**MRP7/ABCC10 expression is a predictive biomarker for the resistance to paclitaxel in non-small cell lung cancer**

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**Abstract**

We used the paclitaxel-resistant human small cell lung cancer subline PC-6/TAX1-1, selected from PC-6 cells by paclitaxel, to test whether MRP7/ABCC10 (ABCC10) confers paclitaxel resistance. We found that gene expression of both ABCB1/MDR1 (ABCB1) and ABCC10 was higher in PC-6/TAX1-1 cells than in PC-6 cells. The expression levels of ABCC10 showed a significant inverse correlation with paclitaxel sensitivity (r = 0.574; P < 0.05) in 17 non-small cell lung cancer (NSCLC) cells unlike the expression levels of ABCB1. Pretreatment with the ABCC10 inhibitor sulfipyrazone altered the sensitivity to paclitaxel in ABCC10-expressing NSCLC cells, concomitant with increased intracellular paclitaxel accumulation. These findings suggest that expression of the ABCC10 gene is induced by paclitaxel and that ABCC10 confers paclitaxel resistance by enhancing the efflux for paclitaxel. To confirm this hypothesis, we tested the effect on paclitaxel cytotoxicity of decreasing the expression of ABCC10 by small interfering RNA and found that this enhanced paclitaxel cytotoxicity in NCI-H23 cells concomitant with increased intracellular paclitaxel accumulation. These data indicate that ABCC10 may be one of the biomarkers for paclitaxel resistance in NSCLC. [Mol Cancer Ther 2008;7(5):1150–5]
Total RNA Extraction and Reverse Transcription-PCR
Total RNA was extracted with TRIzol reagent (Invitrogen) according to the manufacturer’s instructions. Reverse transcription-PCR was done in a volume of 20 μL by SuperScript III Platinum One-Step qRT-PCR Kit (Invitrogen) according to the manufacturer’s instructions. The sequences of the ABCC10 and ABCB1/MDR1 (ABCB1) primers and the PCR conditions were as described previously (13, 14). Amplified products were separated by 2% agarose gel electrophoresis, and bands were visualized by staining with ethidium bromide. We also did real-time PCR with the LightCycler FastStart DNA SYBR Green kit (Roche Diagnostics). We used melting curve analysis to control for specificity of the amplification products. The number of transcripts was calculated from a standard curve obtained by plotting the known input of six different concentrations versus the PCR cycle number at which the detected fluorescence intensity reached a fixed value. The PCR program was 45 cycles of 94°C for 15 s and 60°C for 1 min. For each sample, the data were normalized to that of the housekeeping gene glyceraldehyde-3-phosphate dehydrogenase (GAPDH).

Concentration of Paclitaxel for 50% Cell Survival (IC50)
Cells were cultured at 5,000 per well in 96-well tissue culture plates. To assess cell viability, stepwise 10-fold dilutions of the anticancer drug were added 2 h after plating, and the cultures were incubated at 37°C for 96 h. At the end of the culture period, 20 μL 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium, inner salt solution (CellTiter 96 AQueous One Solution Cell Proliferation Assay) was added, and cells were incubated for a further 4 h; the absorbance was measured at 490 nm using an ELISA plate reader. Mean values were obtained from three independent experiments carried out in quadruplicate. Chemosensitivity is expressed here as the drug concentration for IC50 determined from the concentration-effect relationship using GraphPad Prism version 4 (GraphPad Software).

Inhibition of ABCC10 Activity by Sulfinpyrazone
ABCC10-expressing NCI-H23 and RERF-LC-AI cells and ABCB1-expressing NCU-LC-201 cells (1 × 106) were plated in six-well tissue culture plates. We used the general organic anion transporter inhibitor sulfinpyrazone as an ABCC10 inhibitor as reported previously (7). After 24 h, the cells were exposed to sulfinpyrazone or verapamil, an inhibitor of P-glycoprotein (Pgp) encoded by ABCB1, for 30 min, and we added paclitaxel in the presence of sulfinpyrazone or verapamil. After a further 48 h, we counted the viable cells with trypan blue staining to evaluate the cytotoxicity of paclitaxel.

Intracellular Paclitaxel Concentration
We treated 2 × 105 NCI-H23 cells with paclitaxel (100 nmol/L) for 90 min. After washing three times with cold PBS, the cells were resuspended in RPMI 1640 (2 mL) and homogenized. After centrifugation, the supernatant was stored at -80°C until analysis. Paclitaxel concentrations were quantified by a high-performance liquid chromatography assay as described previously (15).

Transfection and Small Interfering RNA Experiments
Cells (2 × 105) were transfected with small interfering RNA (siRNA) oligonucleotide using Oligofectamine (Invitrogen) to produce a final RNA concentration of 50 nmol/L in serum-free Opti-MEM (Invitrogen) as described previously (5). At 24 h after transfection, we changed the medium to RPMI 1640 supplemented with 10% heat-inactivated fetal bovine serum. After an additional 24 h, total RNA was extracted, or the cells were treated with paclitaxel for 48 h, and then we counted viable cells with trypan blue staining to evaluate the cytotoxicity. The siRNA oligonucleotides for ABCC10 (predesigned siRNA, ID 117707) were purchased from Ambion. The negative control siRNA (Silencer Negative Control 1 siRNA), which does not induce nonspecific effects on gene expression, was also purchased from Ambion.

Statistical Analysis
Spearman’s test was used for correlation analysis between expression of ABCC10 gene and IC50 values for paclitaxel. The differences in the cell viability between samples were evaluated with Student’s unpaired t test. The level of significance was set at 5% using two-sided analysis.

Results
Expression of ATP-Binding Cassette Transporters
We used real-time reverse transcription-PCR to compare the expression levels of ABCB1 and ABCC10 genes in cells of the paclitaxel-resistant small cell lung cancer cell line PC-6/TAX1-1 with those in parent PC-6 cells. Expression levels of both the ABCB1 and the ABCC10 gene were increased in PC-6/TAX1-1 cells compared with parental PC-6 cells (Fig. 1A). We confirmed the gene expression levels by real-time PCR, indicating that expression of the ABCC10 gene was ~2.5-fold higher in PC-6/TAX1-1 cells than in PC-6 cells (Fig. 1A). We detected ABCB1 gene expression in PC-6/TAX1-1 cells but not in PC-6 cells.

We compared the expression levels of the ABCC10 gene in cisplatin-resistant, gemcitabine-resistant, and 7-ethyl-10-hydroxycamptothecin-resistant cell lines with those in the respective parent cell lines. In contrast to the above results, the expression levels did not differ in the pairs of resistant and parent cells (Fig. 1B). We confirmed the ABCC10 gene expression levels by real-time reverse transcription-PCR (data not shown). We did not detect ABCB1 in any of these cells.

Relationship between Cytotoxicity of Paclitaxel and Expression of ABCC10 Gene
Using quantitative real-time reverse transcription-PCR, the expression levels of ABCC10 and ABCB1 genes were determined in 17 NSCLC cell lines. We detected ABCB1 expression in only 4 of the 17 (A549, VMRC-LCD, NCU-LC-201, and NCI-H460), whereas ABCC10 was expressed in all NSCLC cell lines. IC50 values (mean ± SD) for paclitaxel in each cell line were as follows: A549, 13.55 ± 0.98 nmol/L; NCI-H23, 0.39 ± 0.01 nmol/L; PC-9, 5.48 ± 0.46 nmol/L; VMRC-LCD, 0.06 ± 0.01 nmol/L; VMRC-LCF, 12.03 ± 0.73 nmol/L; RERF-LC-AI, 27.46 ± 3.43 nmol/L;
RERF-LC-MT, 0.13 ± 0.05 nmol/L; RERF-LC-OK, 0.99 ± 0.07 nmol/L; RERF-LC-MS, 28.39 ± 5.59 nmol/L; NCU-LC-201, 6.18 ± 1.08 nmol/L; ACC-LC-94, 3.77 ± 0.57 nmol/L; ACC-LC-176, 3.72 ± 1.19 nmol/L; SK-LC-10, 0.15 ± 0.03 nmol/L; PC10, 16.72 ± 1.41 nmol/L; QG56, 0.95 ± 0.12 nmol/L; NCI-H460, 10.14 ± 2.19 nmol/L; and SK-LC-6, 1.01 ± 0.19 nmol/L. We found a clear inverse relationship between \( \text{ABCC10} \) gene expression and paclitaxel sensitivity (IC\(_{50}\)) in NSCLC cells (\( r = 0.574; \) \( P < 0.05; \) Fig. 1C). We also found a clear inverse relationship between \( \text{ABCC10} \) gene expression and paclitaxel sensitivity (IC\(_{50}\)) in 13 NSCLC cell lines that did not express \( \text{ABCB1} \) (\( r = 0.720; \) \( P < 0.01)\).

### Inhibition of Paclitaxel Cytotoxicity by Sulfinpyrazone

To elucidate whether \( \text{ABCC10} \) actually affects paclitaxel sensitivity, we added the \( \text{ABCC10} \) inhibitor sulfinpyrazone at a noncytotoxic concentration with paclitaxel to two \( \text{ABCC10} \)-expressing NSCLC cell lines (NCI-H23 and RERF-LC-AI) that do not express \( \text{ABCB1} \) and to a NSCLC cell line (NCU-LC-201) that expresses \( \text{ABCB1} \) and low levels of \( \text{ABCC10} \). As shown in Fig. 2, the sensitivity of NCI-H23 and RERF-LC-AI cells to paclitaxel was significantly inhibited by sulfinpyrazone pretreatment (30 \( \mu \)mol/L, 30 min) but not by verapamil pretreatment (10 \( \mu \)mol/L, 30 min). In contrast, the sensitivity of NCU-LC-201 cells to paclitaxel was significantly inhibited by verapamil pretreatment (10 \( \mu \)mol/L, 30 min) but not by sulfinpyrazone pretreatment (30 \( \mu \)mol/L, 30 min).

### ABCC10 Suppression and Enhanced Cytotoxicity to Paclitaxel by \( \text{ABCC10} \) siRNA

To confirm the alteration in paclitaxel cytotoxicity by \( \text{ABCC10} \), NCI-H23 and RERF-LC-AI cells were transfected with siRNA directed against \( \text{ABCC10} \); cells transfected with control siRNA or not transfected were used as controls, because sulfinpyrazone acts as an inhibitor of general organic anion transporters. Cells were harvested 48 h after transfection, and extracts were prepared and analyzed by quantitative real-time reverse transcription-PCR. Expression of the \( \text{ABCC10} \) gene was decreased at 48 h after siRNA transfection (Fig. 4A). Forty-eight hours after transfection with \( \text{ABCC10} \) siRNA or negative control siRNA, or with no transfection, NCI-H23 and RERF-LC-AI cells were treated with 1 or 2 or 4 nmol/L paclitaxel for 48 h. The cytotoxicity to paclitaxel was significantly higher for cells in the presence of \( \text{ABCC10} \) siRNA than for either control (Fig. 4B). Because negative control siRNA does not affect gene expression, these results indicate that decreasing the expression of \( \text{ABCC10} \) altered the paclitaxel cytotoxicity.

We also examined the intracellular concentration of paclitaxel in NCI-H23 cells after transfection of siRNA directed against \( \text{ABCC10} \). The intracellular concentration of intracellular accumulation was measured in NCI-H23 cells by high-performance liquid chromatography assay. Paclitaxel accumulation following exposure to paclitaxel (90 min, 100 nmol/L) was higher in NCI-H23 cells that had been pretreated with sulfinpyrazone than verapamil or vehicle NCI-H23 cells (Fig. 3).

### ABCC10 Expression and Paclitaxel Resistance

Figure 1. Expression of \( \text{ABCC10} \) and paclitaxel cytotoxicity. Comparison of \( \text{ABCC10} \) and \( \text{ABCB1} \) gene expression levels in the paclitaxel-resistant cell line PC-6/TAX-1-1 and PC-6 cells. \( \text{ABCC10} \) gene expression was ~2.5-fold higher in PC-6/FU23-26 cells (A). The expression levels of the \( \text{ABCC10} \) gene in cisplatin-resistant, gemcitabine-resistant, and 7-ethyl-10-hydroxycamptothecin-resistant cell lines did not differ from those in the respective parent cell lines (B). There was a clear relationship between \( \text{ABCC10} \) expression and paclitaxel sensitivity in NSCLC cell lines (\( n = 17) \). Each IC\(_{50}\) value is the mean of three independent sensitivity tests done in quadruplicate. Expression levels are relative to expression by glyceraldehyde-3-phosphate dehydrogenase. Statistical significance of the correlations was determined by Spearman’s correlation test. Open circle, NSCLC cells that express \( \text{ABCB1} \) gene; closed circle, NSCLC cells that did not express \( \text{ABCB1} \) gene (C).
paclitaxel was markedly higher for cells exposed to paclitaxel in the presence of ABCC10 siRNA than for control cells (Fig. 4C).

**Discussion**

We have found increased gene expression of ABCC10 in paclitaxel-resistant small cell lung cancer cells. Further, we have analyzed the relationship between ABCC10 expression levels and sensitivity to paclitaxel in NSCLC cell lines, finding a significant correlation. These results indicate that ABCC10 is a biological marker for paclitaxel treatment in NSCLC.

Previously conclusive evidences in paclitaxel-related drug resistance are the multidrug resistance mediated by overexpression of Pgp, encoded by ABCB1 gene. Paclitaxel sensitivity has been shown previously, in 60 cancer cell lines, to have a strong negative correlation with ABCB1 expression (16). Further, and similar to our findings, overexpression of Pgp/ABCB1 has been detected in paclitaxel-resistant cells and inhibition of ABCB1 activity has been shown to restore paclitaxel resistance in paclitaxel-resistant cancer cells (17–19). However, it was reported previously that the expression levels of ABCB1 were low in clinical samples of NSCLC (20). We also found low expression levels of ABCB1 in 17 NSCLC cell lines. These results allow us to hypothesize that Pgp/ABCB1 does not mediate the major paclitaxel efflux and is not associated with paclitaxel sensitivity in NSCLC cells. Furthermore, acquisition of paclitaxel resistance via Pgp-mediated and non-Pgp-mediated mechanisms was shown in established paclitaxel-resistant ovarian carcinoma cells, in which the levels of α-tubulin and β-tubulin and binding of Taxol to microtubules were similar (18). These results support the existence of a non-Pgp-mediated paclitaxel efflux mechanism.

Multidrug resistance in cancer cells is often attributed to ABCC family members, which are involved in the efflux of anticancer drugs by cotransport with glutathione or glutathione-drug or glucuronide-drug conjugates. ABCC family members can be subdivided into two groups: (a) ABCC1-3, ABCC6, and ABCC10, which contain 17 transmembrane segments, and (b) ABCC4, ABCC5, ABCC11, and ABCC12, which lack one of the transmembrane regions and have only 12 transmembrane segments (3, 4). Recently, one of the ABCC family members, ABCC10, was shown to mediate the ATP-dependent transport of several anticancer agents, including paclitaxel (7, 8), although cancer cells transfected with ABCC10 had only low level of resistance to paclitaxel. We therefore examined the relationship between...

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Figure 2. Modification of paclitaxel cytotoxicity by sulfinpyrazone or verapamil and intracellular paclitaxel concentration. NCU-LC-201, NCI-H23, and RERF-LC-AI cells were incubated with 30 μmol/L sulfinpyrazone or 10 μmol/L verapamil for 30 min before treatment with 2 nmol/L paclitaxel. After 48 h, we counted viable cells with trypan blue staining to evaluate the cytotoxicity of paclitaxel. *, P < 0.001; **, P < 0.005; ***, P < 0.05. 1, vehicle; 2, sulfinpyrazone; 3, verapamil; 4, paclitaxel; 5, sulfinpyrazone + paclitaxel; 6, verapamil + paclitaxel.

Figure 3. Intracellular paclitaxel concentration. The intracellular paclitaxel concentration was measured in NCI-H23 cells after exposure to paclitaxel for 90 min. 1, paclitaxel; 2, sulfinpyrazone + paclitaxel; 3, verapamil + paclitaxel.
the expression levels of ABCC10 and sensitivity to paclitaxel, finding a clear inverse relationship. In addition, inhibition of ABCC10 activity or expression altered the cytotoxicity of paclitaxel, concomitant with increasing intracellular paclitaxel concentration. Furthermore, we detected the gene expression of ABCC10 in all NSCLC cell lines tested by real-time PCR in contrast to ABCB1. Although our results did not fully explore the role of ABCC10 in drug resistance, our results suggested that ABCC10 is associated with efflux of paclitaxel and that ABCC10 expression may be one of the determinants of paclitaxel sensitivity in NSCLC.

We found increased expression of ABCC10 in paclitaxel-resistant cells, which provides the first example of paclitaxel treatment inducing ABCC10 expression. In paclitaxel-resistant cells, sulfipyrazone pretreatment did not fully affect the paclitaxel cytotoxicity because of ABCB1 up-regulation (data not shown). We cannot determine whether the paclitaxel efflux activity of ABCC10 is similar to that of Pgp; our results indicate that induction of ABCB1 and ABCC10 expression together by exposure to paclitaxel resulted in acquired resistance to paclitaxel.

We also investigated whether other anticancer agents affect ABCC10 expression. Our comparison of the expression levels of the ABCC10 gene in cisplatin-resistant, gemcitabine-resistant, and 7-ethyl-10-hydroxycamptothecin-resistant cell lines with those in the respective parent cell lines revealed no induction of ABCC10 expression in any drug-resistant cells. These results suggest that the anticancer agents transported by ABCC10 are limited.

ABCC10 transcripts are expressed in a wide range of normal tissues, including colon, skin, and testis (13). Clarifying the substrate for ABCC10 should help in determining the physiologic function of this pump; its expression in diverse cancer cell lines suggests that it has a ubiquitous role in cancer cells. Although the ability of paclitaxel to disrupt microtubule dynamics is well documented, paclitaxel resistance is a major obstacle to the successful treatment of lung cancer in the clinic. Understanding the molecular mechanisms underlying the antitumor effect of paclitaxel, and paclitaxel resistance, may lead to the design of biologically and pharmacologically targeted therapeutic strategies for paclitaxel-resistant tumors and to the improvement of chemotherapy effect and survival of NSCLC patients. Additional clinical research will be needed to investigate whether ABCC10 could be used as a predictive marker of sensitivity and/or resistance to paclitaxel in NSCLC.

Figure 4. Modification of paclitaxel cytotoxicity by ABCC10 siRNA. Gene expression levels of ABCC10 in NCI-H23 and RERF-LC-AI cells transfected with siRNA directed against ABCC10, control siRNA-transfected, or nontransfected cells (A). Cytotoxicity to 1 or 2 or 4 nmol/L paclitaxel in cells transfected with siRNA directed against ABCC10, control siRNA-transfected, or nontransfected cells (B). The intracellular paclitaxel concentration was measured in NCI-H23 cells after exposure to paclitaxel for 90 min (C).
Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

References
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