Key Role of Nuclear Factor-κB in the Cellular Pharmacokinetics of Adriamycin in MCF-7/Adr Cells: The Potential Mechanism for Synergy with 20(S)-Ginsenoside Rh2

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ABSTRACT:
We have previously demonstrated that ginsenoside 20(S)-Rh2 is a potent ATP-binding cassette (ABC) B1 inhibitor and explored the cellular pharmacokinetic mechanisms for its synergistic effect on the cytotoxicity of Adriamycin. The present studies were conducted to elucidate the key factors that influenced ABCB1 expression, which could further alter Adriamycin cellular pharmacokinetics. Meanwhile, the influence of 20(S)-Rh2 on the above factors was revealed for explaining its synergistic effect from the view of ABCB1 expression. The results indicated that 20(S)-Rh2 inhibited Adriamycin-induced ABCB1 expression in MCF-7/Adr cells. Subsequent analyses indicated that 20(S)-Rh2 markedly inhibited Adriamycin-induced activation of the mitogen-activated protein kinase (MAPK)/nuclear factor (NF)-κB pathway, NF-κB translocation to the nucleus, and NF-κB binding activity. Furthermore, 20(S)-Rh2 repressed the Adriamycin-enhanced ability of NF-κB to bind to the human multidrug resistance (MDR1) promoter, and MAPK/NF-κB inhibitors and NF-κB small interfering RNA reversed the Adriamycin-induced expression of ABCB1. Moreover, the cellular pharmacokinetics of Adriamycin was also significantly altered by inhibiting NF-κB. In conclusion, the MAPK/NF-κB pathway mediates Adriamycin-induced ABCB1 expression and subsequently alters the cellular pharmacokinetics of Adriamycin. It was speculated that 20(S)-Rh2 acted on this pathway to lower Adriamycin-induced ABCB1 expression in MCF-7/Adr cells, which provided mechanism-based support to the development of 20(S)-Rh2 as a MDR reversal agent.

Introduction
Inhibition or induction of ATP-binding cassette (ABC) transporters in tumor cells can lead to cellular pharmacokinetic alterations of many chemotherapeutic agents, which attracts much attention in cancer treatment (Hauswald et al., 2009; Kofla et al., 2011). ABCB1 is one of the extensively studied ABC transporters involved in Adriamycin resistance of breast cancer (Kröger et al., 1999). Adriamycin is shown to have predominant nuclear accumulation in wild-type MDA-MB-435 cell lines, whereas it is sequestered away from the nucleus into cytoplasm in ABCB1-transduced MDA-MB-435 cell lines (Shen et al., 2008). The difference between the two types of cell lines in cellular pharmacokinetic behavior of Adriamycin directly correlates with the sensitivity of these cells to the cytotoxic effects of Adriamycin. Because ABCB1 is also located in subcellular organelles, such as nuclei (Zhang et al., 2012), mitochondria (Solazzo et al., 2006), and the Golgi apparatus (Moliniari et al., 1998), its role in subcellular pharmacokinetic behavior and anticancer activity of Adriamycin has been well investigated and has been recognized (Zhang et al., 2012). Therefore, an investigation of the regulation of ABCB1 at the cell surface and in intracellular organelles in multidrug resistance (MDR) tumor cells has great significances for breast cancer studies and treatment.

Many ABC transporter inhibitors have been found to promote the intracellular and subcellular distribution of anticancer agents by inhibiting transmembrane drug efflux, which enhances the binding ability of an anticancer agent to its intracellular target and further...
strengthens its pharmacological effects (Shen et al., 2008, 2009; Zhang et al., 2012). In addition to controlling the activities of ABC transporters, regulating the expressions of ABC transporters might broadly represent a more effective approach to overcoming MDR. ABC transporter expression could be generally classified as regulated at the transcriptional level (Scotto, 2003; Callaghan et al., 2008) and by post-translational modifications (Minami et al., 2009; Xie et al., 2010); transcriptional regulation has been a main focus of previous studies (Gu and Manautou, 2010). Many transcriptional factors including NF-κB (Bentires-Alj et al., 2003), Y-box binding protein-1 (Shen et al., 2011), activator protein-1 (Bark and Choi, 2010), and hypoxia-inducible factor-1 (Han et al., 2007) have been found to bind to the promoter region of the MDR gene to initiate the transcription and expression of ABC transporters. Moreover, several signal transduction pathways have also been demonstrated to be involved in regulating the activities of those transcriptional factors, such as MAPK (Katayama et al., 2007; Manov et al., 2007), phosphatidylinositol 3-kinase (Barancik et al., 2006; Choi et al., 2008), protein kinase C (Liu et al., 2009; Rigor et al., 2010), and NF-κB (Hien et al., 2010; Kim et al., 2011) pathways. However, reports of signal molecules regulating the cellular pharmacokinetics of anticancer agents in cells are limited. Therefore, there is a pressing need to identify potential drugs that target specific key signal molecules to improve cellular pharmacokinetics of anticancer agents through regulating ABCB1 expression.

Ginsenoside Rh2, a protopanaxadiol-type ginsenoside with a dammarane skeleton, is a trace active constituent of ginseng (Kitagawa et al., 1983). Many studies have demonstrated a remarkable synergistic effect of nontoxic Rh2 with anticancer agents in a variety of in vitro and in vivo tumor models (Kikuchi et al., 1991; Jia et al., 2004; Xie et al., 2006). To fully understand this synergistic effect, we have previously demonstrated that Rh2 is a potent ABCB1 inhibitor in vitro and in vivo (Zhang et al., 2010). Then, a cellular pharmacokinetic strategy was conducted to further illustrate the in-depth mechanisms. It was found that 20(S)-Rh2 improved the cellular pharmacokinetic behaviors and pharmacological effects of Adriamycin in MCF-7/Adr cells via cellular/subcellular ABCB1 inhibition (Zhang et al., 2012).

In the present studies, we intended to further elucidate the key factors that can affect ABCB1 expression and thus alter the cellular pharmacokinetic behaviors of Adriamycin. Meanwhile, we also examined the synergistic mechanism of 20(S)-Rh2-mediated interference with these factors affecting ABCB1 expression.

Materials and Methods

Reagents. 20(S)-Ginsenoside Rh2 (purity >98%) was purchased from Jilin University (Changchun, China). 4-(4-Fluorophenyl)-2-(4-methylsulfonylphenyl)-5-(4-pyridyl)-1H-imidazole (SB203580) and 1,4-diamino-2,3-dicyano-1,4-bis(methylthio)butadiene (U0126) were purchased from Cell Signaling Technology (Danvers, MA). Anthra[1-9-c]pyrazolo[6-2H]one (SP600125), 2’a-mino-3’-methoxyflavone (PD98059), pyrroldinedithiocarbamate, 3-[4-(methylphenyl)sulfonyl]-2-(e)-propenilnine (BAY 11-7082), and Adriamycin were purchased from Sigma-Aldrich (St. Louis, MO). Monoclonal antibodies against p-p38, p-ERK, p-JNK, p-ERK, NF-κB p65, p-ERK, p-IκBα, NF-κB p65, IκBα, and IKKβ were purchased from Cell Signaling Technology. The monoclonal antibody against ABCB1 was purchased from Millipore Corporation (Billerica, MA). The antibodies for lamin B and β-actin were purchased from Boster Biological Technology (Wuhan, China). The horseradish peroxidase-conjugated goat anti-mouse/rabbit IgG secondary antibodies were purchased from Cell Signaling Technology. NF-κB p65 siRNAs were purchased from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA). FuGENE HD Transfection Reagent was purchased from Promega (Madison, WI). The electrophoretic mobility shift assay (EMSA) kit was purchased from Viagene Biotech (Ningbo, China). The SimpleChIP Enzymatic Chromatin IP Kit was purchased from Cell Signaling Technology. The SYBR PrimeScript RT-PCR Kit was purchased from Takara Bio (Kyoto, Japan). Deionized water was prepared with a Milli-Q system (Millipore, Milford, MA) and was used throughout.

Cell Culture. The human breast cancer cells MCF-7 and Adriamycin-resistant human breast cancer cells MCF-7/Adr were obtained from the Institute of Hematology and Blood Diseases Hospital (Tianjin, China) and cultured in RPMI 1640 medium supplemented with 10% fetal bovine serum and 100 U/mL penicillin and streptomycin (Invitrogen, Carlsbad, CA) at 37°C with 5% CO₂. The cell medium was changed every other day. Cells were passaged upon reaching ~80% confluence. All of the cells used in this study were between passage 30 and 38 and were negative for mycoplasma infection.

Western Blotting Assay. For Western blotting analysis, crude cell membranes were prepared as described previously (Zhang et al., 2010). Nuclear and cytosolic extracts were isolated according to the KeyGen Nuclear Extract Kit (KeyGen Biotech, Nanjing, China). Protein concentrations were determined by the bicinchoninic acid method using the BCA protein assay kit (Thermo Fisher Scientific, Waltham, MA). The protein samples were separated on an 8% SDS-polyacrylamide gel and transferred onto a polyvinylidene difluoride membrane (Bio-Rad Laboratories, Hercules, CA). The membrane was blocked with 5% nonfat milk in Tris-buffered saline-Tween 20 for 1 h at 37°C and then was incubated with the primary antibodies overnight at 4°C. After washing, the membrane was incubated with horseradish peroxidase-conjugated secondary antibody for 1 h at 37°C. The signals were detected using an enhanced chemiluminescence kit (Thermo Fisher Scientific). The chemiluminescent signal was captured using a ChemiDoc XRS+ System (Bio-Rad Laboratories).

EMSA. The EMSA was performed as described previously (Wang et al., 2010). After drug treatment, nuclear extracts of MCF-7 and MCF-7/Adr cells were prepared and incubated with 1 μg of poly( polyinosinic-polycytidylic acid) in binding buffer for 30 min at 4°C. DNA-binding activity was detected using a biotin-labeled oligonucleotide bio-NF-κB probe (5’-GTAAGTGGACGGAGGCACTTTCCAGGCGCTG-3’) and an EMSA kit according to the manufacturer’s protocol. In competition assays, excess oligonucleotide probe (5’-AGTGGACGGAGGCACTTTCCAGGCGCTG-3’) or mutant probe (5’-AGTGGACGGAGGCACTTTCCAGGCGCTG-3’) was preincubated with nuclear extracts for 15 min at room temperature. In supershift assays, antibodies were added 30 min before the biotin-labeled oligonucleotide. The resulting DNA-protein complex was separated from free oligonucleotide on a 6.5% polyacrylamide gel containing 0.25× TBE (Tris borate-EDTA) buffer. The gels were dried, and the NF-κB bands were analyzed by phosphoimaging using a Cool Imager III (Viagene Biotech).

Pharmacophore Mapping and Molecular Docking. The pharmacophores of IKKβ inhibitors were generated by using the three-dimensional quantitative structure-activity relationship pharmacophore generation protocol implemented in the Discovery Studio package (Accelrys Inc., San Diego, CA) as we have described previously (Sun et al., 2011). Molecules that fit all of the features of the pharmacophore model were calculated for geometric fit values based on how well the molecules mapped onto the pharmacophoric feature location constraints and their deviation distances from the feature centers. A high fit value indicated a good match.

Molecular docking of IKKβ inhibitors to IKKβ was performed on the GOLD 3.01 program as we have described previously (Sun et al., 2011). This program uses a genetic algorithm in which the information regarding the ligand conformation and hydrogen bonding is encoded in a chromosome. In this study, the residues Leu21, Thr23, Gly24, Glu97, Cys99, Asp103, Lys147, Glu149, Asn150, and Glu172 and the surrounding residues within 6.5 Å were defined as the active site, which completely covered the ATP binding pocket of IKKβ.

Chromatin Immunoprecipitation–Quantitative Real-Time Polymerase Chain Reaction Assays. A ChIP assay was performed using a SimpleChIP Enzymatic Chromatin IP Kit according to the manufacturer’s protocol. In brief, drug-treated cells were cross-linked with 1% formaldehyde in culture medium at room temperature for 10 min to preserve the protein-DNA interactions, followed by enzymatic digestion (microwaved nucleases) and sonication to fragment the DNA into pieces of approximately 150 to 900 base pairs. Then, an antibody against NF-κB p65 was added to precipitate the DNA transcription. The antibody–protein-DNA complexes were purified using ChIP-grade protein G magnetic beads. The DNA was further isolated from the complexes using a combination of heat to reverse the cross-linking and treatment with
RNase and proteases, and the DNA was then purified using DNA purification columns. The final ChIP DNAs were used as templates in a Q-PCR assay using the SYBR PrimeScript RT-PCR Kit. The primers for the human MDR1 gene were as follows: forward 5'-GCTGGGAAGATCGCTACTGA-3' and reverse 5'-GGAACCTGAAAATCTCTGAGCA-3'. The resulting transcription values for each gene were normalized for primer pair amplification efficiency using the Q-PCR values obtained with input DNA (unprecipitated genomic DNA) as described previously (Chakrabarti et al., 2002; Rybtsouva et al., 2007).

RNA Interference Assay. MCF-7/Adr cells were seeded on six-well cell culture plates, incubated at 37°C, and transfected 24 h later at 70% confluence. NF-κB p65 was transiently knocked down in MCF-7/Adr cells by NF-κB p65 siRNA (h2) (Santa Cruz Biotechnology, Inc.) targeting human NF-κB p65 mRNA. Control siRNA-A (Santa Cruz Biotechnology, Inc.), a nontargeting siRNA, was used as a negative control. The transfections were performed for 48 h according to the manufacturer’s instructions for the FuGENE HD Transfection Reagent. Then the cells were treated with Adriamycin (10 μM) or 0.1% dimethyl sulfoxide (control) for 24 h and collected for Western blotting analysis.

Cellular Retention Assay. MCF-7/Adr cells were seeded on 24-well cell culture plates, incubated at 37°C, and transfected 24 h later at 70% confluence. Adriamycin was added. After incubation for the designated time (0.5, 1, and 2 h), the retention was stopped. The cells were lysed by three freeze-thaw cycles, and protein concentrations were measured using the Bradford method (Bradford, 1976). Adriamycin levels were determined by LC-MS/MS and further adjusted to the concentrations on the basis of the initial dosing volume. All of the experiments were conducted in triplicate.

Data Analysis. The data are expressed as the mean ± S.E. The statistical analyses included two-tailed Student’s t test and one-way analysis of variance. The difference was considered to be statistically significant if the probability value was less than 0.05 (p < 0.05).

Results

20(S)-Rh2 Inhibited Adriamycin-Induced ABCB1 Expression in MCF-7 and MCF-7/Adr Cells. As shown in Fig. 1, the expression of ABCB1 in MCF-7/Adr cells was approximately 9-fold higher than that in MCF-7 cells. Incubation of MCF-7 and MCF-7/Adr cells with 10 μM Adriamycin led to a further 1.8-fold increase in the expression of ABCB1 (Fig. 1). However, in the presence of 20(S)-Rh2 (1, 5, and 10 μM), the Adriamycin-induced ABCB1 expression was significantly decreased in a concentration-dependent manner (Fig. 1).

20(S)-Rh2 Inhibited Adriamycin-Mediated Activation of the MAPK Pathway in MCF-7/Adr Cells. As shown in Fig. 2A, when MCF-7/Adr cells were treated with 10 μM Adriamycin, the phosphorylation of p38, JNK, and ERK1/2 was markedly activated by 1.5-, 3.2-, and 1.7-fold, respectively. Furthermore, 20(S)-Rh2 (1, 5, and 10 μM) significantly suppressed the phosphorylation of these three MAPKs induced by Adriamycin in a concentration-dependent manner (Fig. 1).

20(S)-Rh2 Inhibited Adriamycin-Mediated Activation of NF-κB Pathway Signaling Molecules in MCF-7/Adr Cells. As shown in Fig. 2B, Adriamycin (10 μM) significantly activated the phosphorylation of IκB kinase β, which subsequently activated the phosphorylation of
IκB. Phosphorylated IκB was ubiquitinated and degraded, which released NF-κB dimers to translocate into the nucleus and be activated by phosphorylation. In the presence of 20(S)-Rh2 (1, 5, and 10 μM), the Adriamycin-activated NF-κB pathway was suppressed in a concentration-dependent manner. 20(S)-Rh2 inhibited the phosphorylation of IκB kinase and IκB, decreased NF-κB and phosphorylation of NF-κB, and prevented the translocation of NF-κB into the nucleus.

20(S)-Rh2 Inhibited Adriamycin-Enhanced NF-κB Binding Activity in MCF-7 and MCF-7/Adr Cells. The EMSA results showed that Adriamycin significantly enhanced the binding of NF-κB to DNA in both MCF-7 and MCF-7/Adr Cells. When the cells were treated with Adriamycin plus 20(S)-Rh2 (1, 5, and 10 μM), the tight NF-κB-DNA binding gradually weakened with increasing concentrations of 20(S)-Rh2 (Fig. 3A, lanes 1–14). The specificity of binding inhibition was demonstrated using nonradioactive consensus NF-κB oligonucleotides, mutant NF-κB oligonucleotides, and different antibodies against NF-κB. Excess nonradioactive consensus NF-κB oligonucleotides competitively inhibited the binding of NF-κB to the bio-NF-κB probe, whereas mutated NF-κB oligonucleotides had no effect. When antibodies against NF-κB were added, the bands were shifted to higher molecule masses, suggesting that the Adriamycin-activated complex consisted of p50 and p65 (Fig. 3B, lanes 15–26).

20(S)-Rh2 Mapped the Pharmacophore of IKKβ Inhibitors and Fitted the Homology Model of IKKβ. As shown in Fig. 4A, 20(S)-Rh2 mapped all of the critical pharmacophore features of IKKβ inhibitors. The fit value of 20(S)-Rh2 was 7.97, which was comparable to that of the positive compound 1 (fit value of 7.79). 20(S)-Rh2 mapped with the hydrophobic aromatic (light blue) of the pharmacophore through the isoamylene side chain and steroid parent ring. Furthermore, 20(S)-Rh2 was also docked into the binding site in the homology model of IKKβ (Fig. 4B). The analysis of the binding pattern of 20(S)-Rh2 with IKKβ indicated that 20(S)-Rh2 formed hydrogen bonds with Glu149, Arg220, and Gln187 and adjointed the Leu21, Phe300, Phe26, Lys43, and Val29 residues of IKKβ, which are all considered to be critical amino acids at the active sites of IKKβ.
20(S)-Rh2 Inhibited Adriamycin-Enhanced NF-κB Binding Ability to the Human MDR1 Promoter in MCF-7/Adr Cells. A ChIP-Q-PCR assay was performed to determine whether NF-κB could bind to the MDR1 promoter. As shown in Fig. 5A, the level of Q-PCR product in the 10 μM Adriamycin-treated group was 2-fold greater than that in the control group, suggesting the function of Adriamycin in promoting NF-κB binding to the MDR1 promoter. When the cells were treated with Adriamycin plus 20(S)-Rh2, the Q-PCR product markedly decreased, indicating that 20(S)-Rh2 can weaken the NF-κB binding to the MDR1 promoter.

NF-κB Inhibitors Lowered Adriamycin-Induced ABCB1 Expression in MCF-7/Adr Cells. As shown in Fig. 5B, treatment of MCF-7/Adr cells with 10 μM Adriamycin for 24 h further elevated the expression of ABCB1 approximately 1.6-fold. When the cells were treated with Adriamycin together with NF-κB inhibitors, the Adriamycin-induced ABCB1 expressions significantly decreased in a concentration-dependent manner.

Inhibition of NF-κB Altered the Cellular Retention and Subcellular Distribution of Adriamycin in MCF-7/Adr Cells. As shown in Fig. 5C, inhibition of NF-κB in MCF-7/Adr cells using the chemical inhibitor Bay 117082 (25 μM) caused the cellular accumulations of Adriamycin to significantly increase approximately 3.8-fold over time. To further quantitatively analyze the subcellular distribution of Adriamycin in the presence or absence of NF-κB, a cell fractionation approach was used to separate the nuclei and mitochondria in MCF-7/Adr cells treated with or without the NF-κB chemical inhibitor Bay 117082 (25 μM) for 24 h. As shown in Fig. 5D, the accumulation of Adriamycin in each subcellular organelle of MCF-7/Adr cells in the control group was as follows: nuclei > mitochondria > cytosol. Inhibition of NF-κB in MCF-7/Adr cells caused accumulation of Adriamycin in the nuclei, mitochondria, and cytosol to significantly increase with time. The nucleus exhibited the highest accumulation of Adriamycin, followed by the cytosol.

Silencing of NF-κB p65 Decreased the ABCB1 Expression and Prevented Adriamycin-Induced ABCB1 Expression in MCF-7/Adr Cells. As shown in Fig. 5E, NF-κB p65 siRNA significantly reduced the expression of NF-κB p65 in MCF-7/Adr cells to approximately 20% of the initial level. Silencing of NF-κB p65 also directly led to a remarkable decrease in ABCB1 expression in MCF-7/Adr cells (Fig. 5F). Furthermore, silencing of NF-κB p65 prevented Adriamycin-induced ABCB1 expression in MCF-7/Adr cells (Fig. 5F).

Silencing of NF-κB p65 Improved the Cellular Retention and Nuclear Distribution of Adriamycin in MCF-7/Adr Cells. NF-κB p65 silencing in MCF-7/Adr cells led to a significant increase in the cellular accumulation of Adriamycin over time (Fig. 5G). In particular, uptake of Adriamycin for 1 and 2 h led to a marked 1.6-fold increase in the cellular accumulation of Adriamycin. Moreover, as shown in Fig. 5H, little Adriamycin (red fluorescence) entered the MCF-7/Adr cells or nuclei (blue fluorescence) at 0.5 h in the control and mock groups. Some weak red fluorescence was present around the nuclei of the cells in the control and mock group until 1 and 2 h. The introduction of NF-κB p65 siRNA into the MCF-7/Adr cells caused a significant enhancement in the rate and extent of Adriamycin distribution in the nuclei. Silencing of NF-κB p65 clearly accelerated the penetration of Adriamycin into the nuclei (purple fluorescence) at 0.5 h after addition of Adriamycin and caused a significant increase in Adriamycin accumulation in the nuclei at 1 and 2 h.

Discussion

Overexpression of ABCB1 is one of the main causes of MDR in cancer treatment because ABCB1 not only promotes the efflux of anticancer agents but also alters the subcellular distribution of anticancer agents within tumor cells; therefore, ABCB1 directly influences the effects of anticancer agents. Thus, regulation of ABCB1 expression potentially plays a key role in overcoming MDR (Bentires-Alj et al., 2003; Katayama et al., 2007).

In our previous studies, nontoxic concentrations of 20(S)-Rh2 exhibited a synergistic effect with Adriamycin in MCF-7/Adr cells in 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium assays; this synergistic effect was attributed to the altered subcellular pharmacokinetics of Adriamycin through inhibition of ABCB1 activity by 20(S)-Rh2 (Zhang et al., 2012). However, in the 3-(4,5-
dimethylthiazol-2-yl)-2,5-diphenyltetrazolium assay, 20(S)-Rh2 was incubated with Adriamycin for 72 h. During such a long period, ABCB1 expression, rather than ABCB1 activity, might also be regulated by 20(S)-Rh2. Therefore, the ABCB1 expression induced by Adriamycin in the absence or presence of 20(S)-Rh2 was examined. As expected, 20(S)-Rh2 did inhibit Adriamycin-
induced ABCB1 expression (Fig. 1), which indicated that regulation of ABCB1 expression might also contribute to the synergistic effect.

Considering that Adriamycin acts as an anticancer agent by stimulating oxidative stress, the potential involvement of the MAPK and NF-κB pathways in the regulation of ABCB1 expression became our focus (Bentires-Alj et al., 2003; Katayama et al., 2007; Kim et al., 2011; Shen et al., 2011) and the activities of MAPK and NF-κB pathways were detected after Adriamycin treatment with or without 20(S)-Rh2. In our experiment, treatment of MCF-7/Adr cells with Adriamycin led to significant stimulation of the MAPK pathways, including p38, JNK, and ERK (Fig. 2A). Similar Adriamycin-induced MAPKs have also been observed in other cells in vitro and in vivo (Liu et al., 2008; Das et al., 2011; Xiao et al., 2012). The addition of 20(S)-Rh2 together with Adriamycin led to marked inhibition of the Adriamycin-induced MAPKs (Fig. 2A). Similar inhibitory effects of 20(S)-Rh2 on activated MAPKs have also been observed in human astroglia cells stimulated by phorbol myristate acetate (Kim et al., 2007).

Through phosphorylation of MAPK signaling cascades, the subsequent downstream effectors (e.g., transcription factors) are finally activated (Crown, 2012). NF-κB is an important transcriptional factor that regulates ABCB1 expression (Bentires-Alj et al., 2003), and a series of events directly relates to this regulatory course, including NF-κB phosphorylation, translocation, and binding (Haddad and Abdel-Karim, 2011). The results indicated that Adriamycin first stimulated the phosphorylation of IκB kinase β, which further led to the phosphorylation of IκB. Upon phosphorylation, IκB is released from the NF-κB triple complex, and the p65-p50 dimer is freed to enter the nucleus (Perkins, 2012). The addition of 20(S)-Rh2 together with Adriamycin caused a marked inhibition of the Adriamycin-stimulated phosphorylation of the above signaling molecules in the NF-κB pathway (Fig. 2B). Similar results have also been observed upon treatment of human astroglial cells with the combination of tumor necrosis factor-α and 20(S)-Rh2 (Choi et al., 2007).

Upon entering the nucleus, the p65-p50 dimer binds to specific genes that have nearby DNA-binding sites for NF-κB and then initiates gene expression. 20(S)-Rh2 has previously been reported to inhibit phorbol myristate acetate-activated NF-κB binding ability in human astroglia cells (Kim et al., 2007). However, no evidence regarding the effects of treating MCF-7/Adr cells with Adriamycin and 20(S)-Rh2 have been found. Results from the EMSA demonstrated that the binding activities of NF-κB were remarkably promoted by Adriamycin and attenuated by 20(S)-Rh2 (Fig. 3A).

Although MAPK signaling cascades are generally considered to activate downstream effectors such as the transcription factor NF-κB (Zhi et al., 2007; Li et al., 2010; Lin et al., 2011), the relationship (parallel versus causal) between the MAPK pathway and the NF-κB pathway in MCF-7/Adr cells treated with Adriamycin remains unclear. Effects of p38, JNK, and ERK inhibitors on the Adriamycin-activated NF-κB pathway suggested that Adriamycin stimulated the NF-κB pathway in a MAPK-dependent manner (Supplemental Fig. 1). Thus, it can be concluded that 20(S)-Rh2 interfered in all the
events in the NF-κB signal transduction pathway through the MAPK pathway.

Pharmacophore mapping and molecular docking further indicated that 20(S)-Rh2 was a potential NF-κB inhibitor. In our previous studies, a novel three-dimensional quantitative structure-activity relationship pharmacophore model was successfully developed and highlighted the important binding features of IKKβ ligands; a homology model of IKKβ was also established for further docking study (Sun et al., 2011). These two models provided deep insight into the characteristics of IKKβ inhibitors from ligand-based and structure-based methods. Hence, in our present research, 20(S)-Rh2 was evaluated using these two models, and good fitting values again proved that 20(S)-Rh2 was a potent NF-κB inhibitor (Fig. 4).

A ChIP-Q-PCR assay was next performed to clarify whether the MAPK/NF-κB pathway participated in regulating Adriamycin-induced ABCB1 expression. Many NF-κB binding sites have been reported in the human MDR1 promoter. One NF-κB binding site (CCTTTCGGGG) is located in the first intron of the human MDR1 gene promoter (Ogretmen and Safa, 1999). Therefore, one NF-κB binding site is proximal in the human MDR1 gene promoter. Thus, a PCR method can be used with human MDR1 gene primers to ascertain whether NF-κB-binding DNA contains the human MDR1 gene and to perform further quantitative comparisons (Shen et al., 2010). In our ChIP-Q-PCR assay, an NF-κB p65-specific antibody was used to preferentially precipitate DNA fragments containing the NF-κB-binding region present in the regulatory sequences of genes from MCF-7/Adr cells, and the MDR1 gene was chosen as our target gene. Adriamycin increased the binding of NF-κB to the MDR1 gene, and the 20(S)-Rh2 significantly decreased this interaction (Fig. 5A). These assays indicated that Adriamycin promoted NF-κB binding to the MDR1 gene promoter to initiate its transcription, and 20(S)-Rh2 interfered with this interaction.

Many NF-κB pathway inhibitors were then applied to Adriamycin-treated MCF-7/Adr cells. It turned out that Adriamycin-induced ABCB1 expression was significantly inhibited (to various extents) in a concentration-dependent manner (Fig. 5B). MAPK pathway inhibitors also achieved similar effects (Supplemental Fig. 2). These results were in accordance with previous reports of ABCB1 expression regulation (Katayama et al., 2007; Guo et al., 2008; Hien et al., 2010; Kim et al., 2011). Because the cellular pharmacokinetics of Adriamycin was mainly determined by ABCB1 in MCF-7/Adr cells (Supplemental Fig. 3) and NF-κB inhibitors lowered ABCB1 expression, the cellular accumulation and nuclear distribution of Adriamycin were significantly promoted by the NF-κB inhibitor (Fig. 5, C and D).

Because of the limited specificity of chemical inhibitors, siRNA (which has greater specificity) against NF-κB p65 was used. As expected, knockdown of NF-κB p65 in MCF-7/Adr not only lowered the ABCB1 expression but also disabled the induction of ABCB1 expression by Adriamycin (Fig. 5F). These assays supported a direct link between the MAPK/NF-κB pathway and ABCB1 expression. Furthermore, knockdown of NF-κB p65 caused the cellular accumulation and subcellular distribution of Adriamycin to be significantly altered (Fig. 5, G and H). These results suggested that the alternation of ABCB1 expression at the cellular and subcellular level was mediated by the NF-κB pathway.

In conclusion, the MAPK/NF-κB pathway mediates Adriamycin-induced ABCB1 expression and subsequently alters the cellular pharmacokinetics of Adriamycin. 20(S)-Rh2 influenced this pathway to down-regulate Adriamycin-induced ABCB1 expression in MCF-7/Adr cells (Fig. 6), which contributed to the improvement of Adriamycin cellular pharmacokinetics and cytotoxicity. Our research highlights the key factors involved in the alternation of Adriamycin cellular pharmacokinetics. It is helpful for the future development of MDR reversal agents with a cellular pharmacokinetic strategy.

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Authorship Contributions

Participated in research design: Zhang, Zhou, and Wang.
Conducted experiments: Zhang, Lu, and Wu.
Contributed new reagents or analytic tools: Sun, Hao, and Wang.
Performed data analysis: Zhang, Lu, and Sun.
Wrote or contributed to the writing of the manuscript: Zhang, Zhou, and Wang.

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