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Distribution of Gefitinib to the Brain is Limited by P-glycoprotein (ABCB1) and Breast Cancer Resistance Protein (ABCG2) Mediated Active Efflux

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P-gp and BCRP limit brain distribution of gefitinib

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List of Abbreviations

CNS, central nervous system; BBB, blood-brain-barrier; MDR1, multi-drug resistance protein 1; P-gp, p-glycoprotein; BCRP, breast cancer resistance protein; TKI, tyrosine kinase inhibitors; A-to-B, apical-to-basolateral; B-to-A, basolateral-to-apical; Peff, effective permeability; B/P, brain-to-plasma; ER, efflux ratio; GBM, glioblastoma multiforme; EGFR, epidermal growth factor receptor; EGFRvIII, epidermal growth factor receptor mutant vIII; Mdr1, gene encoding the murine p-glycoprotein; MDR1, gene encoding the human p-glycoprotein; Bcrp1, gene encoding the murine breast cancer resistance protein.
Abstract

Gefitinib is an orally active inhibitor of the epidermal growth factor receptor (EGFR) approved for use in patients with locally advanced or metastatic non-small-cell lung cancer. It has also been evaluated in several clinical trials for treatment of brain tumors such as high-grade glioma. In this study, we investigated the influence of p-glycoprotein (P-gp) and breast cancer resistance protein (BCRP) on distribution of gefitinib to the central nervous system. In vitro studies conducted in MDCKII cells indicate that both P-gp and BCRP effectively transport gefitinib limiting its intracellular accumulation. In vivo studies demonstrated that transport of gefitinib across the blood-brain barrier (BBB) is significantly limited. Steady-state brain-to-plasma (B/P) concentration ratios were 70-fold higher in the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice (ratio ~7) compared with wild-type mice (ratio ~ 0.1). The B/P ratio after oral administration increased significantly when gefitinib was co-administered with the dual P-gp and BCRP inhibitor elacridar. We investigated the integrity of tight junctions in the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice and found no difference in the brain inulin and sucrose space between the wild-type and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice. This suggested that the dramatic enhancement in the brain distribution of gefitinib is not due to a leakier BBB in these mice. These results show that brain distribution of gefitinib is restricted due to active efflux by P-gp and BCRP. This finding is of clinical significance for therapy in brain tumors such as glioma, where concurrent administration of a dual inhibitor like elacridar can increase delivery and thus enhance efficacy of gefitinib.
Introduction

Malignant gliomas account for approximately 70% of all new cases of malignant primary brain tumors diagnosed in the United States every year. Glioblastoma Multiforme (GBM) is the most common type of glioma, accounting for approximately 60 to 70% of malignant gliomas (CBTRUS, 2008; Wen and Kesari, 2008) and claiming 12,000 lives every year (Davis et al., 2001). Epidermal growth factor receptor (EGFR) and its variant EGFRvIII play a critical role in the development of an aggressive phenotype of GBM; EGFR amplification, mutation and overexpression are associated with poor prognosis and resistance to therapy (Brandes et al., 2008). Several therapeutic strategies targeting EGFR in GBM have been proposed, including the use of monoclonal antibodies against EGFR or EGFRvIII, vaccine therapies, bispecific antibodies, toxin-linked conjugates and small molecule tyrosine kinase inhibitors (Omuro et al., 2007).

In recent years, several small molecule inhibitors targeting the tyrosine kinase EGFR have been introduced in clinical practice. Gefitinib (Iressa, ZD1839, AstraZeneca Pharmaceuticals) is an orally active compound that is a reversible inhibitor of the tyrosine kinase activity associated with EGFR, blocking EGFR signal transduction pathways (Arteaga and Johnson, 2001; Ciardiello and Tortora, 2001; Culy and Faulds, 2002). Despite equivocal results in phase III clinical trials (Giaccone et al., 2004; Herbst et al., 2004), gefitinib was the first drug of its kind to be approved by the United States Food and Drug Administration for monotherapy in patients with locally advanced or metastatic non-small-cell lung cancer after failure of at least one prior chemotherapy regimen. However, results from studies evaluating the use of gefitinib for treatment in GBM have been disappointing. In phase II trials of gefitinib, patients with recurrent or progressive high-grade glioma showed no objective response, with a progression-free survival at 6-months of 13 to 14% (Rich et al., 2004; Franceschi et al., 2007). Similarly, no improvement in overall survival was observed in GBM patients at first relapse.

Studies explaining the failure of gefitinib have suggested that the reasons for this lack of efficacy could be related to the heterogeneous molecular characteristics of individual gliomas (Mellinghoff et al., 2005; Mellinghoff et al., 2007; Sarkaria et al., 2007) or due
to the complexity of signaling pathways such as negative feedback mechanisms and up regulation of alternative pathways (Stommel et al., 2007). However, all of these hypotheses are based on the *a priori* assumption that there is adequate delivery of drug to the invasive tumor cells that can be found several centimeters away from the core tumor mass (Kuratsu et al., 1989; Silbergeld and Chicoine, 1997). It is well known that ATP-binding cassette (ABC) transporter proteins, including p-glycoprotein (P-gp/ABCB1) and the breast cancer resistance protein (BCRP/ABCG2), cause multidrug resistance in tumors and actively extrude targeted therapeutics from the brain (Gottesman et al., 2002; Loscher and Potschka, 2005; Fletcher et al., 2010). Certainly, the lack of gefitinib delivery to the invasive tumor cells residing in the CNS behind an intact blood-brain barrier (BBB) is a plausible partial explanation for the lack of efficacy seen in GBM. There have been no published reports that indicate that transport of gefitinib across the intact BBB to the brain is limited. Several groups have studied the interaction of gefitinib with drug transport proteins *in vitro* and reported contrasting results. Elkind et al. reported in 2005 that BCRP actively pumps gefitinib and prevents its tyrosine kinase inhibitor activity (Elkind et al., 2005). However shortly thereafter, Leggas et al. reported that gefitinib at clinically relevant concentrations is a potent inhibitor of BCRP and P-gp (Leggas et al., 2006). Given the lack of evidence to prove that gefitinib can cross the BBB to produce therapeutic concentrations in the brain, it is important to study the brain distribution kinetics of gefitinib, and the mechanisms that may influence adequate delivery of gefitinib to the target invasive tumor cells. Here we have used *in vitro* cell models to demonstrate that gefitinib is a substrate for the ATP transporters P-gp and BCRP. We have also used transporter deficient mice to study the brain distribution of gefitinib. The objective of this study was to establish the interaction of gefitinib with two important transporters of the ABC super family, P-gp and BCRP, and to show that distribution of gefitinib across an intact BBB is limited due to active efflux by these two transport proteins.

**Methods**

**Chemicals and Reagents**
[14C] Gefitinib was kindly provided by AstraZeneca Pharmaceuticals (Cheshire, U.K.). Unlabelled gefitinib and dasatinib were purchased from LC Laboratories (Woburn, MA). [14C] Sucrose and [3H] vinblastine were obtained from Moravek Biochemicals (La Brea, CA). [3H] Prazosin was purchased from Perkin Elmer (Waltham, MA). [14C] inulin was purchased from American Radiolabeled Chemicals, Inc. (St. Louis, MO). Elacridar (GF120918, N-[4-[2-(6, 7-Dimethoxy-3, 4-dihydro-1H-isoquinolin-2-yl) ethyl]-5-methoxy-9-oxo-10H-acridine-4-carboxamide) was purchased from Toronto Research Chemicals Inc. (Ontario, Canada). Ko143 (Allen et al., 2002) was kindly provided by Dr. Alfred Schinkel (The Netherlands Cancer Institute, Amsterdam, The Netherlands) and zosuquidar (LY335979, (R)-4-((1aR,6R,10bS)-1,2-difluoro-1,1a,6,10b-tetrahydrodibenzo-(a,e) cyclopropa(e) cycloheptan-6-yl)-α-(5-quinoloyloxy) methyl)-1-piperazine ethanol, trihydrochloride) was a gift from Eli Lilly and Co. (Indianapolis, IN). All other chemicals used were HPLC or reagent grade and were obtained from Sigma Chemical Co. (St. Louis, MO).

**In vitro studies**

Epithelial Madine Darby Canine Kidney (MDCKII) cells were used in all *in vitro* studies. Wild-type (WT) and MDR1-transfected cells were a gift from Dr. Piet Borst (Netherlands Cancer Institute), WT and Bcrp1-transfected cells were kindly provided by Dr. Alfred H. Schinkel (The Netherlands Cancer Institute, Amsterdam, The Netherlands). Cells were cultured in DMEM media supplemented with 10% fetal bovine serum (Sigma-Aldrich, St. Louis, MO), penicillin (100U/ml), streptomycin (100µg/ml) and amphotericin B 250 ng/mL (Sigma-Aldrich, St. Louis, MO) and maintained at 37°C with 5% CO2 under humidifying conditions.

**Intracellular Accumulation Studies in MDCKII Cells**

The accumulation studies were done in 24-well polystyrene plates (Thermo Fisher Scientific, Rochester, NY). The wild-type and MDR1 or Bcrp1 transfected cells were seeded at a density of 2 × 10^5 cells/well. The medium was changed on alternate days until the cells formed confluent monolayers. On the day of the experiment, the medium was aspirated and the monolayer was washed twice with 1 mL prewarmed (37°C) assay
buffer. The cells were preincubated with 1 ml of assay buffer for 30 min following which the buffer was aspirated and the experiment was initiated by adding 1 ml of a tracer solution of radiolabeled $[^{14}\text{C}]$ gefitinib to each well. The plates were continuously agitated at 60 rpm in an orbital shaker maintained at 37°C for the duration of the experiment. At the end of the 1-hour accumulation period, the assay buffer containing the radiolabeled drug was aspirated from all wells and the cells were washed twice with 1 ml of ice-cold phosphate-buffered saline. Cells were then solubilized using 0.5 ml of a 1% Triton X100 solution. A 150 μl sample of solubilized cell fractions was drawn from each well in duplicate, 4 ml of scintillation fluid (ScintiSafe Econo cocktail; Fisher Scientific Co., Pittsburgh, PA) was added, and the radioactivity associated with the cell fractions was determined by liquid scintillation counting (LS-6500; Beckman Coulter, Inc., Fullerton, CA). The BCA protein assay (Pierce Biotechnology, Inc., Rockford, IL) was used to determine the protein concentration in the cell fractions and was used to normalize the radioactivity in each well. Drug accumulation in cells was expressed as percentage of the accumulated radioactivity measured in the wild-type control cells (dpm) per microgram of protein. For inhibition studies, the cells were treated with the selective inhibitor (1 μM LY335979 for P-gp; 200 nM Ko143 for BCRP (Dantzig et al., 1999; Allen et al., 2002)) during both the preincubation and accumulation periods. The stock solutions for all the inhibitors used were prepared in dimethyl sulfoxide (DMSO) and diluted using assay buffer to obtain working solutions, so that the final concentration of DMSO was less than 0.1%.

**Directional Flux across MDCKII Monolayers**

Six-well transwells (Corning Inc., Corning, NY) were used in the permeability studies. Cells were seeded at a density of $2 \times 10^5$ cells/well on the polyester semipermeable membrane supports and the medium was changed on alternate days until the cells formed confluent monolayers. On the day of experiment, the monolayers were washed with 2 mL prewarmed (37°C) assay buffer. After a 30-min preincubation period, the experiment was initiated by adding a tracer solution of radiolabeled drug ($^{14}$C-gefitinib) in assay buffer to the donor side (apical side, 1.5 ml; basolateral side, 2.6 ml). Fresh assay buffer was added to the receiver side and 200 μl was sampled from the receiver compartment at 0, 10, 20,
30, 45, 60, and 90 min. The volume sampled was immediately replaced with fresh assay buffer. Additional samples were drawn at 0 and 90 min from the donor compartment. The amount of radioactivity in the samples was determined using liquid scintillation counting. The apical compartment represented the donor for determination of apical-to-basolateral (A-to-B) flux, whereas for determination of basolateral-to-apical (B-to-A) flux, the donor was the basolateral compartment and the apical compartment was sampled at the aforementioned times. When an inhibitor was used in the flux study, the cell monolayers were preincubated with the inhibitor (1 µM LY335979 or 200 nM Ko143) for 30 min, followed by determination of A-to-B and B-to-A flux with the inhibitor present in both compartments throughout the course of the experiment. The apparent permeability ($P_{app}$) was calculated by the following equation,

$$P_{app} = \frac{\left(\frac{dQ}{dt}\right)}{A* C_0} \quad \ldots \ldots \quad (1)$$

where $dQ/dt$ is the mass transport rate (determined from the slope of the amount transported vs. time plot), $A$ is the apparent surface area of the cell monolayer (4.67 cm$^2$), and $C_0$ is the initial donor concentration. The efflux ratio was defined as the ratio of $P_{app}$ in the B-to-A direction to the $P_{app}$ in the A-to-B direction and gives an indication of the magnitude of P-gp or BCRP-mediated efflux. The corrected flux ratio (CFR) was determined by dividing the efflux ratio in the Bcrp1 or MDR1 transfected cells by the efflux ratio in the corresponding wild-type cells.

**In vivo studies**

**Animals**

All animals used in this study were from Taconic Farms, Inc. (Germantown, NY). Animals used were male $\textit{Mdr1a/b}^+\textit{}/$ (P-gp knockout), $\textit{Bcrp1}^+\textit{/}$ (Bcrp1 knockout), $\textit{Mdr1a/b}^+\textit{}/$ $\textit{Bcrp1}^+\textit{/}$ (triple knockout) and wild-type mice of a FVB/N genetic background and were 8 to 10 weeks old at the time of the experiment. Animals were maintained under temperature-controlled conditions with a 12-h light/dark cycle and unlimited access to food and water. All studies were conducted according to the guidelines set by the
Principles of Laboratory Animal Care (National Institutes of Health) and were approved by The Institutional Animal Care and Use Committee (IACUC) of the University of Minnesota.

Brain Distribution of Gefitinib in FVB Mice

The dose formulation of gefitinib was prepared on the day of experiment at a concentration of 5 mg/ml. Gefitinib was suspended in 1% polysorbate 80 solution in saline or in a vehicle consisting of 10% DMSO, 35% propylene glycol, 5% ethanol and 50% saline. All mice received a 25 mg/kg oral dose of gefitinib via oral gavage.

In the first study, wild-type and Mdr1a/b<sup>-/-</sup> Bcrp1<sup>-/-</sup> mice were administered an oral dose of gefitinib (1% polysorbate 80) following which blood and brain were sampled at 15, 30, 60, 90, 120 and 240 minutes post-dose, n=4 at each time point. At the desired time point, animals were euthanized using a CO₂ chamber. Blood was collected by cardiac puncture and transferred to heparinized tubes. Plasma was isolated from blood by centrifugation at 3000 rpm for 10 min at 4°C. Whole brain was immediately removed from the skull, rinsed with cold saline and flash frozen in liquid nitrogen. Plasma and brain specimens were stored at -80°C until analysis by LC-MS/MS.

In another study, wild-type mice received an oral dose of gefitinib (10% DMSO, 35% propylene glycol, 5% ethanol and 50% saline) with or without an intravenous dose of 10 mg/kg elacridar (GF120918) 30 minutes prior to administration of gefitinib. Blood and brain were sampled at 15, 30, 60, 90 and 120 minutes post-dose as described above (n=4 at each time point). Gefitinib brain distribution was also studied after oral administration in a group of wild-type, Mdr1a/b<sup>-/-</sup>, Bcrp1<sup>-/-</sup> and Mdr1a/b<sup>-/-</sup> Bcrp1<sup>-/-</sup> mice and in wild-type mice which received 25 mg/kg LY335979 (20% ethanol, 80% saline), 10 mg/kg Ko143 (20% DMSO, 80% saline) or 10 mg/kg GF120918 (40% propylene glycol, 30% DMSO and 30% saline) intravenously 30 minutes before an oral gefitinib dose. Blood and brain were sampled at 90 minutes post-dose, n=4 at each time point.

Steady State Brain Distribution of Gefitinib
Alzet osmotic mini pumps (Durect Corporation, Cupertino, CA) were used to study the steady state brain and plasma levels of gefitinib. A 70 mg/ml solution of gefitinib in DMSO was filled in the minipumps (model 1003D) and the pumps were equilibrated by soaking them overnight in sterile saline solution at 37°C. The pump operated at a flow rate of 1 µL/hr yielding an infusion rate of 70 µg/hr. Wild-type and Mdr1a/b–/– Bcrp1–/– mice were anesthetized by intraperitoneal administration of 100 mg/kg ketamine and 10 mg/kg xylazine (Boynton Health Service Pharmacy, Minneapolis, MN). The abdominal cavity was shaved and cleaned. Next, a small midline incision was made in the lower abdomen under the rib cage. A small incision was then made in the peritoneal wall directly beneath the cutaneous incision and the primed pump was inserted into the peritoneal cavity. The musculoperitoneal layer was closed with sterile absorbable sutures and the skin incision was closed using sterile wound clips. The animals were allowed to recover on a heated pad. Gefitinib half-life in mice has been reported to be approximately 1 hour (Wang et al., 2008), so an infusion lasting 24 hours was considered to be sufficient to attain steady-state in both brain and plasma. The animals were euthanized 24 and 48 hours post surgery followed by collection of brain and blood as described earlier.

**Determination of Gefitinib Concentrations in Plasma and Brain by LC-MS/MS**

Prior to analysis, frozen samples were thawed at ambient temperature. Brain samples were homogenized using 3 volumes of 5% bovine serum albumin in phosphate-buffered saline using a tissue homogenizer (Fisher Scientific, Pittsburgh, PA). A 50 µL aliquot of plasma and a 100 µL aliquot of brain homogenate were used for analysis. Plasma and brain samples were spiked with 10 ng of dasatinib (IS) as internal standard followed by liquid-liquid extraction using 200 µL buffer of pH 11 (sodium hydroxide: sodium bicarbonate, 50:50) and 1 mL of ice cold ethyl acetate. Samples were shaken vigorously on a mechanical shaker for 10 minutes and centrifuged at 5000 rpm for 15 minutes at 4°C to separate the organic layer. A volume of 750 µL of the top organic layer was transferred to fresh polypropylene tubes and dried under nitrogen. Samples were reconstituted in 100 µL mobile phase and transferred to glass auto sampler vials. A volume of 5 µL sample was injected in the HPLC system using a temperature controlled autosampling device maintained at 10°C. Chromatographic analysis was performed using an Agilent Model
1200 separation system (Santa Clara, Ca, USA). Separation of analytes was achieved using an Agilent Eclipse XDB-C18 RRHT threaded column (4.6mm ID x 50mm) packed with a 1.8-µm ZORBAX Rx-SIL silica stationary phase (Santa Clara, CA, USA). The mobile phase used for the chromatographic separation was composed of acetonitrile: 20mM ammonium formate (containing 0.1% formic acid, pH adjusted to 4 with ammonium hydroxide) (32:68 v/v), and was delivered at a flow rate of 0.25 mL/min. The column effluent was monitored using a Thermo Finnigan™ TSQ® Quantum 1.5 detector (San Jose, CA, USA). The instrument was equipped with an electrospray interface, and controlled by the Xcalibur version 2.0.7 data system. The samples were analyzed using an electrospray probe in the positive ionization mode operating at a spray voltage of 4500V for both gefitinib and dasatinib (internal standard). Samples were introduced into the interface through a heated nebulized probe at 300°C. The spectrometer was programmed to allow the [MH]+ ion of gefitinib at m/z 446.9 and that of internal standard at m/z 488 to pass through the first quadrupole (Q1) and into the collision cell (Q2). The collision energy was set at 9V for gefitinib and 16V for dasatinib. The product ions for gefitinib (m/z 128.1) and the internal standard (m/z 401) were monitored through the third quadrupole (Q3). The scan width and scan time for monitoring the two product ions were 1.5 m/z and 0.5s, respectively. The sensitivity of our assay was at least 7.5 ng/ml with a corresponding CV of ~ 10%.

Evaluating Blood-Brain Barrier Integrity in FVB Wild-type and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice

A group of FVB wild-type and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice received an intravenous dose of 5 µCi [14C] sucrose (n=4). Another group received an intravenous dose of 2.5 µCi [14C] inulin (n=4). Blood and whole brain were harvested at 10 minutes post dose. Brains were homogenized as described earlier. 4 ml of scintillation fluid (ScintiSafe Econo 1 cocktail; Fisher Scientific Co., Pittsburgh, PA) was added to 100 µL of brain or 20 µL plasma specimens and counted using liquid scintillation counting (LS-6500; Beckman Coulter Inc., Fullerton, CA) to determine the radioactivity associated with sucrose and inulin in the samples. Sucrose and inulin concentrations in brain and plasma were determined. Brain space was calculated as the ratio of the brain concentration (nCi/gm) to the plasma
concentration (nCi/ml) and expressed as the percentage of brain volume (µL) exposed to the two compounds.

**Statistical Analysis**

Statistical analysis was conducted using SigmaStat, version 3.1 (Systat Software, Inc., Point Richmond, CA). Statistical comparisons between two groups were made by using two-sample t-test at \( p < 0.05 \) significance level. Multiple groups were compared by one way analysis of variance with the Holm-Sidak post-hoc test for multiple comparisons at a significance level of \( p < 0.05 \).

**Results**

**Intracellular Accumulation of Gefitinib**

Accumulation of gefitinib in MDCKII wild-type (WT) and P-gp or Bcrp1-transfected cells was studied. A positive control, ([\(^3\)H] vinblastine for P-gp or [\(^3\)H] prazosin for BCRP) was used in all accumulation experiments. As seen in **Figure 1A**, [\(^3\)H] prazosin accumulation in the Bcrp1-transfected cells was significantly lower compared to the wild-type cells (\( p < 0.001 \)). Similarly, accumulation of [\(^3\)H] vinblastine was significantly lower in the MDR1-transfected cells (\( p < 0.001 \)) compared to WT (**Figure 1B**). Accumulation of gefitinib in the Bcrp1-transfected cells was significantly lower than that in the wild-type cells (~ 3% of WT control, \( p < 0.001 \)). This difference in accumulation between the two cell types was abolished upon treatment with the BCRP specific inhibitor Ko143 (200 nM) (**Figure 1A**). In the MDR1-transfected cells, accumulation of gefitinib was 50% lower than that in the wild-type cells (\( p < 0.001 \)). Treatment with the P-gp inhibitor LY335979 (1µM) decreased the difference in accumulation (**Figure 1B**).

**Directional Permeabilities of Gefitinib across MDCKII Monolayers**

MDCKII wild-type and Bcrp1 or MDR1-transfected cells were used to determine the directional flux of [\(^{14}\)C] gefitinib. **Figure 2A** demonstrates the directionality in permeability of gefitinib across wild-type and Bcrp1 monolayers. The B-to-A permeability of gefitinib in the Bcrp1 cells was significantly greater than the permeability in the A-to-B direction (\( p < 0.001 \)) yielding an efflux ratio of 55. This directionality in
transport was abolished when the cells were treated with Ko143 (200 nM), such that there was no significant difference between the A-to-B and B-to-A permeabilities (efflux ratio = ~ 1). In the wild-type cells, there was no difference in the permeability of gefitinib in either direction, with an efflux ratio of ~ 1 in the control (no Ko143 treatment) and the KO143 treated cells. The corrected efflux ratio was about 34 in the control and 1.2 in the cells treated with the BCRP inhibitor Ko143. In the MDR1-transfected cells, the permeability was significantly enhanced in the B-to-A direction compared to the A-to-B permeability ($p<0.001$) with an efflux ratio of 8.4 (Figure 2B). The P-gp inhibitor LY335979 reversed the directionality in flux due to P-gp, such that there was no significant difference in the permeability of gefitinib in both directions, and the efflux ratio decreased to 1. Again, the B-to-A and A-to-B permeability was similar in the corresponding wild-type cells. The corrected efflux ratio was approximately 5.1 in the control and 0.9 in the cells treated with LY335979.

**Brain Distribution of Gefitinib in Wild-type and Mdr1a/b^−/− Bcrp1^−/− mice**

We investigated the effect of p-glycoprotein and BCRP on the brain distribution of gefitinib using wild-type and transgenic mouse models. Brain distribution after a 25 mg/kg oral dose of gefitinib was determined in FVB wild-type and Mdr1a/b^+/− Bcrp1^+/− mice. Brain concentrations of gefitinib were significantly lower than the plasma concentrations in the wild-type mice ($p<0.05$), resulting in a brain-to-plasma (B/P) concentration ratio of less than 0.15 at all measured time points (Figure 3). However, gefitinib brain concentrations were significantly enhanced in the Mdr1a/b^+/− Bcrp1^+/− mice compared to those in the wild-type mice ($p<0.05$, Figure 4A). The brain-to-plasma concentration ratio was significantly greater in the Mdr1a/b^+/− Bcrp1^+/− mice at all the measured time points ($p<0.001$). The B/P ratio was on average 16-fold higher in the Mdr1a/b^+/− Bcrp1^+/− mice compared to the wild-type mice (Figure 4B). Plasma concentrations of gefitinib in the Mdr1a/b^+/− Bcrp1^+/− mice were not significantly different compared to the plasma concentrations in the wild-type mice.

**Dual P-gp and BCRP Inhibitor Elacridar Enhances Brain Distribution of Gefitinib**
We investigated if pharmacological inhibition of P-gp and BCRP at the blood-brain barrier enhances the brain exposure of gefitinib in FVB wild-type mice. The dual P-gp and BCRP inhibitor elacridar (GF120918) was used for this purpose. Brain gefitinib concentrations were greater in the elacridar treated group compared to control (Figure 5A). The brain-to-plasma concentration ratio (B/P) was significantly greater in the elacridar treated wild-type mice compared to the control (p<0.05; Figure 5B). The brain-to-plasma ratio increased by more than 4–fold when elacridar was administered along with gefitinib, reaching values greater than 1 at the later time points. This indicates that brain distribution of gefitinib can be significantly improved by concurrent administration of a dual inhibitor like elacridar.

Effect of Pharmacological Inhibition and Genetic Deletion of P-gp and BCRP

We studied the brain distribution of gefitinib in wild-type, Mdr1a/b⁺, Bcrp1⁻/⁻ and Mdr1a/b⁻/⁻ Bcrp1⁻/⁻ mice and in wild-type mice that were pretreated with pharmacological inhibitors of P-gp (LY335979), BCRP (Ko143) and the dual P-gp/BCRP inhibitor elacridar. Figure 6 shows the brain-to-plasma ratios of gefitinib when P-gp and BCRP were pharmacologically inhibited or genetically deleted. Use of LY335979 and Ko143 did not result in any significant change in the B/P ratio of gefitinib, however the B/P ratio increased by ~6-fold in the wild-type mice that were pretreated with the dual inhibitor elacridar (p<0.05). Similarly, in the gene knockout group, the B/P ratio increased by approximately 4-fold in the Mdr1a/b⁻/⁻ mice (p<0.05). While there was no change in the B/P ratio in the Bcrp1⁻/⁻ mice, the ratio increased by greater than 18-fold in the Mdr1a/b⁻/⁻ Bcrp1⁻/⁻ mice (p<0.001).

Steady-State Brain Distribution of Gefitinib

Table 1 summarizes the results from steady state brain and plasma distribution of gefitinib after a continuous intraperitoneal infusion. In the wild-type mice, steady-state brain concentrations of gefitinib were 15-fold lower than the corresponding plasma concentrations (p<0.001). The brain-to-plasma ratio was approximately 0.1 at both the measured time points, indicating a brain tissue partition coefficient of 10% in the wild-type mice. In the Mdr1a/b⁻/⁻ Bcrp1⁻/⁻ mice, brain concentrations were ~ 7-fold greater...
compared to the plasma concentrations \( p<0.001 \). Steady state brain concentrations in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice increased more than 50-fold compared to that in the wild-type mice \( p<0.001 \). The corresponding brain-to-plasma ratios in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice were about 7, indicating a 70-fold increase in brain partitioning of gefitinib compared to the wild-type. There was no difference in the brain-to-plasma ratios between the 24 hr and the 48 hr time points in the two mice groups.

**Blood-Brain Barrier Integrity in FVB \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice**

The integrity of the BBB in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice was evaluated to ensure that the dramatic increase in brain distribution of gefitinib observed in the triple knockout mice was not a result of a leaky blood-brain barrier (compromised tight junctions). This was done by determining the brain spaces of \( ^{[14]} \text{C} \) sucrose and \( ^{[14]} \text{C} \) inulin. At short time points postdose, both inulin and sucrose are limited to the vasculature under normal physiological conditions and are therefore used as markers of intravascular space. The brain spaces of \( ^{[14]} \text{C} \) sucrose and \( ^{[14]} \text{C} \) inulin in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice were not statistically different than those in the wild-type mice. The brain sucrose space at 10 minutes was \( 2.2 \pm 0.2 \% \) in the wild-type mice compared to \( 1.9 \pm 0.3 \% \) in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice. Similarly the brain space of \( ^{[14]} \text{C} \) inulin was \( 2.0 \pm 0.3 \% \) in the wild-type and \( 2.1 \pm 0.6 \% \) in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice (Figure 7). The finding confirmed that there was no change in the integrity of the tight junctions that form the BBB in the \( \text{Mdr1a/b}^{+/+} \text{Bcrp1}^{-/-} \) mice. This suggests that the cumulative change in brain distribution of gefitinib in these mice is due to the simultaneous absence of both drug efflux systems.

**Discussion**

The epidermal growth factor receptor (EGFR) pathway has been an attractive target because it is dysregulated in a significant fraction of malignant gliomas through overexpression, amplification and activating mutations (Rich et al., 2004). Moreover, recent studies have demonstrated that EGFRvIII is required for tumor maintainence in glioma (Mukasa et al., 2010). The EGFR tyrosine kinase inhibitor gefitinib has been evaluated in a number of clinical trials for GBM, however results have been disappointing (Lieberman FS, 2004; Rich et al., 2004). The failure of gefitinib raises
questions pertaining to delivery of drug to its target. Active efflux at the BBB could prevent drugs from attaining therapeutic levels in the brain and is likely one of the main reasons behind resistance to chemotherapy. It has been shown that several other tyrosine kinase inhibitors are avid substrates for P-gp and BCRP and that their brain distribution is limited due to active efflux out of the brain (Dai et al., 2003; Chen et al., 2009; Lagas et al., 2009; Polli et al., 2009). Whether gefitinib crosses the BBB to achieve therapeutic levels in the CNS is an important question that has remained unanswered. We have raised this question herein and demonstrated that gefitinib is a substrate of the ABC transporters P-gp and BCRP and that these two efflux proteins actively efflux gefitinib at the BBB, thereby limiting its brain penetration. We have further demonstrated that steady-state brain partitioning improved by greater than 70-fold due to absence of both P-gp and BCRP in the Mdr1a/b−/− Bcrp1−/− mice and that inhibition of these two transporters by use of a dual inhibitor like elacridar can be a useful therapeutic strategy to improve brain distribution of gefitinib.

In vitro studies conducted in immortalized MDCKII cells that stably overexpress human P-gp or murine BCRP demonstrated that gefitinib is a substrate of the two efflux pumps. It has been reported that gefitinib is an inhibitor of P-gp and BCRP and that concurrent administration increases the bioavailability of topotecan (Leggas et al., 2006). Our study conclusively shows that gefitinib is a substrate for these two transporters. One explanation for the inhibitory effect seen could be given by the high gefitinib concentrations used by Leggas et al. in the above mentioned study. It is also possible that gefitinib competes with other substrates to bind with P-gp and BCRP and saturates the transporters thus leading to their inhibition.

In vivo studies using FVB wild-type mice showed that CNS distribution of gefitinib across the blood-brain barrier is significantly limited. Brain concentrations were on average 18-fold higher in the Mdr1a/b−/− Bcrp1−/− mice than in the wild-type mice. Steady-state brain-to-plasma ratios increased from ~ 0.1 in the wild-type mice to ~ 7 in the Mdr1a/b−/− Bcrp1−/− mice. This dramatic 70-fold increase in the brain partitioning indicates the significant impact the two transporters have on the brain distribution of gefitinib.
The dramatic increase in brain gefitinib concentrations in the \textit{Mdr1a/b}^{+/−} \textit{Bcrp1}^{−/−} mice suggested that inhibition of P-gp and BCRP might be an effective way to improve brain distribution of gefitinib. Therefore, we studied the influence of the dual P-gp and BCRP inhibitor elacridar on the brain distribution of gefitinib in FVB wild-type mice. Treatment with elacridar resulted in enhanced brain levels of gefitinib in the wild-type mice. This finding demonstrates the improvement in delivery of gefitinib to the brain resulting from pharmacological inhibition of active efflux at the BBB. Interestingly, plasma concentrations of gefitinib were not increased in the \textit{Mdr1a/b}^{+/−} \textit{Bcrp1}^{−/−} mice or in the elacridar-treated wild-type mice compared to control wild-type mice, suggesting that under these experimental conditions P-gp and BCRP do not limit oral uptake of gefitinib. This finding is in agreement with other studies which report that oral absorption of TKIs like dasatinib and erlotinib is not influenced by P-gp and BCRP (Kamath et al., 2008; Lagas et al., 2010).

In the study to determine the relative contribution of P-gp and BCRP in active efflux of gefitinib, pharmacological inhibition of BCRP by Ko143 or genetic deletion in \textit{Bcrp1}^{−/−} mice did not result in any significant increase in brain levels of gefitinib. Brain concentrations and the brain-to-plasma ratios increased by greater than 3-fold when P-gp was absent in the \textit{Mdr1a/b}^{+/−} mice. More importantly, concomitant inhibition of P-gp and BCRP by elacridar resulted in a ~ 6-fold increase in the brain-to-plasma ratio while absence of both transporters in the \textit{Mdr1a/b}^{+/−} \textit{Bcrp1}^{−/−} mice had an even greater effect with the B/P ratio increasing by greater than 18-fold. This indicates that P-gp seems to be the dominant transporter when it comes to efflux of gefitinib from the brain. However, the fact that brain concentrations increase only marginally when P-gp is inhibited or absent, suggests that BCRP efflux may compensate for the loss of P-gp. This is highlighted in the \textit{Mdr1a/b}^{+/−} \textit{Bcrp1}^{−/−} mice or by the use of elacridar which resulted in a greater than additive increase in brain gefitinib levels. This is consistent with previous reports for dasatinib (Chen et al., 2009; Lagas et al., 2009) and other published reports for tyrosine kinase inhibitors, including imatinib and lapatinib (Oostendorp et al., 2009; Polli et al., 2009). The \textit{in vivo} finding that BCRP by itself does not influence brain penetration of gefitinib is in agreement with reports for other TKIs. One explanation for this could be the presence of significantly low levels of BCRP in the rodent and human BBB compared...
to overexpressing cell lines as reported by Lee et. al. Difference in protein levels can account for the discrepancies between the in vitro cell and the in vivo models (Lee et al., 2007). It is also possible that there are differences in the capacities of the two transporters at the BBB where P-gp might seem to play a predominant role at the BBB.

Previous studies have reported similar findings where the brain concentrations of dual P-gp/BCRP substrates increased dramatically in the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice (Polli et al., 2009). This raised questions about the validity of the triple knockout mice as a model system to study drug transport to the CNS. Some of these questions pertain to the integrity of the BBB in these mice. We decided to evaluate this by studying the brain distribution of sucrose and inulin. Sucrose and inulin do not readily cross membranes and under normal conditions, shortly after systemic dosing, do not enter the brain to any significant extent. A leakier BBB in the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice would result in higher brain levels of these two compounds compared to the wild-type mice. We observed no differences in the brain concentrations of [<sup>14</sup>C] sucrose and [<sup>14</sup>C] inulin between the wild-type and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice. The brain space was ~2 % for sucrose and inulin in both wild-type and the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice. This confirmed that these mice have an intact blood-brain barrier and therefore the dramatically high brain concentrations of substrate drugs in these mice are most probably due to the simultaneous absence of P-gp and BCRP at the BBB, that would not allow for compensatory transport when one or the other is present.

Limited CNS distribution of gefitinib due to active efflux transport at the BBB can be of significance while trying to elucidate the reasons behind the lack of gefitinib efficacy seen in brain tumors like GBM. It has been suggested that delivery of gefitinib across the BBB might not be an issue in GBM since tumor concentrations 10- to 12-fold higher than plasma concentrations have been reported (McKillop et al., 2005; Hofer and Frei, 2007). One explanation for this increased tumor penetration of gefitinib can be given by the breakdown of the BBB at the contrast-enhancing tumor core. Also, while the BBB may be disrupted at or near the core, there is increasing evidence to show that it is still intact near the growing edge of the infiltrative tumor (Fine et al., 2006; Blakeley et al., 2009),
the site where invasive tumor initiating cells reside. Tumor recurrence after surgical removal and radio-chemotherapy questions the delivery of drug to the non-tumor containing areas of brain that may only have limited access to the drug. Brain tumor initiating cells residing behind an intact BBB can pose significant delivery problems and might be one of the main reasons behind the recurrence of tumor after surgery. Despite recent advances in therapy, malignant glioma remains essentially fatal, with a median survival of 10-12 months. There are no studies that examine the failure of gefitinib chemotherapy in GBM that address the lack of drug delivery to the intended molecular target in tumor-initiating cells that reside behind an intact BBB. This lack of adequate delivery may be an important reason for the ineffectiveness of gefitinib in brain tumors like GBM.

In conclusion, we have shown here that the ATP transporters P-gp and BCRP actively efflux gefitinib at the blood-brain barrier and limit its CNS distribution. We have highlighted that gefitinib is another example where P-gp and BCRP can work together to dramatically limit brain distribution of dual substrates. We have also shown that the tight junctions that form the BBB are intact in the Mdr1a/b<sup>b<sup>-/-</sup> Bcrp1<sup>-/-</sup> mice and that the enhanced CNS distribution seen in these mice is due to the absence of P-gp and BCRP. Finally, coadministration of the dual P-gp/BCRP inhibitor elacridar was able to significantly enhance brain distribution of gefitinib. This can be of importance in therapy for GBM, where limited distribution to the target tumor cells, i.e., the invasive glioma cells behind an intact blood-brain barrier, might be one of the reasons behind the lack of efficacy seen with gefitinib.

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Footnotes

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Reprint Requests

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Legends for Figures

Figure 1. Intracellular accumulation of $[^{14}\text{C}]$ gefitinib in MDCKII cells. (A)
Accumulation in wild-type (black bar) and Bcrp1-transfected (gray bar) cells.
Gefitinib accumulation in the Bcrp1-transfects was about 30-fold lower compared to that
in wild-type cells ($^{*}p<0.001$). This difference in accumulation was abolished when
BCRP was inhibited using the specific inhibitor Ko143. (B) Accumulation in wild-type
(black bar) and MDR1-transfected (gray bar) cells. Gefitinib accumulation was
significantly lower in the MDR1-transfected cells compared to wild-type ($^{*}p<0.001$).
Treatment with LY335979 reduced the difference in accumulation between the two cell
types. Results presented as mean ± SE, n = 18.

Figure 2. Flux of $[^{14}\text{C}]$ gefitinib across MDCKII cell monolayers. (A) Gefitinib
permeability across wild-type and Bcrp1-transfected cells. In the Bcrp1- transfected
cells, the B-to-A permeability (gray bar) of gefitinib was significantly greater than the
A-to-B permeability (black bar) ($^{*}p<0.001$). This directionality in transport was
abolished when cells were treated with the BCRP specific inhibitor Ko143. (B)

Permeability across wild-type and MDR1-transfected cells. The B-to-A permeability
(gray bar) was significantly greater than the A-to-B permeability (black bar) in the
MDR1- transfected cells ($^{*}p<0.001$). P-gp inhibition by LY335979 abolished this
directionality in transport such that there was no difference in permeability between the
two directions. Results presented as mean ± SE, n = 9.
Figure 3. Brain and plasma concentrations of gefitinib in FVB wild-type mice after a 25 mg/kg oral dose of gefitinib. Brain gefitinib concentrations (○) were significantly lower than the plasma concentrations (●) demonstrating the limited brain penetration of gefitinib. (mean ± SE, n = 4, * p<0.05 compared to wild-type control)

Figure 4. Brain distribution of gefitinib in wild-type and Mdr1a/b(-/-) Bcrp1(-/-) FVB mice after an oral dose of 25 mg/kg gefitinib. Brain concentrations (A) and corresponding Brain-to-Plasma (B/P) concentration ratios (B) of gefitinib in wild-type (●) and Mdr1a/b(-/-) Bcrp1(-/-) (▲) mice. Brain concentrations in the Mdr1a/b(-/-)Bcrp1(-/-) mice were significantly greater than the wild-type. The B/P ratios increased by greater than 16-fold in the Mdr1a/b(-/-) Bcrp1(-/-) mice indicating the enhancement in brain distribution of gefitinib due to absence of P-gp and BCRP at the BBB. Results are represented as mean ± SE. (* p<0.05, ** p<0.001 compared to wild-type control).

Figure 5. Effect of P-gp & BCRP inhibition on brain distribution of gefitinib. Brain concentrations (A) and corresponding brain-to-plasma (B/P) concentration ratios (B) of gefitinib in the vehicle treated (●) and elacridar treated (▲) wild-type mice. Brain concentrations increased in the wild-type mice when elacridar was administered prior to gefitinib. The B/P ratios were also significantly greater in the elacridar treated group suggesting that dual inhibitors like elacridar can be used to improve brain penetration of substrate drugs. Results are represented as mean ± SE. (* p<0.05, ** p<0.001 compared to vehicle control).
Figure 6. (A) Effect of pharmacological inhibition of drug efflux transporters on brain distribution of gefitinib in wild-type FVB mice. Wild-type mice received 25 mg/kg gefitinib via oral gavage 30 minutes after i.v. administration of 25 mg/kg LY335979, 10 mg/kg Ko143 or 10 mg/kg GF120918 (elacridar). (B) Effect of genetic deletion of drug efflux transporters on brain distribution of gefitinib in FVB mice. Wild-type, Mdr1a/b<sup>+/−</sup>, Bcrp1<sup>−/−</sup> and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice were administered 25 mg/kg gefitinib. Whole brain tissue was collected at 90 minutes postdose (n=4 at each time point) and analyzed for gefitinib. The values are presented as mean ± S.E. (**p<0.05, compared to wild-type control).

Figure 7. Integrity of the blood-brain barrier in Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice. Brain spaces of sucrose and inulin in wild-type (black bar) and Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> (gray bar) mice. The brain spaces of sucrose or inulin in the Mdr1a/b<sup>−/−</sup> Bcrp1<sup>−/−</sup> mice were similar to that in the wild-type mice indicating that the BBB is intact in these mice. The values are presented as mean ± S.E (n = 4).
Tables

Table 1. Steady-state brain distribution of gefitinib in wild-type and Mdr1a/b\(^{-/-}\) Bcrp1\(^{-/-}\) FVB mice after a continuous intraperitoneal infusion of gefitinib. Steady-state brain concentrations were 16-fold lower than the plasma concentrations in the wild-type mice. Brain concentrations at steady-state in the Mdr1a/b\(^{-/-}\) Bcrp1\(^{-/-}\) mice were 7-fold greater than the plasma concentrations and up to 100-fold greater than the brain concentrations in the wild-type mice. (mean ± S.E.; * \(p<0.05\) compared to plasma, † \(p<0.05\) compared to wild-type, ns not significant compared to 24 hr time point)

<table>
<thead>
<tr>
<th>Group</th>
<th>Time</th>
<th>N</th>
<th>Plasma C(_{ss}) (µg/ml)</th>
<th>Brain C(_{ss}) (µg/gm)</th>
<th>Brain-to-Plasma Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type (control)</td>
<td>24 hour</td>
<td>5</td>
<td>0.49 ± 0.08</td>
<td>0.03 ± 0.01(^*)</td>
<td>0.07 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>48 hour</td>
<td>4</td>
<td>0.21 ± 0.05</td>
<td>0.01 ± 0.01(^*)</td>
<td>0.10 ± 0.05(\text{ns})</td>
</tr>
<tr>
<td>Mdr1a/b(^{-/-}) Bcrp1(^{-/-})</td>
<td>24 hour</td>
<td>4</td>
<td>0.24 ± 0.07</td>
<td>1.7 ± 0.5(^*)†</td>
<td>7.3 ± 0.5(\text{†})</td>
</tr>
<tr>
<td></td>
<td>48 hour</td>
<td>4</td>
<td>0.19 ± 0.10</td>
<td>1.2 ± 0.6(^*)†</td>
<td>7.1 ± 0.9(\text{ns})</td>
</tr>
</tbody>
</table>
Figure 1A

A bar graph showing Gefitinib Accumulation - Percent of Control (Mean ± SE) for different conditions: Wild-type Cells (Control) and Bcrp1-Transfected Cells. The conditions include Prazosin (positive control), Prazosin + 200 nM Ko143, Gefitinib, and Gefitinib + 200 nM Ko143.
Figure 1B

![Graph showing gefitinib accumulation in percent of control for different treatments.](image-url)
Figure 2A

![Graph showing apparent permeability of gefitinib](image-url)
Figure 2B

![Graph showing apparent permeability of gefitinib](image-url)
**Figure 3**

A line graph showing gefitinib concentrations in plasma and brain over time. The x-axis represents time in minutes, ranging from 0 to 140, and the y-axis represents gefitinib concentrations (ng/ml, ng/gm) ranging from 0 to 2500. The graph includes error bars indicating the mean ± SE for each data point. Significant differences are indicated by asterisks (*).
Figure 4A

[Graph showing Gefitinib Brain Concentration (ng/gm) over time for Wild-type and Mdr1a/1b(−/−)Bcrp1(−/−) mice.]

- Wild-type: Solid line with circles.
- Mdr1a/1b(−/−)Bcrp1(−/−): Dashed line with triangles.

Bars indicate mean ± SE, with significance levels indicated by asterisks: **p < 0.01, *p < 0.05.
Figure 4B

![Graph showing brain-to-plasma concentration ratio (Cb/Cp) over time for Wild-type and Mdr1a/1b(-/-)Bcrp1(-/-) groups.](image-url)
Figure 5A

![Graph showing Gefitinib Brain Concentration (ng/gm) over time (minutes). The graph compares Vehicle Control (solid line) and 10 mg/kg Elacridar (dashed line). Error bars indicate the standard error of the mean (SE). The y-axis represents Gefitinib Brain Concentration (ng/gm) ranging from 0 to 1000, and the x-axis represents time in minutes from 0 to 140 with intervals at 20, 40, 60, 80, 100, 120, and 140. There is a significant difference marked by **].
Figure 6

A

Brain-to-Plasma Concentration Ratios (Cb/Cp)
(Mean ± SE)

Pharmacological Inhibition

Wild-type (control)
25mg/kg LY335979
10mg/kg Ko143
10mg/kg GF120918

B

Wild-type (control)
Mdr1a/b<sup>+/−</sup>
Bcrp<sup>+/−</sup>
Mdr1a/b<sup>−/−</sup> Bcrp<sup>−/−</sup>

Genetic Deletion

**
Figure 7

Brain Space (Percent of Total Brain Volume) (Mean ± SE)

- [14C] Sucrose
- [14C] Inulin

Wild-type Control
Mdr1a/1b(-/-)Bcrp1(-/-)