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The Gut Microbiota Ellagic Acid-Derived Metabolite Urolithin A and Its Sulfate Conjugate Are Substrates for the Drug Efflux Transporter Breast Cancer Resistance Protein (ABCG2/BCRP)

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Supporting Information

ABSTRACT: The breast cancer resistance protein (BCRP/ABCG2) is a drug efflux transporter that can affect the pharmacological and toxicological properties of many molecules. Urolithins, metabolites produced by the gut microbiota from ellagic acid (EA) and ellagitannins, have been acknowledged with in vivo anti-inflammatory and cancer chemopreventive properties. This study evaluated whether urolithins (Uro-A, -B, -C, and -D) and their main phase II metabolites Uro-A sulfate, Uro-A glucuronide, and Uro-B glucuronide as well as their precursor EA were substrates for ABCG2/BCRP. Parental and Bcrp1-transduced MDCKII cells were used for active transport assays. Uro-A and, to a lesser extent, Uro-A sulfate showed a significant increase in apically directed translocation in Bcrp1-transduced cells. Bcrp1 did not show affinity for the rest of the tested compounds. Data were confirmed for murine, human, bovine, and ovine BCRP-transduced subclones as well as with the use of the selective BCRP inhibitor Ko143. The transport inhibition by Uro-A was analyzed by flow cytometry compared to Ko143 using the antineoplastic agent mitoxantrone as a model substrate. Results showed that Uro-A was able to inhibit mitoxantrone transport in a dose-dependent manner. This study reports for the first time that Uro-A and its sulfate conjugate are ABCG2/BCRP substrates. The results suggest that physiologically relevant concentrations of these gut microbiota-derived metabolites could modulate ABCG2/BCRP-mediated transport processes and mechanisms of cancer drug resistance. Further in vivo investigations are warranted.

KEYWORDS: *urolithin, ellagic acid, ABCG2/BCRP transporters, gut microbiota, Bcrp1-MDCKII cells*

INTRODUCTION

ABCG2/BCRP is an ATP-binding cassette (ABC) transporter that mediates energy-dependent translocation of substrates from cells in the intestine, liver, kidney, mammary gland, etc., across cellular membranes, affecting the pharmacokinetics and disposition of drugs and other compounds such as xenotoxins and endogenous compounds in tissues and mediating drug−drug interactions.[1,2] The multifunctional behavior of ABCG2/BCRP linked to great substrate specificities for a wide range of compounds supported its important role in homeostatic processes.[3,4] In addition, the modulation of ABCG2/BCRP transporters can affect chemotherapeutic treatments by modulating the pharmacokinetic behavior of anticancer drugs.[5−7]

Some in vitro and in vivo studies using BCRP-overexpressing cell lines and/or knockout mice have indicated that plant-derived polyphenols such as flavonoids and the stilbene resveratrol can interact directly with BCRP by modulating both its transport function and ATPase activity.[8−12] Recently, the important role of ABCG2/BCRP in the transport of glucuronide and sulfate conjugates of polyphenols including the flavonoids naringenin, genistein, and daidzein,[13−15] as well as resveratrol conjugates,[16] has been described.

Urolithins are dibenzopyran-6-one derivatives produced from ellagitannins and ellagic acid (EA) by the gut microbiota through the loss of one lactone ring present in ellagic acid (EA) and successive removals of hydroxyl groups[17−19] (Figure 1). Urolithins have been found in plasma, urine, feces, and tissues in a number of animals including the pig,[20] rat,[21−23] mouse,[24] beef cattle,[25] etc. Urolithins are also produced by humans, and their occurrence has been reported in plasma, feces, urine,[17,19,26,27] and also prostate tissue[28] after the intake of ellagitannin-containing foods such as pomegranates, strawberries, raspberries, walnuts, and oak-aged wines. Phase II derived conjugates of urolithins reach the plasma and systemic organs at low micromolar concentrations, whereas high concentrations of the aglycone forms can be found in the gut.[20,23]

In the past decade, after our first report about the occurrence of urolithins in humans,[17] numerous in vitro and in vivo studies have shown a wide range of biological activities of urolithins, mainly attributed to Uro-A, such as anticancer,[23,24,29−31] anti-

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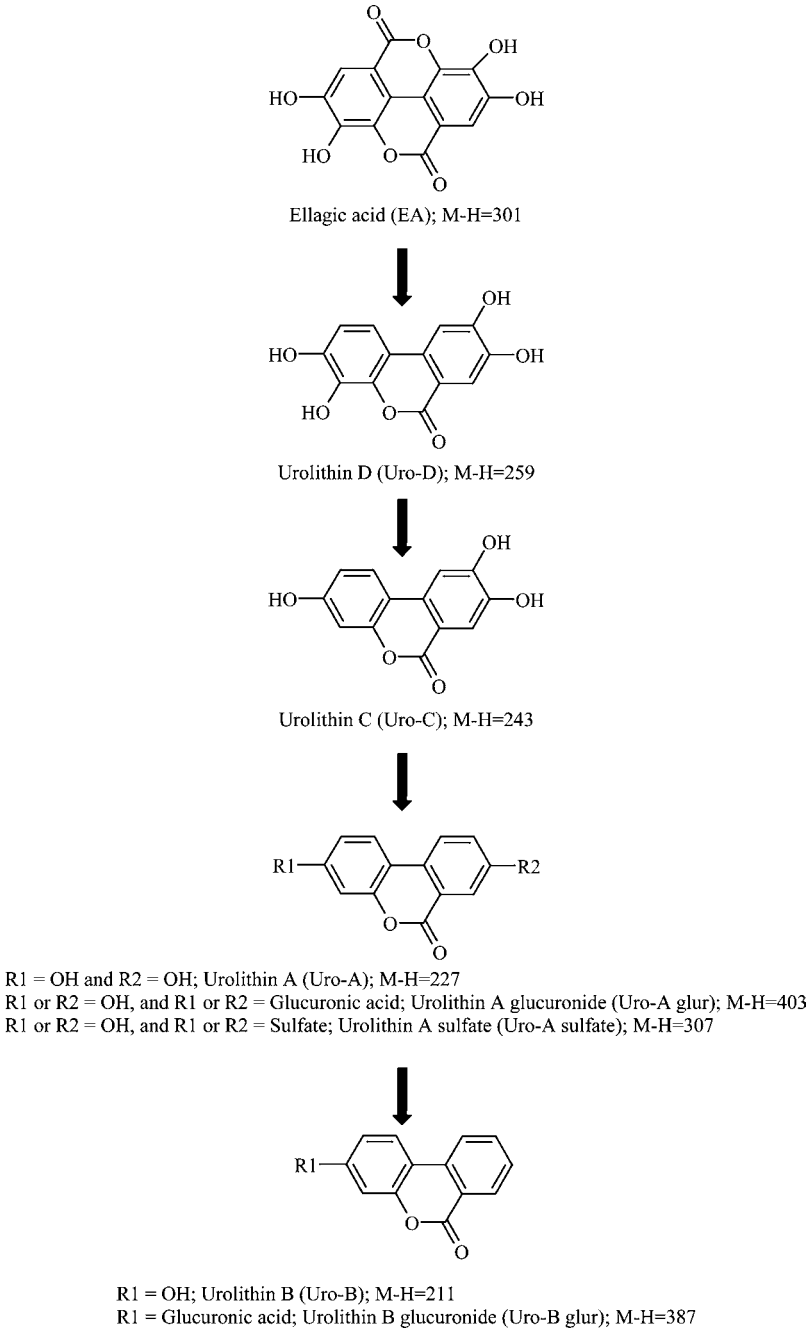

Figure 1. Chemical structures of EA, Uro-D, Uro-C, Uro-A, and Uro-B. The arrows designate the sequence of metabolic steps carried out by the gut microbiota.

inflammatory,[32−36] antibacterial,[37] and estrogenic/antiestrogenic.[38] However, the possible role of ABC transporters in the bioavailability of urolithins remains unknown.

Our aim was to evaluate whether ellagic acid (EA), urolithins A, B C, and D (Uro-A, Uro-B, Uro-C, and Uro-D), and their main glucuronide and sulfate derivates (Uro-A glucuronide, Uro-B glucuronide, and Uro-A sulfate) might be ABCG2/BCRP substrates and/or inhibitors.

MATERIALS AND METHODS

Materials. EA was purchased from Sigma-Aldrich (St. Louis, MO, USA). Urolithin A (3,8-dihydroxy-6*H*-dibenzo[*b*,*d*]pyran-6-one; Uro-A) and urolithin B (3-hydroxy-6*H*-dibenzo[*b*,*d*]pyran-6-one; Uro-B) were synthesized as described previously.[39] Uro B glucuronide (Uro-B glur) was prepared according to the method of Lucas et al.[40] Urolithin A glucuronide (Uro-A glur) and urolithin A sulfate (Uro-A sulfate) were prepared as a mixture of regioisomers (Figure 2). Experimental procedure and ^{1}H NMR data for the synthesis of Uro-A and Uro-A sulfate are detailed in the Supporting Information. Briefly, Uro-A was first monoprotected with a silyl protecting group (Figure 2A). Random (*tert*-butyldimethylsilyl) (TBDMS) protection[41] of Uro-A and subsequent chromatographic separation afforded the two possible monophenolic derivatives **1** and **2** as a regioisomeric mixture (1:1) and the double-silylated Uro-A. The glycosylation reaction of acceptors **1** and **2** with glucuronosyl donor **3** was performed using the same conditions described previously[40] to give compounds **4** and **5** as a regioisomeric mixture (83%). Ester hydrolysis and deprotection of acetyl and TBDMS groups were carried out in one step by using K_2CO_3 and KF in a methanol−water solution. Reverse phase purification of the crude afforded a 1:1 regioisomeric mixture of

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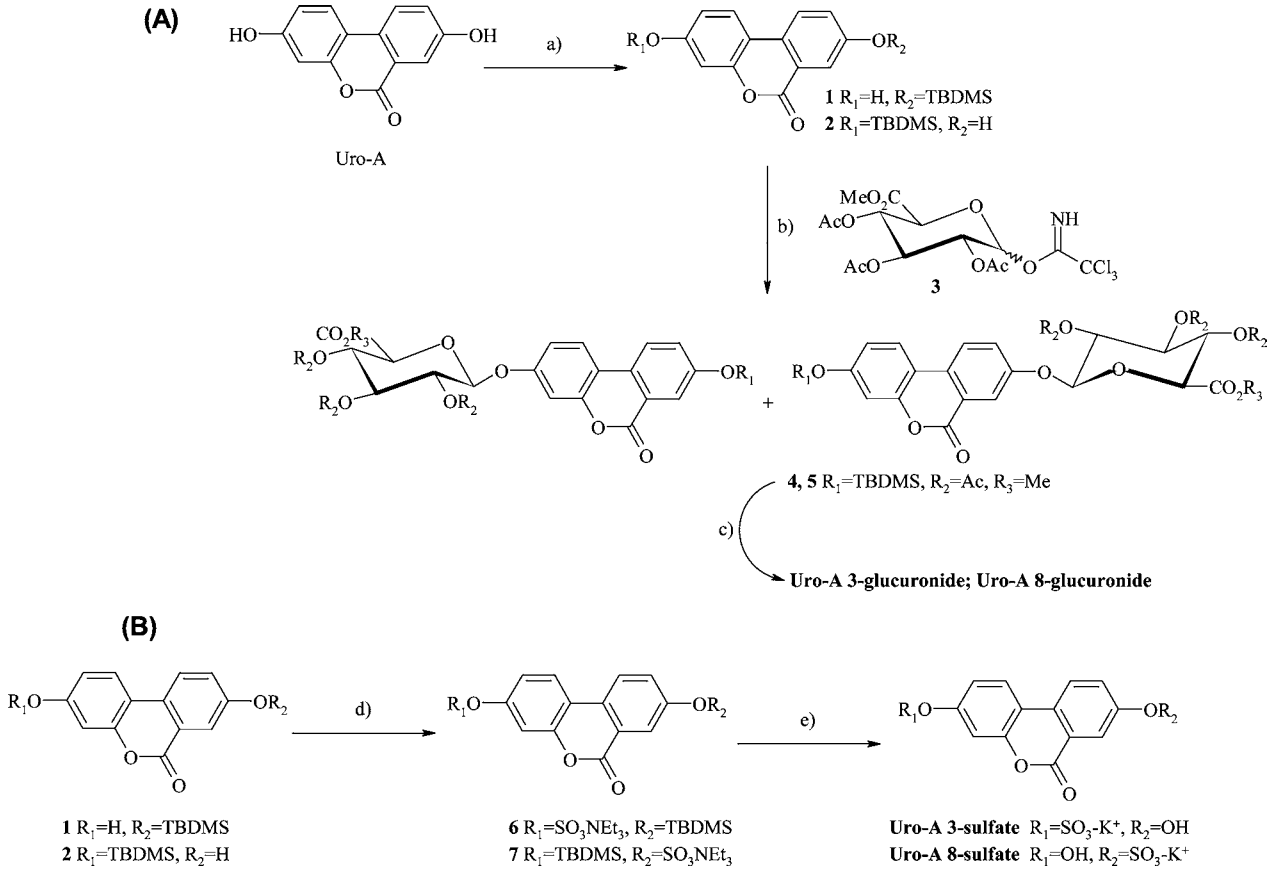

Figure 2. (A) Synthesis of Uro-A glucuronates: (a) TBDMSTfO, DIPEA (*N*,*N*-diisopropylethylamine), CH_2Cl_2; (b) $BF_3{}^{\bullet}OEt_2$; CH_2Cl_2, glucuronate donor **3**; (c) K_2CO_3, KF, MeOH/H_2O (5:1). (B) Synthesis of Uro-A sulfates: (d) $SO_3{}^{\bullet}NMe_3$, NEt_3, CH_3CN, 100 °C, 20 min, MW; (e) KF, MeOH.

Uro-A 3-glucuronide and Uro-A 8-glucuronide (Figure 2A). Uro-A sulfate was also prepared as a mixture of regioisomers following a similar strategy to the one used for the glucuronate derivatives (Figure 2B). Sulfation of the monosilylated urolithin derivatives **1** and **2** was carried out with $SO_3{}^{\bullet}NMe_3$ as sulfating reagent, NEt_3 as base, and acetonitrile as solvent at 100 °C under microwave radiation for 20 min. The reaction afforded the sulfated 1:1 mixture of urolithin derivatives **6** and **7** in 92% yield (Figure 2B). Final silyl deprotection with KF and reverse phase purification gave a 1:1 mixture of Uro-A 3-sulfate and Uro-A 8-sulfate (73% yield). Urolithin C (3,7,8-trihydroxy-6*H*-dibenzo[*b*,*d*]pyran-6-one, Uro-C) and urolithin D (2,3,7,8-tetrahydroxy-6*H*-dibenzo[*b*,*d*]pyran-6-one, Uro-D) were purchased from Dalton Pharma Services (Toronto, Canada). Purity was >95% in all tested compounds. Dimethyl sulfoxide (DMSO), diethyl ether, and HPLC reagents, formic acid and acetonitrile (ACN), were obtained from Panreac (Barcelona, Spain). Methanol (MeOH) was from Lab-Scan (Gliwice, Poland). Ko143 was purchased from Tocris (Bristol, UK). Ultrapure Millipore water was used for all of the experiments.

Cell Lines and Cell Culture Conditions. Mardin−Darby canine kidney (MDCKII) cells and their human BCRP-transduced and murine Bcrp1-transduced subclones were kindly provided by Dr. A. H. Schinkel, Netherlands Cancer Institute (Amsterdam). MDCKII cells stably transduced with bovine and ovine variants of ABCG2 have recently been generated by the research group.[42,43] Culture conditions were as previously described.[44] The cells were cultured in Dulbecco's modified Eagle's medium (DMEM) containing GlutaMAX (Life Technologies, Inc., Madrid, Spain) and supplemented with penicillin (50 U/mL), streptomycin (50 μg/mL), and 10% (v/v) fetal calf serum (MP Biomedicals, Cambridge, UK) at 37 °C in the presence of 5% CO_2. The cells were trypsinized every 3−4 days for subculturing. All of the test samples were solubilized in DMSO (<0.5% in the culture medium) and were filter sterilized (0.2 μm) prior to addition to the culture media. Control cells were also run in parallel and subjected to the same changes in medium with 0.5% DMSO.

Transport Studies. Transepithelial transport assays using Transwell plates were carried out as described previously[10,42] with minor modifications. Cells were seeded on microporous polycarbonate membrane filters (3.0 μm pore size, 24 mm diameter; Transwell 3414; Costar) at a density of 1.0×10^6 cells per well. Cells were grown for 3 days, and the medium was replaced every day. Transepithelial resistance was measured in each well using a Millicell ERS ohm-meter (Millipore). Wells registering a resistance of ≥200 Ω, after correction for the resistance obtained in blank control wells, were used in the transport experiments. The measurement was repeated at the end of the experiment to check the tightness of the monolayer.

Before the start of the experiment, medium on both sides of the monolayer was replaced with 2 mL of Optimem medium (Life Technologies), without serum. After 2 h of preincubation, the experiment was started by replacing the medium in either the apical or basolateral compartment with fresh Optimem medium containing 20 μM of the compound tested (except the preliminary screening, which was performed at 10 μM). Aliquots of 100 μL were taken from the opposite compartment at 2 and 4 h and stored at −20 °C until LC-MS analysis. In the cotreatments assays, the inhibitor Ko143 (1 μM) was added 2 h before each compound and remained during all of the experiment. Experiments were carried out in triplicate.

Accumulation Assays. In vitro accumulation assays were carried out as described previously using mitoxantrone (MXR, 10 μM) as fluorescent substrate.[45] In brief, subconfluent cultures were used after 36 h from seeding. Cells were incubated in Optimem medium with or without Ko143 inhibitor (1 μM) or EA and urolithins A, B, C, and D at different concentrations for 60 min before the addition of MXR. All compounds were applied on the apical side. Accumulation of MXR was allowed for 1 h at 37 °C. Then, cells were washed, trypsinized,

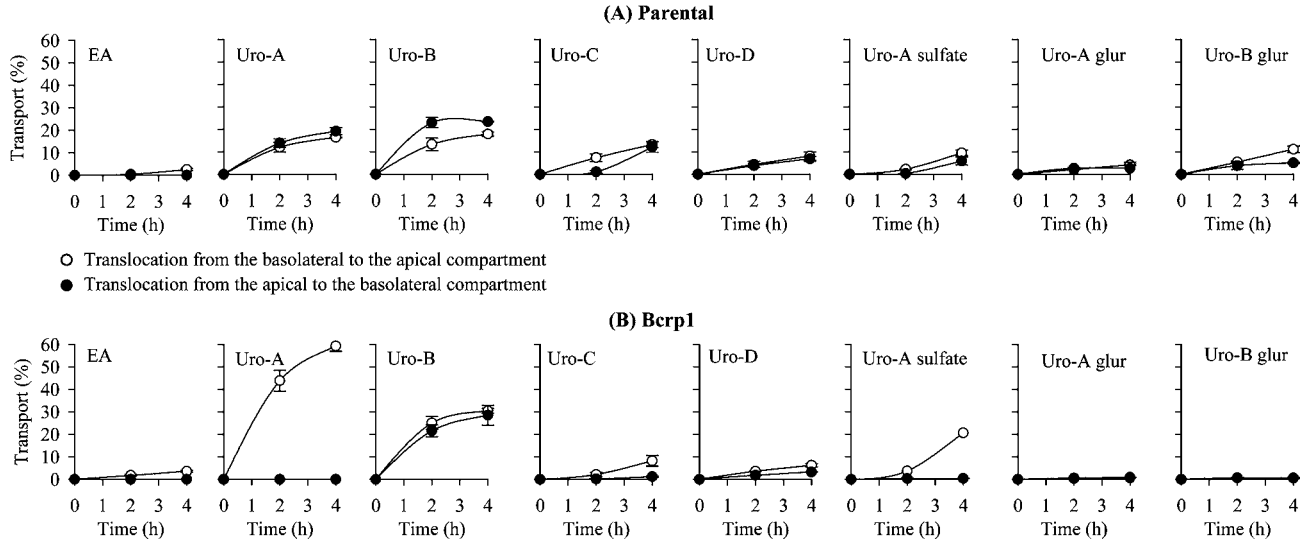

Figure 3. Transepithelial transport of tested compounds (10 μM) in (A) parental MDCKII cells and (B) their murine Bcrp1-transduced derivatives: (○) translocation from the basolateral to the apical compartment; (●) translocation from the apical to the basolateral compartment. The experiment was started with the addition of each compound to one compartment (basolateral or apical). After 2 and 4 h, the percentage of each compound appearing in the opposite compartment was measured by LC-MS and plotted. Data are expressed as mean values ± SD (n = 3).

collected, and resuspended in PBS with 2.5% fetal calf serum. Relative cellular accumulation of MXR of at least 5000 cells was determined by flow cytometry using a FACSCalibur cytometer (BD Biosciences, Franklin Lakes, NJ, USA). Samples were gated on forward scatter versus side scatter to exclude cell debris and clumps. Excitation and emission wavelengths for MXR were 635 and 650 nm, respectively. The fluorescence of the accumulated substrate in tested populations was quantified from histogram plots using the median of fluorescence (MF). At least three independent experiments were performed.

BCRP inhibition increases accumulation of MXR in Bcrp1/BCRP-transduced cells and thus increases MF. Possible background fluorescence of urolithins was checked in appropriate channels, but the fluorescence was negligible. Flow cytometry data were processed and analyzed using WinMDI version 2.8 software.

Percentage of inhibition was calculated according to the following equation: % inhibition = (MF with tested compound in BCRP cells − MF without tested compound in BCRP cells)/(MF with inhibitor Ko143 in BCRP cells − MF without tested compound in BCRP cells) × 100.

Sample Processing for the Analysis of Urolithins and Their Derivates. Cell media after transport studies was processed as described elsewhere.[35] Briefly, ACN (100 μL) was added to 100 μL of culture media, vortexed, and centrifuged at 16435g for 10 min. The supernatant was then concentrated in a Speedvac concentrator Savant SPD121P (Thermo Scientific, Alcobendas, Spain) and the residue redissolved in 100 μL of MeOH and filtered (0.45 μm) before analysis by LC-MS using the conditions described below.

LC-MS Analysis. Aliquots of processed cell media were analyzed using an LC-MS system (1200 Series, Agilent Technologies, Madrid, Spain). The HPLC system was equipped with a 100 × 3 mm i.d., 2.7 μm, reverse phase C18 column (Poroshell 120, Agilent) and a single-quadrupole mass detector in series (6120 Quadrupole, Agilent). Water/formic acid (99:1, v/v) and ACN were used as mobile phases A and B, respectively, with a flow rate of 0.5 mL/min. The linear gradient started with 5% of solvent B in solvent A, reaching 18% solvent B at 7 min, 28% at 17 min, 50% from 22 min, and 90% at 27 min, which was maintained up to 29 min. The initial conditions were re-established at 29 min and kept under isocratic conditions up to 33 min. Injections (5 μL) were made for each sample at 25 °C. The mass detector was a quadrupole mass spectrometer equipped with an ESI system (capillary voltage, 3.5 kV; dry temperature, 350 °C; drying gas flow, 9 L/min; nebulizer pressure, 40 psi). MS spectra were measured in selective ion monitoring (SIM) mode using [M − H] ions for measuring all tested compounds. MS data were acquired in the negative ionization mode. Identification of all tested compounds was carried out by direct comparison (UV spectra and MS) with available standards and confirmed by their spectral properties, molecular mass, and fragmentation pattern. Calibration curves were obtained for each tested compound with good linearity (r^2 > 0.999). EA was quantified at 360 nm and urolithins and their conjugates were quantified at 305 nm using the corresponding available standards.

Statistical Analysis. All data are presented as mean values ± SD (n = 3). A two-tailed unpaired Student's t test was used for statistical analysis of the data. A p value of <0.05 was considered to be significant.

RESULTS

Initial Screening of the Transport of Urolithins and EA on Parental and Bcrp1-Transduced MDCKII Cell Models. As initial screening, we used the polarized canine kidney cell line MDCKII and its subclone transduced with murine Bcrp1 cDNAs to test the possible role of Bcrp1 in the in vitro transport of EA, urolithins, and some representative in vivo conjugates (Figure 1) at 10 μM for 2 and 4 h.

In the MDCKII parental cell line, both Uro-A and Uro-B aglycones showed similar apically and basolaterally directed translocations, with percentages of transport around 20% at 4 h, whereas the transport values for the rest of compounds were lower (Figure 3A).

In the murine Bcrp1-transduced MDCKII cell line the most remarkable results were found for Uro-A and Uro-A sulfate, in which translocation from the basolateral to the apical compartment significantly increased in comparison with parental cells (Figure 3B). The rest of the compounds showed no changes in the Bcrp1-transduced MDCKII cell line compared to parental cells. Overall, these results showed an efficient transport of Uro-A by murine Bcrp1 and a moderate transport for its sulfate conjugate in the cell line assayed.

Transport of Uro-A and Uro-A Sulfate by Human, Murine, Bovine, and Ovine BCRP-Transduced Subclone Cells in the Absence or Presence of Ko143. As the transport of Uro-A by murine Bcrp1-transduced subclone cells was higher than in the rest of compounds, we next determined the vectorial transport of Uro-A (20 μM) across human, murine, bovine, and ovine BCRP-transduced MDCKII cells.

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The transport of Uro-A on all transduced subclones showed a significant time-dependent increase in the apically directed translocation, whereas the basolaterally directed translocation was drastically decreased versus parental cells (around 10% of transport at 4 h) (Figure 4). Among the transduced subclones, the apically directed translocation of Uro-A was higher on murine Bcrp1 (around 40% of transport at 4 h) followed by ovine BCRP (around 30% of transport at 4 h), human BCRP (around 20% of transport at 4 h), and finally bovine BCRP (around 16% of transport at 4 h) (Figure 4).

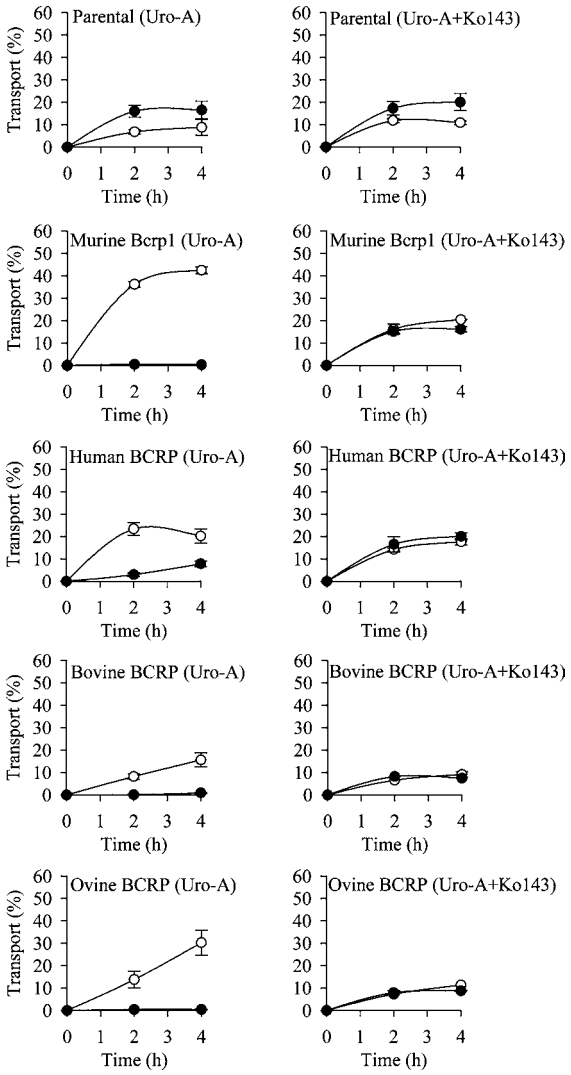

Figure 4. Transepithelial transport of Uro-A (20 μM) in parental MDCKII cells and in their murine Bcrp1- and human, bovine, and ovine BCRP-transduced subclones in the absence or presence of Ko143 (1 μM): (○) translocation from the basolateral to the apical compartment; (●) translocation from the apical to the basolateral compartment. The experiment was carried out as indicated in Figure 2. Data are expressed as mean values ± SD (n = 3).

In addition, we next confirmed the transport of Uro-A mediated by ABCG2/BCRP by performing a cotreatment with a selective BCRP inhibitor, Ko143 (1 μM) on all MDCKII subclones. The BCRP-mediated transport of Uro-A was completely inhibited in all transduced cells, resulting in a vectorial translocation pattern equal to that of the MDCKII parental cell line (Figure 4) and thus confirming that Uro-A is transported by ABCG2/BCRP.

Due to the small available amount of the standard Uro-A sulfate, we focused on the study of the transport of this metabolite by only murine Bcrp1 and human BCRP (Figure 5). There was a significant increase in the apically directed translocation for Uro-A sulfate using human BCRP-transduced MDCKII cells (2.5-fold increase compared to parental cells; around 50% of transport at 4 h), which was higher than that observed for murine Bcrp1 (Figure 5). Therefore, these data confirmed that Uro-A sulfate is also a natural ABCG2/BCRP substrate.

Inhibitory Activity Evaluation. To show the potential inhibitory effect of urolithins on ABCG2/BCRP, the ability of these compounds to reverse the reduced MXR accumulation in cells transduced with the transporter was tested in flow cytometry experiments. Percentage of inhibition of the different concentrations of Uro-A for Bcrp1/BCRP-transduced cells was related to the effect of reference inhibitor Ko143 (set at 100% inhibition of ABCG2/BCRP).

Our results showed that Uro-A was able to inhibit ABCG2/BCRP increasing, in a dose-dependent manner, the accumulation of MXR in human BCRP and murine Bcrp1 transduced cells, showing percentages of inhibition of 40−50% at 50 μM (Figure 6). This result supported the strong interaction between Uro-A and the transporter, showing its important potential as inhibitor because other tested compounds such as urolithins B, C, and D and EA at 50 and 100 μM did not show any inhibition (data not shown).

■ DISCUSSION

Uro-A, the most abundant urolithin produced by humans,[46] has been reported to be the most active urolithin with acknowledged in vitro[23,24,29,30,33,35] and in vivo[32,47] anti-inflammatory and anticarcinogenic activities. With regard to the biological activity of the phase II conjugates, the main in vivo circulating conjugate, Uro-A glur, has shown to decrease the TNF-α-induced inflammation in endothelial cells.[36]

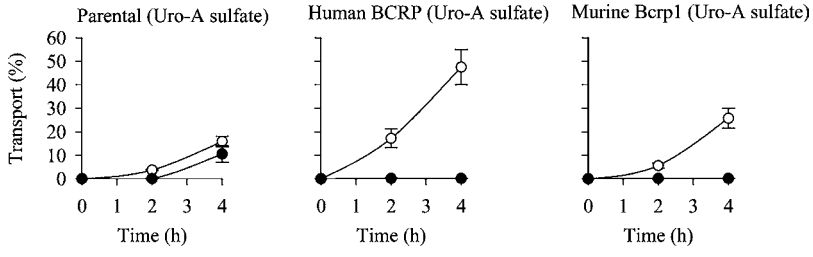

Figure 5. Transepithelial transport of Uro-A sulfate (20 μM) in parental MDCKII and in their murine Bcrp1- and human BCRP-transduced derivatives: (○) translocation from the basolateral to the apical compartment; (●) translocation from the apical to the basolateral compartment. The experiment was carried out as indicated in Figure 2. Data are expressed as mean values ± SD (n = 3).

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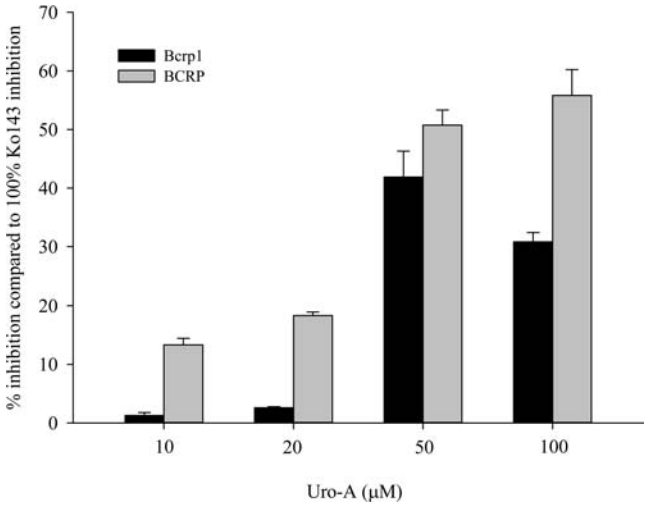

Figure 6. Percentage of inhibition of the different concentrations of Uro-A for Bcrp1/BCRP-transduced cells in mitoxantrone accumulation assays. Data are expressed as mean values ± SD (n = 3). Percentage of inhibition was related to the effect of reference inhibitor Ko143 (set at 100% inhibition of ABCG2/BCRP).

Taking into account the above, we evaluated whether urolithins and some representative circulating conjugates could be substrates for ABCG2/BCRP at a physiologically relevant concentration (20 μM).[20,23] For this purpose we examined their active transport using a parental and murine Bcrp1-transduced MDCKII cell model. Our results indicated that only Uro-A, and also its sulfate conjugate, showed a significant increase in the apically directed translocation together with a decrease of the basolaterally directed translocation compared to parental cells. In contrast, Bcrp1 showed no affinity for the urolithin precursor EA and the rest of the urolithins and glucuronide conjugates.

Our results indicate that the affinity of ABCG2/BCRP for urolithins seems to be influenced by the number and position of hydroxyl groups in the urolithin scaffold. In the present study, BCRP showed affinity only for Uro-A, with two hydroxyl groups in 3- and 8-positions (Figures 1 and 2). In this regard, a structure−activity relationship (SAR) study comparing the BCRP inhibitory effect of 12 different flavonoids indicated that flavones were more efficient than flavonols, isoflavones, and flavanones due to the occurrence of hydroxyl groups (OH−) at the 5-position, in contrast to positions 3 and 7 in flavones.[48] More recently, another SAR study in flavonoids confirmed that an OH− group in the 5-position contributed positively to BCRP inhibition because the replacement of this OH− group by a 3-methoxy group resulted in a decrease in the affinity.[49] Our results in urolithins also support the potential role of OH− groups in the interaction with BCRP. The presence of an OH− group at the 8-position, but not at the 3-position, might favor the interaction with BCRP, which was supported by the lack of interaction between BCRP and Uro-B, with only one OH− group at the 3-position (Figure 1). In the case of urolithin A conjugates (sulfate and glucuronide), the possible explanation is more difficult. The chemical synthesis of Uro-A glur and Uro-A sulfate yielded a mixture of 50% Uro-A 3-glur and 50% Uro-A 8-glur for the glucuronides and also 50% Uro-A 3-sulfate and 50% Uro-A 8-sulfate in the case of the sulfate conjugate (Figures 1 and 2). Therefore, some affinity of BCRP for Uro-A glur should be expected because the 8-position was 50% available, as in the case or Uro-A sulfate. However, whereas Uro-A sulfate was a BCRP substrate, Uro-A glur was not transported at all (Figure 3). In addition, the occurrence of additional hydroxyl groups (Uro-C and Uro-D; Figure 1) decreased the affinity of BCRP for urolithins. Overall, the above rationale is coincident, at least in part, with that launched in a previous study where estrogenic receptors (α and β) showed higher affinity for Uro-A than for Uro-B.[38] The transport of Uro-A sulfate (Figure 5) confirms that ABCG2/BCRP might be a general phytoestrogen transporter for a structurally diverse array of phytoestrogen sulfates including sulfate conjugates of enterolignans, isoflavones, and coumestans, under physiological conditions.[50] Interestingly, it was also found that the inhibitory potency against ABCG2/BCRP of daidzein-7-glucuronide was 100-fold lower than that of daidzein, whereas daidzein-4-sulfate showed an inhibitory potency comparable to that of daidzein.[51]

In the present study, the affinity of ABCG2/BCRP for Uro-A was also confirmed for bovine and ovine BCRP as well as for human BCRP transporters in the line of recent studies that have included the comparative inhibition among murine Bcrp1, bovine and ovine BCRP, and human BCRP.[14,42,52,53] In vitro results showed an efficient and dose-dependent inhibition of Uro-A with percentages observed of 40−50% with a concentration of 50 μM for human BCRP and murine Bcrp1 in MXR accumulation assays, in agreement with known BCRP inhibitors such as the flavonoid biochanin A.[54] In addition, these data showed the potential of Uro-A as a reversal agent in chemotherapy treatments with regard to the multidrug resistance (MDR) phenotype.[7]

These results indicate that urolithins, also produced by cattle,[25,55] could interact with BCRP, affecting the oral bioavailability of drugs (antibiotics and others) and drug transport across barriers as previously described for the isoflavones genistein and daidzein.[10] On the other hand, the contribution of the phytochemical glucuronide transport by ABCC2/MRP2 and ABCC3/MRP3[15,56] should be considered in further studies taking into account the plasma metabolic profile of urolithins.[17]

The present study shows, for the first time, that Uro-A and Uro-A sulfate are transported by ABCG2/BCRP in the apically directed translocation. Moreover, Uro-A acts as inhibitor of the transporter in vitro. On the contrary, the urolithin precursor EA as well as Uro-B, -C, and -D and the phase II conjugates Uro-A glur and Uro-B glur were not transported. It has been reported that the dietary consumption of ellagitannin- or ellagic acid-containing foods (pomegranate, strawberries, walnuts, etc.) can exert anti-inflammatory effects due to the in vivo formation of Uro-A by the gut microbiota.[32,46] However, the results obtained here also suggest that Uro-A might influence the pharmacokinetics and bioavailability of drug levels, which could lead to potential adverse effects. Therefore, further in vivo studies should clarify this hypothesis.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedure for the synthesis of Uro-A glucuronide and Uro-A sulfate. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ABBREVIATIONS USED

ABC, ATP-binding cassette; ACN, acetonitrile; BCRP, breast cancer resistance protein; cDNA, cDNA; DIPEA, *N*,*N*-diisopropylethylamine; DMSO, dimethyl sulfoxide; EA, ellagic acid; Glur, glucuronide; HPLC, high-performance liquid chromatography; MDCKII, Mardin−Darby canine kidney; MDR, multidrug resistance; MeOH, methanol; MRP, multidrug resistant protein; MXR, mitoxantrone; OH−, hydroxyl group; SD, standard deviation; SIM, selective ion monitoring; SAR; structure−activity relationship; TBDMS, *tert*-butyldimethylsilyl; TNF-α, tumor necrosis factor-alpha; Uro-, urolithin

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