EPIDERMAL GROWTH FACTOR-MEDIATED ACTIVATION OF THE MAP KINASE CASCADE RESULTS IN ALTERED EXPRESSION AND FUNCTION OF ABCG2 (BCRP)

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ABSTRACT:

Epidermal growth factor (EGF) is a multifunctional growth factor known to play a major role in proliferation and differentiation processes. EGF-induced differentiation is a prerequisite for function of various cell types, among them cytotrophoblasts, a functionally important cellular fraction in human placenta. Stimulation of cytotrophoblasts with EGF results in formation of a multinuclear syncytium representing the feto-maternal interface, which protects the fetus against exogenous substances. It is well established that part of this protection system is based on ATP-binding cassette (ABC) transporters such as ABCG2 (breast cancer resistance protein, BCRP). However, little is known about regulation of transport proteins in the framework of EGF-mediated cellular differentiation. In the present work we show a significant increase of ABCG2 expression by EGF in cytotrophoblasts, BeWo, and MCF-7 cells on both mRNA and protein levels. This increase resulted in decreased sensitivity to the ABCG2 substrates mitoxantrone and topotecan. In each cell type, EGF increases expression of ABCG2 by activation of mitogen-activated protein kinase cascade via phosphorylation of extracellular regulated kinase (ERK)1/2 and c-jun NH-terminal kinase/stress-activated protein kinase (JNK/SAPK). Consequently, the increase of ABCG2 by EGF was abolished by pretreatment of cells with the tyrosine kinase inhibitor 4-(3-chloroanillino)-6,7-dimethoxyquinazoline (AG1478) or the mitogen-activated protein kinase inhibitor 2’-amino-3’-methoxyflavone (PD 98059), thereby reestablishing sensitivity toward mitoxantrone. Moreover, analysis of ABCG2 expression during placental development revealed a significant increase in preterm versus term placenta. Taken together, our data show regulation of ABCG2 expression by EGF. In view of EGF signal transduction as a target for drugs (e.g., gefitinib), which are in turn substrates and/or inhibitors of ABCG2, this regulation has therapeutic consequences.

ABSTRACT:

Epidermal growth factor (EGF) is a multifunctional growth factor that binds to cell surface receptors with intrinsic tyrosine kinase activity (Carpenter and Cohen, 1979). There is evidence that EGF plays a pivotal role in proliferation and differentiation processes of a variety of cell types. Eukaryotic cells respond to an activation of EGF receptor (EGFR) by initializing signal pathways, including mitogen-activated protein kinase (MAPK) cascades (Levin and Errede, 1995). Phosphorylation of EGFR activates intracellular MAPKs like ERK1/2 (extracellular regulated kinase) or JNK/SAPK (c-jun NH-terminal kinase/stress-activated protein kinase) (Minden et al., 1994; Wu et al., 2001). Phosphorylation of these kinases can result in the activation of c-jun and c-fos, which are able to bind to AP-1 binding sites controlling the transcription of genes of proliferation and differentiation (Cano et al., 1995). Moreover, EGFR plays a major role in formation and propagation of various tumor entities by affecting apoptosis, proliferation, and angiogenesis (Lockhard and Berlin, 2005).

It is known that EGF plays a vital role in differentiation of human cytotrophoblasts (Maruo et al., 1987; Morrish et al., 1997). These cells act as the progenitor cells of syncytiotrophoblasts, which form the outer layer of placental villi representing the structure of placenta that is free floating in maternal blood. Tight control of this differentiation is a prerequisite for placentation function, and the effects of EGF have been shown in various studies addressing differentiation of cytotrophoblasts. Indeed, it has been demonstrated that maturation of these

ABBREVIATIONS: EGF, epidermal growth factor; EGFR, epidermal growth factor receptor; TKI, tyrosine kinase inhibitor; AP-1, activation protein-1; MEM, modified Eagle’s medium; FCS, fetal calf serum; MAPK, mitogen-activated kinase; ERK1/2, extracellular regulated kinase; pERK1/2, phosphorylated extracellular regulated kinase; JNK/SAPK, c-jun NH-terminal kinase/stress-activated protein kinase; pJNK/SAPK, phosphorylated c-jun NH-terminal kinase/stress-activated protein kinase; PCR, polymerase chain reaction; BSA, bovine serum albumin; β-hCG, β-human chorionic gonadotropin; PD, PD 98059: 2’-amino-3’-methoxyflavone; AG, AG1478: 4-(3-chloroanilino)-6,7-dimethoxyquinazoline; ABC, ATP-binding cassette; MEK, mitogen-activated protein kinase kinase; BCRP, breast cancer resistance protein; PBS, phosphate-buffered saline; PAG, polyacrylamide gel electrophoresis; TBST, Tris-buffered saline (0.5 M Tris, 1.5 M NaCl) supplemented with 0.1% Tween; CHAPS, 3-[3-cholamidopropyl]dimethylammonio]-1-propanesulfonic acid; ANOVA, analysis of variance.
cells is propagated by in vitro treatment with EGF, resulting in increased β-human chorionadotropin and human placental lactogen secretion, and subsequent morphologic changes (Morrish et al., 1997). In vivo, EGFR has been detected in the apical and basal membrane of syncytiotrophoblasts (Kawagoe et al., 1990). Malplacentation and dysfunction of human placenta is assumed to be associated with variations in levels of signaling molecules, thereby identifying an important role of EGF as one of the syncyti-al-promoting factors (Barber et al., 2005).

The protective function of human placenta is in part based on the polarized expression of elimination transporters such as various members of the ATP-binding cassette (ABC) transporter family. Understanding of the expression of transporters in human placenta is pivotal to assess pharmacological and toxicological risks associated with the administration of drugs during pregnancy (Holcberg et al., 2003).

ABC2 or breast cancer resistance protein (BCRP) is one member of this family. The gene of this transporter is located on chromosome 4q22 and forms a 70-kDa half-transporter containing one ATP-binding site and six transmembrane domains (Litman et al., 2001). The half-size prompted the assumption that ABCG2 homodimerizes for transport activity (Kage et al., 2002, Sugimoto et al., 2005). There is further evidence suggesting that ABCG2 forms homotetramers (Xu et al., 2004). It has been shown that ABCG2 promotes multidrug resistance for a wide range of toxic exogenous substances, including mitoxantrone, paclitaxel, and topotecan (Doyle et al., 1998; Haimeur et al., 2004). Moreover, it is assumed that ABCG2 is involved in control of bioavailability and distribution of these drugs because the transporter has been described to be expressed in a variety of human tissues, with very high levels in the syncytiotrophoblasts of placenta (Maliepaard et al., 2001).

In general, the regulation of ABCG2 is poorly understood. Aside from increased expression in multidrug-resistant cancer cells, different results indicate a physiological change in transporter expression such as induced expression during lactation in breast (Jonker et al., 2005). Furthermore Bailey-Dell et al. (2001) described multiple AP-1 binding sites in the promoter of ABCG2, thereby identifying a target for EGF-mediated c-Jun and c-Fos activation. We therefore investigated the influence of EGF on expression and function of ABCG2.

In this study we show a significant increase in ABCG2 expression and function by EGF mediated via phosphorylation of ERK1/2 and JNK/SAPK. This effect is specific for ABCG2 since the expression of other transporters such as ABC2 was not affected. Increased mRNA and protein levels in human trophoblasts, BeWo, and MCF7 cells were associated with increased drug resistance. Increased expression can be diminished by inhibitors of tyrosine kinase and MEK, thereby reversing the increased drug resistance. Taken together, these data indicate regulation of ABCG2 by EGF, which is of potential relevance for both placental function and drug treatment.

Materials and Methods

Materials. After written informed consent, placental tissue samples were obtained from women undergoing caesarian sections or normal birth. Chorionic villous tissue for isolation of cytotrophoblasts was obtained after caesarian sections or normal birth. Choriocarcinoma cell line BeWo was cultured in Medium 199 Earle’s with 5% FCS (Seromed-Biochrom KG), and 1% nonessential amino acids (Seromed-Biochrom KG). BeWo and MCF7 cells were associated with increased drug resistance. Increased expression can be diminished by inhibitors of tyrosine kinase and MEK, thereby reversing the increased drug resistance. Taken together, these data indicate regulation of ABCG2 by EGF, which is of potential relevance for both placental function and drug treatment.

Isolation of Total RNA from Placental Tissue Samples. After delivery, the tissue samples were immediately frozen in liquid nitrogen. After homogenization using a micro-dismembranator (Braun, Melsungen, Germany) RNA was isolated from 60 mg of tissue powder using a RNA Isolation Kit from QIAgen GmbH (Hilden, Germany). The isolation was performed according to the manufacturer’s instructions. After elution, the amount of RNA was quantified by photometry. Integrity of the RNA was controlled by denaturing MOPS-agarose gel electrophoresis.

Isolation of Cytotrophoblasts. Isolation of cytotrophoblasts was performed as described before (Meyer zu Schwabedissen et al., 2005b). Placental tissue was separated from vessels, decidua, and connective tissue. The chorionic villous tissue was mechanically dissected in ice-cold 0.9% sodium chloride. After several washings with ice-cold 0.9% sodium chloride, the homogenate was enzymatically disrupted by incubating three times for 20 min at 37°C in Hanks’ balanced salt solution (Seromed-Biochrom KG, Berlin, Germany) containing 25 mM Hepes pH 7.4 (Sigma-Aldrich), 1.5 mg/ml trypsin (Sigma-Aldrich), and 0.9 mg/ml DNase I (Roche Diagnostics, Mannheim, Germany). After sifting through a 0.1-mm polyester mesh, 25 ml of the eluate were layered over 5 ml of 90% fetal bovine serum and centrifuged at 2200g for 10 min at room temperature. The pelleted cells were resuspended in pre-warmed Dulbecco’s MEM-Earle’s medium with 25 mM Hepes, pH 7.4, containing 0.01 mg/ml DNase I. After supplementation of 25 ml of the cell solution with 5 ml of 90% Percoll-Hanks’ balanced salt solution-25 mM Hepes (pH 7.4), centrifugation was performed at 500g for 15 min. The cell pellet was resuspended in cold Dulbecco’s MEM-Earle’s medium with 25 mM Hepes, pH 7.4. Subsequently, cytotrophoblasts were separated using a discontinuous Percoll gradient. After centrifugation for 30 min at 2500g, cells between the 40% and 50% Percoll bands were collected, washed, and resolved in M199 Earle’s medium. The living cells were counted and viability was controlled by trypan blue staining. Then, the cells were pelleted by centrifugation at 500g and suspended in FCS containing 10% dimethyl sulfoxide; 1 × 10⁶ cells/vial were stored in liquid nitrogen after freezing at −80°C using an isopropanol-bathing cell-freezing container.

Purification of Cytotrophoblasts. The isolated cytotrophoblasts were purified as described by Douglas and King (1989) using an immunomagnetic cell separation method. The thawed cells were washed several times with ice-cold 0.9% sodium chloride. After centrifugation for 5 min at 600g and 4°C, the pelleted cells were resuspended in 2 ml of 0.5% BSA in phosphate-buffered saline (PBS), pH 7.4. Subsequently, for labeling of contaminating cells, the suspension was incubated with 5 μl of anti-HLA-DR and 5 μl of anti-HLA-ABC antibodies (Leinco Technologies Inc., St. Louis, MO) on ice for 30 min each. The suspension was washed with 2 ml of 0.5% BSA in PBS and resuspended in 200 μl of 0.5% BSA-PBS. Then, 25 μl of anti-mouse IgG Dynabeads (Dynal, Hamburg, Germany) were added and incubated for 30 min under continuous rotation at 4°C. Subsequently, the cell solution was cleaned by using a magnetic concentrator. This procedure was repeated. The cytotrophoblasts in supernatant were collected and centrifuged at 600g for 5 min at 4°C. The purified cytotrophoblasts were washed several times with 0.9% sodium chloride and resuspended in Medium 199 Earle (Seromed-Biochrom KG) supplemented with 10% FCS (Seromed-Biochrom KG) and 100 units/ml penicillin/streptomycin (Seromed-Biochrom KG), and 2.5 ng/ml EGF (Sigma-Aldrich). Cell culture was performed in six-well dishes in a humidified atmosphere supplemented with 5% CO₂ at 37°C.

Cell Culture of BeWo and MCF-7 Cells. BeWo cells were cultured in Medium 199 Earle (Seromed-Biochrom KG) supplemented with 10% FCS (Seromed-Biochrom KG) and l-glutamine (Seromed-Biochrom KG). MCF-7 cells were cultured in MEM Earle medium (Seromed-Biochrom KG) supplemented with 10% FCS (Seromed-Biochrom KG), l-glutamine (Seromed-Biochrom KG), and 1% nonessential amino acids (Seromed-Biochrom KG). Cell culture was performed at 37°C with 5% CO₂ in a humidified atmosphere. To investigate the effect of EGF on BeWo and MCF-7 cells, the cells were treated with medium supplemented with different concentrations of the growth factor. For RNA analysis, cells were cultured in six-well dishes using 3 ml of medium per well. After incubation for indicated times, cells were harvested using PeqGold RNA pure, as described in the section on RNA isolation of cells. For Western blot analysis, the cells were cultured in 60-mm dishes using 4 ml of medium.

Isolation of RNA from Cultured Cells. After incubation with 250 μl of the guanidine thiocyanate containing the buffer PeqGold RNA pure (PeqLab, Erlangen, Germany), the cell lysate was collected. Then, 100 μl of chloroform were added to the lysate, mixed, and incubated for 5 min at room temperature.
After centrifugation for 15 min at room temperature at maximum speed, the clear supernatant was collected and mixed with 250 μl of isopropanol. After incubation for 15 min at room temperature, the precipitated RNA was pelleted by centrifugation at maximum speed (10 min at room temperature). The RNA was washed twice with 75% ethanol, dried, and dissolved with 50 μl of RNase-free water. The amount of RNA was determined as described above.

**Cell Lysis and Preparation of Protein Extracts from Cells.** Before harvesting by scraping off the dishes, the cells were washed three times with prewarmed PBS. The detached cells were collected with 750 μl of PBS and pelleted by centrifugation. The cells were resuspended in 5 mM Tris/HCl, pH 7.4, supplemented with protease inhibitors (1 mg/l aprotinin, 0.5 mM leupeptin, and 100 μM phenylmethylsulfonyl fluoride). To support cell lysis, the lysates were shock-frosted in liquid nitrogen four times. Thereafter, crude membranes were isolated by centrifugation for 45 min at 100,000g and 4°C. The supernatant was collected and the pellet was resuspended in 5 mM Tris/HCl. Protein concentration was measured according to the bichinchoninic acid method. The separated intracellular and crude membrane fractions were stored at −80°C.

**Real-Time Reverse Transcription-PCR.** Total RNA was reverse-transcribed in a 25-μl reaction volume containing 500 ng of RNA using the TaqMan Reverse Transcript Kit (Applied Biosystems, Weiterstadt, Germany) as described in the manufacturer’s instructions. The amounts of ABCG2, ABCC2, and β-actin mRNA as well as 18S rRNA were measured by TaqMan quantitative real-time PCR with an ABI Prism 7700 sequence detection system (Applied Biosystems). The sequences of primers and probes used for establishing the amount of ABCG2- or ABCC2-mRNA were as follows: ABCG2 forward primer, 5'-CTGGAACATGATTAGGAAAGC-3'; ABCG2 reverse primer, 5'-GAGATTCTTCAAGCGCCGAC-3'; ABCG2 probe, 5'-6FAM-CAGTCGAGATGTGAACCTGGACAT-XTp; ABCC2 forward primer, 5'-TGAAGGATTTCAACAGATTATATTTACCTGTGA-3'; ABCC2 reverse primer 5'-CCATTGAACTGGCTGAATAAGC-3'; and ABCC2 probe, 5'-6FAM-ACCTGCTTCTGGTCTAATCCTGAAT-XTp. The endogenous genes β-actin and 18S rRNA were determined using TaqMan PreDeveloped Assay Reagents (Applied Biosystems). The quantitative PCR was carried out in a 25-μl reaction volume containing a 200 nM concentration of each primer and the TaqMan probe, PCR Master Mix, and 0.4 U/reaction TaqDNA Polymerase. The PCR Master Mix contains deoxynucleoside-5'-triphosphates, MgCl2, glycerol, KCl, and RoxDye. Ten nanograms of the cDNA were used for amplification of ABCG2, ABCC2, and β-actin mRNA and 0.15 ng of cDNA for detection of 18S rRNA. Cloned PCR products used for amplification were used as standard samples. The transporters expression was normalized to 18S rRNA for tissue samples or products of defined copy numbers were used as standard samples. The transcribed mRNA and 0.15 ng of cDNA were used for detection of 18S rRNA. Cloned PCR products were designed for amplification of ABCG2- or ABCC2-mRNA as described in the manufacturer’s instructions.

**Statistical Analysis.** The quantitative data are given as mean ± S.D. Statistical analysis was carried out using analysis of variance (ANOVA) or the Kruskal-Wallis test. Differences were considered significant if p < 0.05.

**Results**

Expression of ABCG2 in Human Placenta of Different Gestational Age. Total mRNA was isolated from human early preterm (n = 15), late preterm (n = 14), and term placentas (n = 29). Analysis of the demographic data revealed no significant difference in the age of...
pregnant women [age of pregnant women (years) ± S.D.; early preterms, 27 ± 7; late preterms, 27 ± 6; terms, 28 ± 6]. The mean gestational age ± S.D. was 28 ± 1 week for early preterms, 35 ± 3 weeks for late preterms, and 39 ± 2 weeks for terms. Crude membranes were prepared from a subset of these samples (early preterms n = 10, late preterms n = 7, and terms n = 10). Detection of mRNA expression was performed using real-time reverse transcription-PCR. Comparison of the ABCG2 mRNA amount normalized to that of 18S rRNA revealed a reduced expression of the transporter in the group of term placentas [ABCG2 mRNA/18S rRNA ratio × 1000 ± S.E.M.: early preterms 1.50 ± 0.78 (n = 15), late preterms 1.053 ± 0.603 (n = 13), and 0.688 ± 0.44 (n = 29); ANOVA test, p < 0.05] (Fig. 1A). Moreover, Western blot analysis of crude membrane preparations was performed using the anti-ABCG2 antibody BXP-21. Band intensity was normalized to that of an internal standard. As shown in Fig. 1B, there is a reduction of the protein expression of ABCG2 in the group of human term placentas [mean ABCG2 protein amount ± S.E.M.; early preterms, 4.15 ± 1.25 (n = 10); late preterms 3.41 ± 0.65, n = 7, and terms, 2.80 ± 0.80, n = 10; ANOVA, p < 0.05]. Immunofluorescent staining of paraffin-embedded tissue sections was performed using the BXP-21 antibody to analyze whether there is any change in localization of this transporter during gestation. As shown in Fig. 1C, ABCG2 is expressed in the syncytiotrophoblast in human preterm and term placentas. There is no alteration in localization of the transporter. These cells form the outer layer of the placental villi.

Expression of ABCG2 in Differentiating Cytotrophoblasts. The progenitor cells of the syncytiotrophoblasts can be isolated from human placenta. In culture, these cells differentiate by forming a multinuclear syncytium. This morphological change was controlled by light microscopy (data not shown) and is accompanied by biochemical differentiation measured by synthesis and secretion of β-hCG into the supernatant (data not shown). Detection of ABCG2 expression by in vitro differentiated cells of three different cytrophoblast preparations revealed a statistically significant change in ABCG2 mRNA level compared with the progenitor cells (ABCG2 mRNA/18S rRNA ratio × 1000: 0 h, 0.8 ± 0.01; 48 h in culture, 4.5 ± 1.25; 72 h, 3.45 ± 0.5; ANOVA, p < 0.05).

Analysis of ABCG2 Expression in BeWo Cells. Expression of ABCG2 in BeWo cells was determined by Western blot analysis and immunofluorescence microscopy. Expression of ABCG2 was detected by immunofluorescent staining of cells cultured for 48 h on coverslips. As shown in Fig. 2A, the majority of the transporter is located in the membrane. This localization was not altered by treatment with EGF. Moreover, Western blot analysis was performed after separation and electrotransfer of crude membrane fractions of cultured BeWo cells. As shown in Fig. 2B, there is a constant expression of the transporter during culture.

Induction of ABCG2 in Cultured BeWo Cells Mediated by EGF. To study the influence of EGF on the expression of ABCG2 in BeWo cells, the cells were treated with 2.5 and 5 ng/ml EGF. As shown in Fig. 3A, analysis of ABCG2 expression revealed an increase of ABCG2 mRNA by EGF. Stimulation for 48 h with 2.5 ng/ml EGF is accompanied by a 5.7-fold increase of ABCG2 mRNA expression (ABCG2/β-actin ratio ± S.D.; n = 3; 48 h, control, 0.47 ± 0.02; 48 h with 2.5 ng/ml EGF, 2.59 ± 0.07; 48 h with 5 ng/ml EGF, 2.96 ± 0.05; ANOVA, p < 0.05). In addition, Western blot analysis of crude membrane fractions was performed. BeWo cells were incubated for 24 h with 2.5 ng/ml to 5 ng/ml EGF. The expression of the transporter was normalized to that of β-actin [ABCG2/β-actin ratio, percentage of control ± S.D. (n = 3): native cells, 100%; cells treated with solvent, 108.1 ± 8.1%; cells treated with 2.5 ng/ml EGF, 135.63 ± 12.8%; 5 ng/ml 179.8 ± 23.1%; ANOVA, p < 0.05]. As shown in Fig. 3B, there is also an increase of ABCG2 protein expression.

ABC2 Expression in EGF-Stimulated BeWo Cells. Recently, we described an increase of ABCC2 and ABCC5 in differentiating cytrophoblasts (Meyer zu Schwabedissen et al., 2005a,b). These cells were treated with EGF. Similar unpublished data were obtained.
for ABCB1. To answer the question whether the induction of the transporter mRNA by exogenous EGF is specific for ABCG2, we tested the effect of EGF stimulation on ABCC2 expression in BeWo cells. We decided to take this transporter, because ABCB1 expression levels do not reach the detection limit in BeWo cells and ABCC5 showed very low expression. As shown in Fig. 3C, BeWo cells exhibit no statistically significant change of ABC2 mRNA amount during the treatment with EGF (ABCC2/β-actin mRNA ratio ± S.D.: 0 h, control, 0.039 ± 0.005; 48 h, control, 0.045 ± 0.016; 48 h with 2.5 ng/ml EGF, 0.052 ± 0.023; ANOVA, p > 0.05).

Drug Resistance of EGF-Treated BeWo Cells. To study whether the EGF-dependent increase of ABCG2 expression alters sensitivity of cells to toxic agents, we performed viability assays after treatment with mitoxantrone, topotecan, or doxorubicin. Control cells were treated in the same way with the solvents only. Sensitivity of BeWo cells to cytotoxic substances was analyzed using the ALAMAR Blue detection system. Data are expressed as mean ± S.D. * p < 0.05, Student’s t test.

As shown in Fig. 3D, EGF-treated cells exhibit a statistically significant increase in viability after 24 h of incubation with mitoxantrone in concentrations of 3.32 μM, 10 μM, 33.16 μM, and 100 μM compared with control cells. In detail, after 24 h with 10 μM mitoxantrone, only 48 ± 1% of the native cells were viable, whereas 76 ± 3% of the cells treated with EGF for 48 h were viable (Student’s t test, p < 0.05). Similar effects were shown for topotecan (10 μM topotecan in native cells, 62 ± 0.1%; or EGF-stimulated cells, 82 ± 4%; Student’s t test, p < 0.05), but not for doxorubicin-treated cells.

Treatment with EGF Activates MAPK Cascades. Activation of EGF receptor is accompanied by initiating intracellular signaling
pathways. We analyzed whether the MAP kinases ERK1/2 and JNK/SAPK were phosphorylated and thereby activated by treatment of BeWo cells with EGF.

Western blot analysis of pERK1/2 (phosphorylated ERK), ERK1/2, and β-actin was performed using the intracellular protein fraction of BeWo cells treated with or without 2.5 ng/ml EGF. The protein was separated by SDS-10% PAGE and electrotransferred to nitrocellulose. First, detection of pERK was performed. After detection using a chemiluminescent detection reagent, the blots were stripped and reincubated with anti-ERK and anti-actin antibodies, respectively. B, analysis of the activation of JNK was performed in the same way, using specific antibodies for pJNK and actin. Representative immunoblots are shown.

Expression of ABCG2 in MCF-7 Cells. There is evidence that BeWo cells differentiate when treated with EGF. In fact, we did not see a loss of basolateral membranes as described by differentiating cytotrophoblasts. In addition, we did not detect a significant increase of the pregnancy hormone β-hCG secreted into the supernatant. However, we studied the effects of EGF in another cell system. Breast cancer cells are described to express an EGF receptor, and ABCG2 was originally described in these cells (Doyle et al., 1998). Therefore, we decided to use them for analysis of the EGF effect.

MCF-7 cells were cultured with 2.5 ng/ml EGF. Real-time PCR of cells treated with the growth factor revealed an increase of the transporter as shown in Fig. 5A. The expression level of the transporter was low compared with that of BeWo cells. However, after 48 h of incubation, the EGF-treated cells showed a 5.4-fold increased expression of ABCG2 mRNA (ABCG2/β-actin mRNA ratio ± S.D.; n = 3; 0 h, control, 0.0018 ± 0.0003; 48 h, control, 0.0018 ± 0.0007; 48 h with 2.5 ng/ml EGF, 0.0098 ± 0.002; Kruskal-Wallis test, p < 0.05). These results were supported by Western blot analysis of crude membrane preparations indicating an increase in protein level after 24 h (Fig. 5B). Moreover, Western blot analysis of intracellular protein fraction showed an activation of the ERK1/2 (Fig. 5C) and JNK/SAPK (Fig. 5D) after stimulation with EGF.

Inhibition of the EGF-Mediated Increase Using the Tyrosine Kinase Inhibitor AG1478 or the MEK Inhibitor PD 98059. Assuming that the increase of ABCG2 is mediated by EGF and subsequent activation of the EGF-coupled intracellular signal cascade, we tested whether the increase in transporter expression can be reduced using the tyrosine kinase inhibitor (TKI) AG1478 (AG) or the MEK inhibitor PD 98059 (PD). Therefore, BeWo cells were treated with 2.5 ng/ml EGF after 30 min of incubation with the inhibitor. Control cells were incubated with the solvents of the inhibitor and EGF, respectively. As shown in Fig. 6A, the increase of the mRNA amount could be reduced using the described inhibitors. Measuring the expression of ABCG2 after 48 h of incubation revealed a ratio of 2.5 ± 0.30 in cells treated with EGF, 0.92 ± 0.26 in BeWo cells treated with EGF and the TKI AG1478, or 1.13 ± 0.07 in cells treated with EGF and the MEK inhibitor PD 98059, whereas the ABCG2/β-actin mRNA ratio in control cells was measured as 0.44 ± 0.02.

Moreover, treatment of BeWo cells with 2.5 ng/ml EGF and a 10 μM concentration of each inhibitor diminished the increase of protein expression of the transporter as shown in Fig. 6B [ABCG2/β-actin ratio, percentage of control ± S.D. (n = 3: control cells, 100%; cells
the cells were treated with 10 min. Then, the cells were stimulated with EGF (2.5 ng/ml) for 48 h. Subsequently, representative immunoblot. C, BeWo cells were incubated with the inhibitors for 30 min are expressed as percentage of control; mitoxantrone was established using the ALAMAR Blue detection system.

Cell viability. DMSO was added in control cells. Then, BeWo cells were stimulated with EGF (2.5 ng/ml), 157.57 ± 3.07%; or with 2.5 ng/ml EGF and PD 98059 98.19 ± 15.59%; ANOVA, p < 0.05).

Furthermore, sensitivity of cells treated with a 10 μM concentration of each inhibitor and 2.5 ng/ml EGF to mitoxantrone was not reduced but remained at the level of control cells (Fig. 6C). After 48 h of incubation with mitoxantrone (10 μM), 75 ± 5% of the BeWo cells stimulated with 2.5 ng/ml EGF were still viable in comparison with control cells. At the same time, only 54.68 ± 0.26% of the nonstimulated cells or 41.29 ± 4.34% of the cells treated with EGF and the inhibitor PD 98059 are viable. In contrast, 52.13 ± 1.69% of the BeWo cells treated with AG1478 for inhibition of EGF-mediated tyrosine kinase activation were viable after treatment with 10 μM mitoxantrone for 48 h. Similar effects were detected in MCF-7 cells (data not shown).

Signal Cascade in Differentiating Cytotrophoblasts. We addressed the question whether the increase of ABCG2 expression in cytotrophoblasts can be abolished by inhibition of the intracellular MAP kinase cascade using the MEK inhibitor PD 98059 or the tyrosine kinase inhibitor AG1478, respectively, as shown in BeWo and MCF cells. Therefore, cultured cytotrophoblasts were treated with a 10 μM concentration of the inhibitors. Analysis of the β-hCG secretion into the medium revealed that biochemical differentiation is reduced by treatment with the tyrosine kinase inhibitor AG1478 and the MEK inhibitor PD 98059 (inset, Fig. 8A). As shown in Fig. 8A, analysis of the amount of ABCG2 mRNA during the process of differentiation showed that both inhibitors were able to reduce the increase of ABCG2 expression mediated by exogenous EGF significantly (ABCG2/β-actin mRNA ratio ± S.D.; 0 h, control, 0.003 ± 0.002; 48 h with EGF, 0.074 ± 0.020; 48 h with EGF and 10 μM AG, 0.006 ± 0.007; and 48 h with EGF and 10 μM PD, 0.011 ± 0.015; ANOVA, p < 0.05). Western blot analysis of crude membrane fractions of cultured cytotrophoblasts revealed that the inhibitors are able to diminish the ABCG2 protein amount in differentiating cytotrophoblasts (Fig. 8B).

Studying the activation of intracellular signal transduction of EGF established by Western blot analysis of the intracellular protein fraction showed that exogenous EGF activates ERK1/2 and JNK/SAPK (Fig. 8C). Moreover, supplementation of the tyrosine kinase or MEK inhibitor diminished the phosphorylation of these intracellular kinases (Fig. 8C).

Analysis of the Predictive Value of the Model Cell Line BeWo Using Two-Dimensional SDS-PAGE. BeWo cells are a commonly used model for villous cytotrophoblasts. Because the number of cells-treated with 2.5 ng/ml EGF and AG1478 99.59 ± 3.07%; or with 2.5 ng/ml EGF and PD 98059 98.19 ± 15.59%; ANOVA, p < 0.05).

FIG. 6. AG1478 (AG) and PD 98059 (PD) diminish the EGF-mediated increase of ABCG2 in BeWo cells. A, BeWo cells were pretreated for 30 min with the tyrosine kinase inhibitor AG1478 or the MEK inhibitor PD 98059. The same amount of AG1478, respectively, as shown in BeWo and MCF cells. Therefore, cultured cytotrophoblasts were treated with a 10 μM concentration of the inhibitors. Analysis of the β-hCG secretion into the medium revealed that biochemical differentiation is reduced by treatment with the tyrosine kinase inhibitor AG1478 and the MEK inhibitor PD 98059 (inset, Fig. 8A). As shown in Fig. 8A, analysis of the amount of ABCG2 mRNA during the process of differentiation showed that both inhibitors were able to reduce the increase of ABCG2 expression mediated by exogenous EGF significantly (ABCG2/β-actin mRNA ratio ± S.D.; 0 h, control, 0.003 ± 0.002; 48 h with EGF, 0.074 ± 0.020; 48 h with EGF and 10 μM AG, 0.006 ± 0.007; and 48 h with EGF and 10 μM PD, 0.011 ± 0.015; ANOVA, p < 0.05). Western blot analysis of crude membrane fractions of cultured cytotrophoblasts revealed that the inhibitors are able to diminish the ABCG2 protein amount in differentiating cytotrophoblasts (Fig. 8B).

Studying the activation of intracellular signal transduction of EGF established by Western blot analysis of the intracellular protein fraction showed that exogenous EGF activates ERK1/2 and JNK/SAPK (Fig. 8C). Moreover, supplementation of the tyrosine kinase or MEK inhibitor diminished the phosphorylation of these intracellular kinases (Fig. 8C).

Analysis of the Predictive Value of the Model Cell Line BeWo Using Two-Dimensional SDS-PAGE. BeWo cells are a commonly used model for villous cytotrophoblasts. Because the number of cells
isolated from a placenta is limited and because the interindividual variability can reduce reproducibility of experiments performed with isolated cytotrophoblasts, these cells are often used as model for studying effects on cytotrophoblasts.

A high degree of similarity in physiological reactions of BeWo cells and cytotrophoblasts very likely requires high similarity in protein inventory. We now compared the intracellular protein fraction of BeWo cells and cytotrophoblasts by two-dimensional gel electrophoresis to evaluate the use of BeWo cells as a model of cytotrophoblasts.

The protein pattern of freshly isolated cytotrophoblasts purified by immunomagnetic cell separation, cultured BeWo cells, and the breast cancer cell line MCF-7 were compared. The Delta2D software used provides the possibility to overlay two different gel images. Comparison of the intracellular protein pattern showed similarity mainly in the abundant proteins of BeWo cells and undifferentiated cytotrophoblasts (Fig. 9). The intracellular protein fraction of MCF-7 cells also shows similarities. In addition to these, we found a lot of protein spots in the enriched intracellular protein fraction in cytotrophoblasts that did not have a partner in the gel image of MCF-7 cells, pointing to a higher variety of expressed proteins in this cell type.

**Discussion**

The present data point to a regulation of ABCG2 by EGF and EGFR-mediated signal transduction. We show that ABCG2, a membrane protein known to be involved in uptake-limiting transport processes, is reduced in human placenta with further gestational age (Fig. 1). This is in accordance with recent data that show a reduction of this transporter in rat placenta (Yasuda et al., 2005).

ABCG2 transport activity plays a pivotal role in the fetus-protecting capacity of placenta (Jonker et al., 2000). In addition, several physiologic substrates were shown to be transported by ABCG2, including exogenous and endogenous porphyrins (Jonker et al., 2002) and sulfated conjugates of steroids like 17β-estradiol sulfate (Suzuki et al., 2003). Moreover, it is assumed that ABCG2 is involved in the regulation of folate homeostasis of eukaryotic cells. Ifergan et al. (2004) were able to show that folate mono- and polyglutamates are transported by ABCG2. Moreover, folate deprivation was shown to be accompanied by a down-regulation and retrieval from the membrane of the transporter (Ifergan et al., 2004). The lower expression of ABCG2 in human term placenta described in this study (Fig. 1) could be an adaptive mechanism on the increasing demands of the developing fetus in view of the folate homeostasis.

Furthermore, it has been shown that ABCG2 is involved in transport of cytotoxic xenobiotics including mitoxantrone, etoposide, and topotecan (Sarkadi et al., 2004). Assuming that proliferating cells are more sensitive for teratogenic effects induced by xenobiotics, it seems to be reasonable that the expression of the protective transporter is higher in the more vulnerable early period of pregnancy.

One mechanism of the regulation of ABCG2 could be EGF. There is evidence for the pivotal role of EGF in pregnancy, inasmuch as deficiency of maternal EGF production causes significant fetal losses and asymmetrical intrauterine growth retardation in mice (Kamei et al., 1999). Moreover, Li et al. (2003) showed that failed fetal response to maternally produced EGF and, therefore, impaired syncytialization is associated with preeclampsia.

EGF is known as one of the syncytial-promoting factors inducing morphological and biochemical maturation of cytotrophoblasts in vitro (Maruo et al., 1987; Morrish et al., 1997). In this study, we describe an increase of ABCG2 expression during the process of in vitro maturation of cytotrophoblasts. Differentiation of these progenitor cells was induced by supplementation of 2.5 ng/ml EGF. The in
vitro increase of ABCG2 in cytotrophoblasts was diminished by the tyrosine kinase inhibitor AG1478 and the MEK inhibitor PD 98059 (Fig. 9). It is noteworthy that in the presence of these inhibitors, the secretion of the differentiation marker β-hCG was reduced.

To study the ABCG2 increase after exposure to EGF, we looked for a suitable cell model of villous cytotrophoblasts. BeWo cells are frequently used for this purpose. It is not known, however, whether BeWo cells originally isolated from a choriocarcinoma show a similar protein pattern in comparison to cytotrophoblasts. We therefore compared BeWo cells and undifferentiated cytotrophoblasts in two-dimensional gels and found a high degree of similarity, mainly of the high abundance proteins. In combination with previously shown similarities in cell function, including transport processes or metabolism, BeWo cells seem to be a suitable model to mimic primary cytotrophoblasts (Pattillo and Gey, 1968; Moe et al., 1994; Liu et al., 1997).

In accordance with experiments in cytotrophoblasts, the stimulation of BeWo cells with the growth factor was accompanied by increased expression of ABCG2 mRNA and protein amount. The stimulation was mediated by an activation of MAPK cascade and was consequently inhibited by treatment with the TKI AG1478 or the MEK inhibitor PD 98059. Moreover, the increased expression of ABCG2 mediated by EGF showed functional relevance, since stimulation resulted in reduced sensitivity for topotecan or mitoxantrone, which are both known ABCG2 substrates. In contrast, no change in the sensitivity to doxorubicin, a drug not transported by wild-type ABCG2, was detected (Honjo et al., 2001).

Recently, it has been shown that sorting of ABCG2 to the membrane is induced by exogenous EGF. This effect has been associated with increased phosphorylation of Akt in transfected cells. Most likely, this is not a direct interaction between Akt and the ABCG2 gene expression since there is no putative consensus site for Akt (Takada et al., 2005). In addition, it is noteworthy that EGF exerts its antiapoptotic cell-protecting and syncytial-promoting effect independently of PI3K/Akt pathway in trophoblasts like cells (Perkins et al., 2002). Therefore, it seems to be unlikely that the effect described in EGF-promoted differentiating cytotrophoblasts is induced via Akt.

Recently, we described an induction of ABCC2 (MRP2) and ABCC5 (MRP5) during the process of cytotrophoblastic differentiation (Meyer zu Schwabedissen et al., 2005a,b); therefore, specificity of the effect of EGF on ABCG2 was assessed by measuring the amount of ABCC2 in stimulated BeWo cells. No significant change in expression of this transporter was detected during the time course of EGF treatment, indicating specific regulation of ABCG2.

It is known that differentiation of cytotrophoblasts is associated with an activation of β-hCG. Moreover, it is assumed that the positive effect of EGF on differentiation of cytotrophoblasts depends on the permissive effects of human choriogonadotropin, which is produced by the mature cells (Yang et al., 2003). To exclude the possibility that the increase of ABCG2 observed in cytotrophoblasts is based on induced β-hCG production of stimulated cells, we used the breast cancer cell line MCF-7, which is not described to produce β-hCG but expresses both the EGF receptor and ABCG2. Because we found similar effects of EGF on ABCG2 expression in MCF-7 cells, which, again, had functional consequences and were inhibited by tyrosine kinase or MEK inhibitor, we conclude that the effects of EGF on ABCG2 are not restricted to cytotrophoblasts and BeWo cells.

Expression of elimination transporters including ABCG2 is suggested to be one of the cellular mechanisms involved in drug resis-
tance of cancer cells (Polgar and Bates, 2004). In addition, overexpression of EGFR has been associated with drug resistance and, therefore, poor prognosis (Lockard and Berlin, 2005). In this study, we showed an increase of ABCG2 mediated by EGFR stimulation. Therefore, it is conceivable that activation of the intracellular MAPK cascade by EGFR is involved in the modulation of drug resistance mediated by ABCG2.

There are a variety of drugs targeting the EGFR axis, and they show promising results in tumor therapy (Lockard and Berlin, 2005). One of these substances is gefitinib (Iressa; ZD1839), an inhibitor of EGFR tyrosine kinase activity, which inhibits the activation of the MAPK cascade. It is likely that this inhibitor is associated with a loss of induction of the elimination transporter and therefore enhances drug sensitivity of coadministered substrates. In addition, gefitinib has been shown to inhibit ABCG2 transport activity directly by interaction with this eliminating transporter (Yanase et al., 2004; Nakamura et al., 2005).

In summary, our results indicate that EGFR induces the expression of ABCG2 via the MAPK cascade. Therefore, it seems likely that production of EGFR in the maternal organism is not only an inducer of syncytialization, but also a regulator of functional activity of the syncytium. Because ABCG2 is also described to play a major role in syncytialization, but also a regulator of functional activity of the syncytium, it seems likely that ABCG2 via the MAPK cascade. Therefore, it seems likely that production of EGFR in the maternal organism is not only an inducer of syncytialization, but also a regulator of functional activity of the syncytium. Because ABCG2 is also described to play a major role in syncytialization, but also a regulator of functional activity of the syncytium, it seems likely that ABCG2 via the MAPK cascade.

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References

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EXOGENOUS EGF INCREASES ABCG2 (BCRP) EXPRESSION

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