr>
<td>Red Clover</td>
<td>13.5 ± 0.07</td>
</tr>
<tr>
<td>Biochanin A</td>
<td>17.3 ± 0.07</td>
</tr>
</tbody>
</table>

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regions of the intestine and the liver (Table 2). The same statement can be made when using $V_{\text{max}}$ as the indicator of conjugate formation. This novel finding again demonstrates the importance of studying the enzyme-transporter coupling process as a whole using the intact cell system, where one can measure the dynamic interplay between conjugating enzymes and efflux transporters.

This enzyme-transporter coupling has been proposed to account for the intestinal disposition of apigenin in Caco-2 cells (Hu et al., 2003a). Here, we have showed again that the overall efficiency of enzyme-transporter coupling could affect in vivo/in situ excretion. For example, a more rapid excretion of formonononetin conjugates into lumen or bile was caused by more rapid excretion of these conjugates since formonononetin was glucuronidated much slower than biochanin A. Additionally, the percent decrease in the excretion of metabolites (about 3 times) was far less than percent decrease in metabolism of formonononetin (>10 times) when using the red clover extract. Therefore, we found formonononetin conjugates in the bile and luminal perfusate even though the same metabolites could not be found within 30 min using the microsomes. Taken together, these results demonstrate again that cellular excretion of conjugated isoflavones is under the control of enzyme-transporter coupling. As such, the use of an isoflavone mixture can significantly impact the in vivo disposition of its individual component in a way not readily expected from performing only one set of studies (either microsomal metabolism or perfusion).

The enzyme-transport coupling may also be used to compare how efficient the coupling process functions in the intestine versus liver. Although intestinal microsomes metabolized biochanin A and formonononetin much more efficiently (higher intrinsic clearance values) than liver microsomes (Fig. 7; Table 2), there were more metabolites in bile (40–50% more) when a pure isoflavone was perfused (Fig. 4). Assuming biliary metabolites are produced in liver, the hepatic coupling process must be more efficient than intestinal coupling process, even if we have perfused 100% of the intestine (i.e., double the length). This is because the concentration of these isoflavones in the hepatocytes (probably less than 1 $\mu$M) is expected to be much lower than that in the enterocytes, which is expected to be closer to the perfusate concentration of 10 $\mu$M. An alternative explanation for the higher biliary excretion is that the intestinal conjugates are transported into the hepatocytes and then excreted into the bile. This possibility is supported by a recent study by O'Leary et al. (2003), which showed a slow but measurable uptake of phase II conjugates by human liver HepG2 cells. Lastly, the large number of hepatocytes that can contribute to the conjugate excretion via MRP2 may also be used to explain the difference. Future studies are needed to sort if any or all of these factors are involved.

Besides phase II metabolism, there was also significant phase I metabolism. Daidzein and genistein were found in bile after treating the bile with $\beta$-glucuronidase + sulfatase (Fig. 1). In addition, conversion of biochanin A to genistein in rat liver microsomes was found to be rapid and saturable (Fig. 10). Multiple cytochrome P450 isoforms probably participate in this demethylation reaction since the Eadie-Hofstee plot is curvilinear, which was shown previously using human liver microsomes (Tolleson et al., 2002; Hu et al., 2003b). Nevertheless, demethylation in rats appeared to be faster than that in human liver microsomes (Tolleson et al., 2002).

In conclusion, our studies clearly showed that formonononetin and biochanin A are metabolized by multiple isoforms of UGT. In addition, intestinal and hepatic excretion of isoflavone conjugates is affected by the coupling efficiency of the conjugating enzymes and efflux transporters. As a consequence, the disruption of the major component will significantly decrease the excretion of formononetin conjugates. Taken together, our studies indicate that the efficiency of organ specific coupling will determine the relative magnitudes of intestinal versus hepatic excretion of isoflavone conjugates, which in turn will affect the relative contribution of enteric recycling versus enterohepatic recycling.

References


Hu M, Krausz K, Chen J, Ge X, Li J, Gelboin HL, and Gonzalez FJ (2003b) Identification of CYP1A2 as the main isoform for the phase I hydroxylated metabolism of genistein and a produg converting enzyme of methylated isoflavones. Drug Metab Dispos 31:924–931.


