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CTEN/tensin 4 expression induces sensitivity to paclitaxel in prostate cancer

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ABSTRACT

BACKGROUND. Recently, we established paclitaxel-resistant prostate cancer cell lines (PC-3-TxR and DU145-TxR). To determine the mechanisms of paclitaxel resistance in PC-3-TxR cells, we compared the gene expression profiles between PC-3 and PC-3-TxR cells. Our results indicated that expression of the CTEN (C-terminal tensin like protein, tensin 4) gene was down-regulated by 10-fold in PC-3-TxR cells. We investigated the possibility that CTEN overexpression restores paclitaxel sensitivity.

METHODS. We investigated how knockdown and overexpression of CTEN in androgen-independent cell lines affect paclitaxel sensitivity by colony formation assay and growth inhibition assay. To determine the mechanisms by which CTEN affects paclitaxel sensitivity, we investigated the relationships between CTEN and F-actin or EGFR in PC-3 cells. We also examined the association between expression of CTEN and grade of prostate cancer by immunohistochemistry using tissue microarray analysis.

RESULTS. Down-regulation of CTEN, which is located in the cytoskeleton, played an important role in paclitaxel resistance in PC-3-TxR cells. Knockdown of CTEN expression in PC-3 cells induced paclitaxel resistance. Overexpression of CTEN in PC-3-TxR and DU145-TxR cells restored paclitaxel sensitivity. CTEN expression was inversely correlated with F-actin and EGFR expression. Then

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knockdown of actin and EGFR in PC-3-TxR cells recovered paclitaxel sensitivity, indicating that CTEN down-regulation mediates paclitaxel resistance through elevation of EGFR and actin expression. Moreover, CTEN expression was inversely correlated with Gleason score.

CONCLUSIONS. These results strongly suggested that CTEN plays an important role in paclitaxel sensitivity and that CTEN expression level may be a prognostic predictive factor for PCa patients.

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INTRODUCTION

Prostate cancer (PCa) is a major public health problem as it is the most commonly diagnosed cancer and the leading cause of cancer-related death in American men (1). Hormonal therapy (*i.e.*, androgen deprivation) initially induces antitumor response in more than 90% of patients. However, it eventually fails and the PCa progresses to an androgen-insensitive stage that is essentially incurable (2). Chemotherapy plays an increasingly important role in the management of androgen-insensitive metastatic PCa. Recently, taxanes (paclitaxel or docetaxel) in combination with other agents, such as estramustine phosphate, or dexamethasone, for treating hormone-refractory PCa and have been shown to induce good antitumor responses (3–6). Paclitaxel acts as an antitumor drug by disrupting the cell cycle through stabilizing microtubule polymers (7). The microtubule cytoskeleton is a highly regulated system. At different times in the cell cycle, microtubules can be very stable or highly dynamic. Stability and dynamics are regulated by interaction with a large number of proteins that themselves may change at specific points in the cell cycle (8). Exogenous ligands such as paclitaxel can disrupt the normal processes by either increasing or decreasing microtubule stability and inhibiting their dynamic behavior (8).

Although hormone-resistant PCa initially responds to paclitaxel-based chemotherapy, PCa eventually becomes resistant to paclitaxel. One of main mechanisms of drug resistance is overexpression of the multiple drug resistance gene (MDR-1)-encoded P-glycoprotein, a drug transporter belonging to

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the ATP-binding cassette (9). Taxane resistance has also been observed in several cancers. For example, in breast cancer, down-regulation of the gene encoding ribopholin II (RPN2) mediates docetaxel resistance by reducing glycosylation of P-glycoprotein (10). In ovarian cancers, overexpression of FOXO1 involving oxidative stress also contributes to drug resistance (11). In pancreatic cancer, inhibition of BCL-2 alters diverse pathways that control cell survival and thus overcomes paclitaxel resistance (12).

We have previously established paclitaxel-resistant DU145-TxR and PC-3-TxR cells from DU145 and PC-3 cell lines. In DU145 cells, paclitaxel resistance was due to overexpression of P-glycoprotein in DU145-TxR (13). However, in PC-3-TxR cells, knockdown of MDR-1 gene expression did not reverse paclitaxel resistance, suggesting that other mechanisms are involved in paclitaxel resistance of PC-3-TxR cells (13). Therefore, we performed cDNA microarray using mRNA from the parent cell lines PC-3 and PC-3-TxR and compared differentially expressed genes. Approximately 40000 genes were screened by cDNA microarray analysis. A total of 201 (1.34%) of the screened genes were up-regulated by more than twofold, and 218 (1.45%) of the genes were down-regulated by more than twofold in PC-3-TxR cells compared with PC-3 cells (13). We hypothesized that some of these genes mediated paclitaxel resistance in PC-3-TxR cells. We initially focused on C-terminal tensin-like protein (CTEN), gene expression of which was down-regulated by 10-fold in PC-3-TxR cells (13).

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CTEN is a recently isolated focal adhesion molecule. Human CTEN cDNA encodes a 715-amino acid sequence containing the Src homology 2 (SH2) and phosphotyrosine-binding (PTB) domains, which are similar to the COOH termini of tensin molecules that belong to the four-member tensin family (tensin 1, tensin 2, tensin 3, and CTEN) (14). The proteins encoded by these genes are localized to the cytoplasmic side of focal adhesions (14). In the present study, we examined whether decreased CTEN expression contributes to paclitaxel resistance in PCa cells

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MATERIALS AND METHODS

Antibodies and reagents. The following primary antibodies were used: polyclonal anti-CTEN serum was raised by immunization of peptide 653-655 amino acid into a rabbit (Takara Bio, Otsu, Japan), rabbit polyclonal anti-GAPDH, anti-actin, and anti-EGFR were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). Goat anti-rabbit IgG (H+L)-HRP Conjugate was purchased from Bio-Rad (Hercules, CA). Paclitaxel (PTX) was purchased from (Bristol Pharmaceuticals Y.K. Tokyo, Japan). Estramustine phosphate (EMP), docetaxel (DTX), doxorubicin (DOX), VP-16 (etoposide), vinblastine (VLB), and cisplatin (CDDP) were purchased from Sigma (St. Louis, MO). EGFR inhibitor PD153035 was purchased from Calbiochem (La Jolla, CA).

Cell lines and Cell culture. Paclitaxel-resistant PC-3-TxR and DU145-TxR cells were generated and

maintained as described previously (13). The PC-3-TxR cells were cultured in 10 nM paclitaxel to maintain their drug-resistant phenotypes. Before each experiment, these cells were grown for a minimum of one day in normal medium. The PC-3 and PC-3-TxR cells were maintained in RPMI1640 (Sigma) supplemented with 5% fetal bovine serum (FBS) and 1% penicillin/streptomycin (Invitrogen, Carlsbad, CA). DU145 and DU145-TxR cells were maintained in Dulbecco's modified Eagle's medium (DMEM; Sigma) supplemented with 5% FBS.

Proliferation assay. Cell growth or growth inhibition assay was performed by plating 2×10^5 cells on 6-well plates. After cultured for 24 h, cells were treated with the indicated concentrations of anticancer agents (PTX, EMP, DTX, DOX, VP-16, VLB, and CDDP) or EGFR inhibitor PD153035 and cultured for an additional 48 h. At the end of the culture period, the cells were trypsinized and counted using a hemocytometer. The relative cell numbers compared with untreated controls were plotted as cell viability.

Plasmid transfection. To generate a CTEN expression plasmid, the open reading frame of the CTEN gene was generated by RT-PCR using cDNA synthesized from PC-3 cells using the forward primer 5′-ATCTCTGGGATGTCAGTGAGGCTGGTTG-3′ and the reverse primer 5′-GATGATGGTGACTGCTGAAGGCCATAGC-3′. After double digestion with *Xba*I and *Bam*HI, the PCR product was cloned into the respective restriction sites of the pBK-CMV-neo vector (Stratagene, La Jolla, CA). The insert was confirmed by sequencing from both directions, and the plasmid was named

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pBK-CMV-CTEN. PC-3-TxR and DU145-TxR cells were transfected with pBK-CMV-CTEN or pBK-CMV-neo using Lipofectamine reagent (Invitrogen, San Diego, CA) Eight h after transfection, the cells were cultured in medium containing 800 μg/mL G418 (Sigma) and selected as stable CTEN-overexpressing cells.

Colony formation assay. Cells were seeded at a density of 1.0×10^3 on 6-well plates, and allowed to adhere for 24 h. The cells were then treated with the indicated concentrations of paclitaxel, and medium was replaced with fresh medium after 24 h and every 3 days thereafter. The cells were allowed to grow for 10 days, then fixed using methanol and stained with 1% crystal violet, and the numbers of colonies containing >50 cells were counted. Treatment with each dose was performed in triplicate and the experiments were performed at least three times. The relative numbers of colonies compared with untreated controls were plotted as cell viability.

RNA interference analysis. The specific Stealth CTEN and actin small interfering RNA (siRNA) were synthesized by Invitrogen. CTEN and actin target siRNA sequence were 5′-AAUGUAGGAGUCAAGGUCCUCUGGG-3′ and 5’-AUCUCUUUCUGCAUGCGGUCAGCGA-3’, respectively. Validated Stealth EGFR siRNA and non-targeting siRNA (NT siRNA) were purchased from Invitrogen. For CTEN knockdown, PC-3, PC-3-TxR, DU145, and DU145-TxR cells were plated into 6-well plates at 3×10^5 cells/well, respectively. Cells were then transfected with 20 nM of CTEN siRNA or NT siRNA using X-treme GENE siRNA Transfection Reagent (Roche, Indianapolis, IN) for

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24 h. Total proteins were extracted 48 h after transfection. Twenty-four h after transfection with 20 nM NT siRNA or CTEN siRNA, cells were treated with the indicated concentrations of paclitaxel for 48 h, cultured for 48 h, and counted using a hemocytometer. For actin and EGFR knockdown, 24 h after transfection with 20 nM of NT siRNA, actin, or EGFR siRNA, cells were treated with the indicated concentrations of paclitaxel for 48 h and counted.

Western blot analysis. Twenty-four h after plating, total protein was extracted from PC-3, PC-3-TxR, DU145, and DU145-TxR cells as described previously (15). The subcellular protein (cytosol membrane nucleus and cytoskeleton protein) was extracted using a ProteoExtract Subcellular Proteome Extraction kit (Calbiochem). Aliquots of 30 µg of total protein of subcellular proteins were separated by 10% Ready Gel J (Bio-Rad), and electroblotted onto PVDF membranes (Bio-Rad), blocked with 5% skimmed milk, and reacted with anti-CTEN or rabbit polyclonal anti-GAPDH (Santa Cruz). The first antibody was recognized by goat anti-rabbit secondary antibody (Bio-Rad) and visualized using enhanced chemiluminescence (Amersham Pharmacia Biotech, Piscataway, NJ).

Immunofluorescence. Staining for tubulin, filamentous actin (F-actin) and CTEN protein was performed by overnight incubation using commercial kits in accordance with the manufacturer's instructions (Oregon Green® 488 conjugate kit, Phallotoxins and Zenon™ Tricolor Mouse and Rabbit IgG Labeling Kit; Molecular Probes, Eugene OR), Briefly, cells were fixed with 4% paraformaldehyde for 10 min, washed three times with PBS, and blocked with 5% bovine serum albumin (Sigma) for 15

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min. Slides were then washed three times with PBT (0.1% Triton X-100 in PBS), incubated with anti-CTEN antibody for 1 h at 37°C, and cells were washed three times with PBT. The cells were then incubated with 5 µg/mL Alexa Flour 555 goat anti-rabbit IgG to detect anti-CTEN antibody in 1% BSA/PBT for 1 h at 37°C. The cells were also washed 3 times with PBT, and then incubated with Oregon Green® 488 conjugate kit to detect tubulin and Alexa Flour 488 phalloidin diluted 1:200 from stock solution for 1 h at 37°C to detect F-actin. The cells were washed 3 times with PBS, and mounted with Vectashield mounting medium with 4', 6-diamidino-2-phenylindole (DAPI) to detect nuclei. The slides were imaged using a confocal microscope.

Immunohistochemistry of tissue microarray. PR951 and PR952 tissue microarrays (TMA) comprised of 176 cores from 88 cases containing normal tissue, matched for Gleason score at surgery were purchased from Biomax (Rockville, MD). TMA sections were pretreated in 0.01 M sodium citrate buffer for 10 min in a microwave oven after overnight incubation at 37°C. Endogenous peroxidase was blocked with 0.3% hydrogen peroxide, followed by incubation with PBS containing 10% normal goat serum. Specimens were incubated with anti-CTEN antibody at a dilution of 1:150. The antibody-antigen complex was visualized using the DakoCytomation LSAB+ system-HRP (Dako, Carpinteria, CA). All sections were counterstained with hematoxylin.

Statistical analysis. The statistical significance of differences in proliferation was determined by two-way ANOVA with *post hoc* test. Dunnett's test was also performed to determine the significance of

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intensity differences on western blotting analysis. * $P < 0.05$ and ** $P < 0.01$ were considered statistically significant. Kruskal-Wallis test was used to determine the statistical significance of differences in immunohistochemical staining. The data represent the means ± SD of three replicates.

RESULTS

Down-regulation of CTEN expression in paclitaxel-resistant PC-3 cells

In a previous study, we established paclitaxel-resistant PC-3 cells (PC-3-TxR) from androgen-independent PCa cells (PC-3). First, we investigated the expression level of a-tubulin and b-tubulin that form microtubules. There were no differences in their expression between PC-3 and PC-3-TxR cells (Fig. 1A). We also examined the distribution pattern of microtubules in these cells, but there were also no differences in distribution of microtubules in PC-3 and PC-3-TxR cells (Fig. 1B). Next, we reconfirmed paclitaxel resistance in PC-3-TxR cells using colony formation assay. PC-3-TxR cells were more resistant to paclitaxel than the parental PC-3 cells (LD_{50}: PC-3-TxR and PC-3, 30.2 nM and 2.0 nM, respectively) (Fig. 2A). To investigate which genes are responsible for paclitaxel resistance, we focused on those that were down-regulated in paclitaxel-resistant cells. Thus, we investigated the CTEN gene, which was down-regulated by 10-fold in PC-3-TxR cells compared with PC-3 cells (13). Western blot analysis showed that CTEN was strongly expressed in PC-3 cells but not in PC-3-TxR cells (Fig. 2A). To investigate whether down-regulation of CTEN expression occurred only during the

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process of establishment of PC-3-TxR cells, in which the cells were grown for a long period in paclitaxel, or whether paclitaxel treatment rapidly and directly affects CTEN expression, we treated PC-3 cells with paclitaxel and examined CTEN expression. Treatment with paclitaxel caused down-regulation of CTEN expression in PC-3 cells in a dose-dependent manner at 48 h (Fig. 2B), indicating that paclitaxel can rapidly down-regulate CTEN expression. Down-regulated CTEN expression in PC-3-TxR cells was irreversible even if we removed paclitaxel from the culture medium for maintenance of PC-3-TxR cells for at least 3 months (data not shown).

Involvement of CTEN in paclitaxel sensitivity

We next investigated whether down-regulation of CTEN contributes to the development of paclitaxel resistance. Then we determined the effect of re-expression of CTEN on paclitaxel resistance in PC-3-TxR cells. We compared the sensitivity to paclitaxel between PC-3-TxR cells transfected with a CTEN expression vector (PC-3-TxR/CTEN) and those transfected with empty pBK-CMV-neo vector (PC-3-TxR/Neo). CTEN protein was detected at much higher levels in PC-3-TxR/CTEN compared to PC-3-TxR/Neo cells (Fig. 2C). CTEN overexpression did not affect the proliferation of PC-3-TxR cells (Fig. 2C). To investigate whether CTEN overexpression affects paclitaxel resistance, we compared paclitaxel sensitivity between PC-3-TxR/Neo and PC3-TxR/CTEN by colony formation assay. The survival curve for paclitaxel was shifted to the left by CTEN overexpression (LD_{50} of PC-3-TxR/Neo

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and PC-3-TxR/CTEN: 15.2 nM and 4.5 nM, respectively) (Fig. 2D), indicating that CTEN overexpression restored sensitivity to paclitaxel although the degree of restoration was not to the level of sensitivity observed in parental PC-3 cells (Fig. 2A).

To determine whether a decrease in CTEN expression level confers resistance to paclitaxel, we transfected PC-3 cells with CTEN siRNA or non-target (NT) siRNA. Transfection with CTEN siRNA repressed the expression of CTEN protein in PC-3 cells compared with NT siRNA (Fig. 2E). PC-3 cells transfected with CTEN siRNA showed greater resistance to paclitaxel than PC-3 cells transfected with NT siRNA (LD_{50} of PC-3/NT siRNA and PC-3/CTEN siRNA: 1.7 nM and 26.1 nM, respectively) (Fig. 2E). These data indicated that reduced CTEN expression can induce paclitaxel resistance in PC-3 cells.

CTEN overexpression recovers paclitaxel sensitivity in other prostate cancer cells

We investigated whether CTEN overexpression affects paclitaxel sensitivity of other paclitaxel-resistant PCa cells as well as PC-3-TxR cells. Previously, we established paclitaxel-resistant DU145 (DU145-TxR) cells in addition to PC-3-TxR cells (13). We first reconfirmed that DU145-TxR cells were resistant to paclitaxel compared to DU145 cells (Fig. 3A). We had previously shown that increased expression of P-glycoprotein contributes to paclitaxel resistance of DU145-TxR cells (13). Both DU145 and DU145-TxR cells expressed similarly low levels of CTEN (Fig. 3A). Therefore, we examined whether increased expression of CTEN could reverse paclitaxel resistance of DU145-TxR

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cells. These cells were stably transfected with pBK-CMV-CTEN (DU145-TxR/CTEN cell) or pBK-CMV-neo (DU145-TxR/Neo) (Fig. 3B). Overexpression of CTEN did not affect cell proliferation of DU145-TxR cells (Fig. 3B). Then, CTEN overexpression did not reduce P-glycoprotein levels in DU145-TxR/CTEN (Fig. 3C). However, CTEN overexpression partially restored paclitaxel sensitivity (Fig. 3D, compare with DU145 in Fig. 3A), suggesting that mechanisms other than P-glycoprotein were involved in restoration of paclitaxel sensitivity by CTEN.

CTEN overexpression partly recovers the sensitivity to other anti-tumor drugs

We also compared the cross-resistance to other anticancer drugs, *i.e.*, DTX (docetaxel), VBL (vinblastine), VP-16 (etoposide), CDDP (cisplatin), DOX (doxorubicin), and EMP (estramustine phosphate), between PC-3-TxR/Neo and PC-3-TxR/CTEN cells. CTEN overexpression restored the sensitivity to DTX, which belongs to the taxane family similar to paclitaxel (Fig. 4). CTEN overexpression also partially restored the sensitivity for CDDP, VP-16, VBL, DOX, and EMP, suggesting that CTEN affects the sensitivity to different anticancer drugs through a common pathway although the main mechanisms of drug resistance are different among these drugs (Fig. 4).

Mechanisms of paclitaxel resistance by down-regulation of CTEN

To investigate the mechanisms by which decreased CTEN expression promotes paclitaxel

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resistance in PCa cells, we first examined the differences in expression level of apoptosis-related proteins because paclitaxel initiates the apoptotic process by binding to b-tubulin and promoting its polymerization (16). We observed no differences in expression of a-tubulin, b-tubulin, caspase 3, 7, 8, 9, 10, bcl-2, bcl-xL, or bax proteins among PC-3, PC-3-TxR, PC-3-TxR/Neo, and PC-3-TxR/CTEN cells by western blotting analysis (data not shown). These results suggested that alterations of the apoptotic response do not account for the development of paclitaxel sensitivity.

We next examined the localization of CTEN protein in PC-3 cells. The results of western blotting analysis of various subcellular fractions indicated that CTEN protein was localized mainly at the cytoskeleton in PC-3 cells (Fig. 5A). Immunofluorescence analysis showed that CTEN expression was down-regulated by treatment with paclitaxel as shown in Fig. 1C (Fig. 5B). As CTEN was localized at the cytoskeleton similar to other tensins, we investigated the effects of paclitaxel on the expression of F-actin, which is also localized at the cytoskeleton. This analysis indicated that F-actin was up-regulated by paclitaxel in PC-3 cells (Fig. 5B). To determine whether the effects of paclitaxel on expression of F-actin in PC-3 cells are due to the changes in CTEN expression induced by paclitaxel, we compared CTEN expression with F-actin expression in PC-3, PC-3-TxR, PC-3-TxR/Neo, and PC-3-TxR/CTEN cells. Immunofluorescence analyses of CTEN and F-actin revealed an inverse correlation between CTEN and F-actin expression among these cell lines (Fig. 5C). Moreover, knockdown of CTEN in PC-3 cells by CTEN siRNA transfection induced F-actin expression (Fig. 5C). To confirm whether

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down-regulation of actin expression changed paclitaxel sensitivity, we knocked down actin expression by transfection of actin siRNA into PC-3-TxR cells and examined paclitaxel sensitivity. Knockdown of actin partially restored paclitaxel sensitivity (Fig. 5D). These results suggest that one of the mechanisms through which paclitaxel resistance is induced by down-regulation of CTEN expression is associated with elevation of actin, which is localized to the same region as CTEN.

Another mechanism of paclitaxel resistance by down-regulation of CTEN

Recently, several groups demonstrated that epidermal growth factor receptor (EGFR) is involved in paclitaxel resistance. Paclitaxel-resistant cells expressed higher levels of EGFR, and EGFR tyrosine kinase inhibitor was more effective in resistant cells than in paclitaxel-sensitive cells (17–20). Therefore, we postulated that CTEN may affect EGFR expression and modulate paclitaxel sensitivity. To explore this possibility, we compared the expression of EGFR between PC-3 and PC-3-TxR cells. EGFR expression was elevated to a greater extent in PC-3-TxR cells than in the parental PC-3 cell line (Fig. 6A). To confirm the effect of CTEN on EGFR expression, we compared EGFR expression between PC-3-TxR/Neo and PC-3-TxR/CTEN cells. Overexpression of CTEN in PC-3-TxR down-regulated EGFR expression (Fig. 6A). In addition, we knocked down CTEN in PC-3, which resulted in up-regulation of EGFR expression (Fig. 6A). Having determined that CTEN inversely regulates EGFR expression, we next evaluated whether EGFR expression affects paclitaxel sensitivity.

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Knockdown of EGFR expression by transfection of EGFR siRNA into PC-3-TxR cells restored paclitaxel sensitivity (Fig. 6B). Next, we investigated the effects of CTEN knockdown in PC-3 and CTEN overexpression in PC-3-TxR on sensitivity to the EGFR inhibitor PD153035. There were no differences in sensitivity to PD153035 regardless of the increase or decrease of CTEN expression and EGER expression in these cells. These data suggested that PD153035 has the same effect on these cells as long as EGER is expressed (Fig. 6C). We also examined whether PD153035 affected paclitaxel sensitivity in PC-3-TxR cells. Administration of 1 μM PD153035, which did not affect proliferation of PC-3-TxR cells (Fig. 6C), diminished paclitaxel resistance in PC-3-TxR cells (Fig. 6D). These results indicated that overexpression of EGFR induced by down-regulation of CTEN mediates paclitaxel resistance in PC-3-TxR cells.

CTEN protein expression correlates with Gleason Score and metastasis in prostate cancer

To examine whether the CTEN protein is differentially expressed in PCa tissues compared to benign tissues, immunohistochemical staining was performed on tissue microarray specimens comprised from 89 cores from 44 cases containing normal tissue. All specimens were graded using the Gleason score. CTEN was differentially expressed in PCa specimens and non-neoplastic tissues (Fig. 7 and Table 1). In non-neoplastic tissues, 15 of 16 (94%) expressed high CTEN, 25 of 28 (89%) Gleason score 6 or 7 PCa tissue samples showed high CTEN expression level, 6 of 12 (50%) Gleason score 8 PCa tissues

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showed intermediate expression of CTEN, and 26 of 32 (81%) Gleason score 9 or 10, PCa tissues showed low or no expression of CTEN. Positive staining for CTEN was located mostly in epithelial cells, but was also noted in some extracellular areas surrounding neoplastic glands and epithelial cells. This study showed that CTEN protein expression was inversely correlated with pathological Gleason scores of PCa ($P < 0.001$); CTEN protein was down-regulated in poorly differentiated PCa tissue.

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DISCUSSION

Although hormone-refractory PCa initially respond to taxanes, eventually the PCa develops resistance to the taxanes and progresses to end stage disease. Therefore, it is extremely important to understand the mechanisms by which PCa becomes resistant to taxanes to overcome the development of taxane resistance. The strategy to determine the mechanisms that contribute to taxane resistance is to identify genetic or epigenetic aberrations underlying sensitivity/resistance. One mechanism of paclitaxel resistance is overexpression of P-glycoprotein, the effect of which is mediated by pumping taxanes out of the cell (9). However, this mechanism is not always applicable to all cells. Although PC-3-TxR cells have increased levels of P-glycoprotein expression, knockdown of P-glycoprotein had no impact on paclitaxel resistance indicating that P-glycoprotein does not mediate paclitaxel resistance in PC-3-TxR cells (13). Therefore, we explored other mechanisms of paclitaxel resistance and showed that

down-regulation of CTEN/tensin 4 induces paclitaxel resistance in PC-3-TxR cells. Moreover, overexpression of CTEN not only in PC-3-TxR cells but also in DU145-TxR cells, in which overexpression of P-glycoprotein was the main reason for paclitaxel resistance (13), restored paclitaxel sensitivity. Furthermore, overexpression of CTEN partly restored sensitivity to other drugs (DTX, CDDP, VP-16, EMP, DOX, and VBL). Previously, we confirmed cross-resistance of PC-3-TxR cells for these drugs except CDDP and VP-16 (13). At that time, we could not clarify the mechanism through which PC-3-TxR became resistant to these drugs. The results of the present study suggested that the reduced expression of CTEN may be a common mechanism of drug resistance and that CTEN overexpression by some strategies, such as gene therapy, may improve chemosensitivity regardless of CTEN expression in cancer cells.

CTEN is a recently identified focal adhesion molecule that is specifically expressed in the prostate (14). CTEN belongs to the four-member tensin family, the proteins belonging to which are localized to the cytoplasm of focal adhesions (14). Tensin 1, the prototype of the family, interacts with actin filaments in multiple ways (21), and contains an Src homology 2 (SH2) domain that binds to phosphotyrosine-containing proteins (22,23). CTEN (C-terminal tensin-like) is a distant member of the family with a smaller molecular mass than the others. CTEN shows homology to other tensin family members through the presence of the SH2 and PTB domains but it does not have the actin-binding domain found in other tensin family members (14). The function of CTEN in the cytoskeleton, if any,

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remains unknown.

In the present study, we showed that modulation of CTEN expression inversely affects paclitaxel resistance. Due to the role of tensins in the cytoskeleton, we examined whether alteration of CTEN expression had an impact on cytoskeletal proteins. Although CTEN does not have an actin-binding domain, down-regulation of CTEN in PC-3-TxR cells induced F-actin expression. The cytoskeleton is crucial for many cellular processes. For example, the function of cytoskeletal F-actin is linked to the invasive and metastatic phenotypes of malignant cancer cells (24,25). The cytoskeleton is composted of intermediate filaments, microfilaments, microtubules, the microtrabecular lattice, and other structures characterized by a polymeric filamentous nature and long-range order within the cell. The various elements of the cytoskeleton not only serve in the maintenance of cellular shape but also have roles in other cellular functions, including cellular movement, cell division, endocytosis, apoptosis, and movement of organelles (26 – 29). Cytoskeletal proteins provide the structural foundation that allows cells to exist in a highly organized state (30). These reports suggest that elevation of F-actin by CTEN down-regulation may modify the cytoskeletal cell structure to confer resistance to paclitaxel.

Similar to F-actin, we also confirmed that paclitaxel resistance caused by CTEN down-regulation was partially mediated through elevation of EGFR expression. Moreover, EGFR tyrosine kinase inhibitor restored paclitaxel sensitivity in PC-3-TxR cells. Kitazaki *et al*. showed that an EGFR tyrosine kinase inhibitor directly inhibited the function of P-glycoprotein in multidrug-resistant

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cancer cells (31). However, there seems to be little interaction between P-glycoprotein and EGFR in PC-3-TxR cells as paclitaxel resistance of PC-3-TxR cells was not involved in P-glycoprotein in our previous study (13). Recently, Pu *et al*. showed that the EGFR inhibitor PD168393 potentiated the cytotoxic effects of paclitaxel synergistically with Bad, p53, and $p21^{Waf1/Cip1}$ induction and ERK1/2 inactivation (32). Coley *et al*. demonstrated that ERK-phosphorylation and survivin were involved in EGFR activation in drug-resistant cells (18). These data suggest that combination therapy with taxanes and EGFR tyrosine kinase inhibitors will provide new strategies to overcome paclitaxel resistance. Our findings suggest that CTEN may be an upstream target to inhibit EGFR activity and thus may be worthy of further exploration for inhibition of drug resistance.

Paclitaxel down-regulated CTEN expression within 48 h. Little is known about how CTEN expression is regulated by paclitaxel. Liao *et al.* demonstrated that b-catenin up-regulated CTEN expression in colon cancer (33). However, we found no differences in b-catenin expression among PC-3, PC3-TxR, DU145, and DU145-TxR cells. We are currently investigating the mechanism of regulation of CTEN by paclitaxel.

Although we did not observe a difference in cell proliferation between PC-3-TxR/Neo and PC-3-TxR/CTEN *in vitro*, CTEN expression was inversely associated with PCa Gleason score. Our findings were in agreement with those of a previous report that CTEN expression was lower in PCa than in the normal prostate (14). In contrast, CTEN mRNA expression was correlated with tumor progression

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in lung and colon cancer (33,34). This discrepancy could be due to the differences in tissue type. In addition, the CTEN gene localizes to chromosome 17q21, a region frequently deleted in PCa (35,36). Furthermore, due to tissue differences, the function of CTEN as a focal adhesion molecule may be different among different cancer tissues. Regardless, our results suggest that the expression level of CTEN could be a biomarker of PCa progression. In addition, the observation that only 60% of men with androgen non-responsive PCa respond to initial taxane therapy indicates that a large number of PCa patients are initially resistant to taxanes. If we could predict the responsiveness to taxanes prior to chemotherapy, we could avoid administration of unnecessary and toxic taxane-based treatment regimens. Our results suggest that evaluation of CTEN expression in PCa tissues may be a useful way to predict taxane responsiveness. Unfortunately, it is extremely difficult to obtain recurrent samples from patients before chemotherapy because the recurrence is often in bone metastatic lesions and not in the prostate. We are now collecting data from HRPC patients treated with taxanes and will investigate the correlation between CTEN expression at diagnosis and duration of taxanes responsiveness.

In conclusion, we showed that down-regulation of CTEN causes paclitaxel resistance in PCa cells. This was associated with elevation of F-actin and increased EGFR, which contributed to this resistance. Moreover, expression of CTEN was inversely correlated with Gleason Score, indicating that poorly differentiated PCa may have increased resistance to taxane-based therapy. Accordingly, defining the function and regulation of CTEN may lead to new chemotherapy strategies for those patients

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initially resistant or that later develop resistance to taxanes.

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The first and second authors contributed equally to this work and should be viewed as joint first authors.

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Legends

Figure 1. Cellular microtubule structures of PC-3 and PC-3-TxR cells. (**A**) Western blotting analysis of a-tubulin and b-tubulin protein expression. (**B**) Tubulin polymerization of PC-3 and PC-3-TxR cells. Tubulins were stained with an Oregon Green® 488 conjugate kit (green) and DAPI (blue). PC-3-TxR cells exhibited similar tubulin polymerization (Green) to the parental PC-3 cell line.

Figure 2. Down-regulation of CTEN expression is related to paclitaxel resistance in PC-3 cells. (**A**) CTEN expression and paclitaxel sensitivity in PC-3 and PC-3-TxR cells. Total proteins extracted from untreated PC-3 and PC-3-TxR cells were subjected to western blotting analysis of CTEN and GAPDH. Anti-CTEN antibody and anti-GAPDH antibody were used for detection of 76 kD CTEN and 37 kD GAPDH protein, respectively. Colony formation assay was performed as described in Materials and Methods. (**B**) Regulation of CTEN expression by paclitaxel. Western blotting analysis of CTEN was performed after treatment of PC-3 cells with paclitaxel for 48 h. The relative intensity compared with untreated PC-3 cells was columned. (**C**) Proliferation of PC-3-TxR/Neo and PC-3-TxR/CTEN cells. The numbers of PC-3-TxR/Neo and PC-3-TxR/CTEN cells were counted 24, 48, 72, and 96 h after inoculation of 2×10^3 cells. NS: no significant difference. (**D**) Sensitivity of PC-3-TxR/Neo and

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PC-3-TxR/CTEN cells. Total proteins extracted from PC-3-TxR/Neo and PC-3-TxR/CTEN cells were subjected to western blotting analysis of CTEN and GAPDH. Colony formation assay of PC-3-TxR/Neo and PC-3-TxR/CTEN cells after treatment with paclitaxel for 24 h (**A**). (**E**) knockdown of CTEN expression in PC-3 cells by CTEN siRNA transfection. Twenty-four h after transfection with NT siRNA or CTEN siRNA, total proteins from PC-3 cells were extracted and subjected to western blotting analysis of CTEN and GAPDH. Growth inhibition by paclitaxel was examined after transfection with NT siRNA (PC-3/NT siRNA) or CTEN siRNA (PC-3/CTEN siRNA) as described in Materials and Methods.

Figure 3. Overexpression of CTEN increases sensitivity to paclitaxel in DU145-TxR cells. (**A**) Total proteins from DU145 and DU145-TxR cells were subjected to western blotting analysis for CTEN and GAPDH. Colony formation assay of DU145 and DU145-TxR cells were performed as described in Materials and Methods. (**B**) Total proteins from DU145-TxR/Neo and DU145-TxR/CTEN cells were subjected to western blotting analysis of CTEN and GAPDH. DU145-TxR/Neo and DU145-TxR/CTEN cell proliferation were compared after inoculation of 2×10^4 cells. NS: no significant difference. (**C**) Comparison of P-glycoprotein expression among DU145, DU145-TxR, DU145-TxR/Neo, and DU145-TxR/CTEN. (**D**) Colony formation assays of DU145-TxR/Neo and DU145-TxR/CTEN cells were performed as described in Fig. 1.

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Figure 4. Comparison of sensitivity to several drugs between PC-3-TxR/Neo and PC-3-TxR/CTEN cells. PC-3-TxR/Neo and PC-3-TxR/CTEN cells were exposed to the indicated concentrations of DTX, CDDP, VP-16, VLB, EMP, and DOX for 24 h and the numbers of the cells were counted 48 h after exposure.

Figure 5. Localization of CTEN protein and involvement of actin in paclitaxel resistance. (**A**) The subcellular protein fractions (cytoplasm, membrane, nucleus, and cytoskeleton protein) were extracted as described in Materials and Methods and subjected to western blotting analysis for CTEN. (**B**) Immunofluorescence analysis of CTEN and F-actin after treatment with paclitaxel. After PC-3 cells were treated with or without paclitaxel (30 nM) for 24 h, immunofluorescence analyses were performed using rabbit anti-CTEN antibody (red), F-actin (green) as described in Materials and Methods, and the blue signal represents nuclear DNA staining (400× magnification). (**C**) Immunofluorescence analysis of CTEN and F-actin in PC-3, PC-3-TxR, PC-3-TxR/Neo, and PC-3-TxR/CTEN cells and PC-3 transfected with NT siRNA or CTEN siRNA. Immunofluorescence analysis was performed as described in (**B**). (**D**) Effects of actin expression on paclitaxel sensitivity. PC-3-TxR cells transfected with NT siRNA (20 nM) or actin siRNA (5, 10, or 20 nM) for 24 h were subjected to western blotting analysis of actin and GAPDH. Anti-actin antibody and anti-GAPDH antibody were employed for detection of 43

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kD actin and 37 kD GAPDH protein, respectively. PC-3-TxR cells transfected with 20 nM NT or actin siRNA for 24 h were treated with paclitaxel for 24 h. Then, the cells were cultured for 48 h in normal medium.

Figure 6. Effects of CTEN on EGFR expression and involvement of EGFR for paclitaxel resistance. (**A**) Western blotting analysis of EGFR. Total proteins from PC-3, PC-3-TxR, PC-3-TxR/Neo, and PC-3-TxR/CTEN were subjected to western blotting analysis. Total proteins from PC-3/NT siRNA, and PC-3/CTEN siRNA were also subjected to western blotting analysis. Anti-CTEN, anti-EGFR, and anti-GAPDH antibodies were employed for detection of CTEN, EGFR, and GAPDH, respectively. (**B**) Effects of EGFR siRNA on paclitaxel sensitivity. Twenty-four h after transfection of PC-3-TxR cells with 20 nM NT siRNA or EGFR siRNA, the cells were treated with paclitaxel for 24 h. Then, the cells were cultured for 48 h in normal medium. (**C**) Effects of EGFR inhibitor PD153035 on cell viability of PC-3/NT siRNA and PC-3/CTEN siRNA. Twenty-four h after transfection of PC-3 cells with 20 nM NT siRNA or CTEN siRNA, the cells were treated with the indicated concentration of PD153035 for 48 h and the numbers of cells were counted. (**D**) Effects of EGFR inhibitor PD153035 on paclitaxel sensitivity. PC-3-TxR cells were treated with paclitaxel with or without 1 μM PD153035 for 48 h and the numbers of cells were counted.

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Figure 7. Immunohistochemistry of CTEN in prostate tissue. Representative examples of photomicrographs (40× and 200× magnification) showing CTEN expression in the normal prostate and prostate cancer on tissue microarray analysis. (**A**) CTEN expression in normal prostate tissue (intensity +++). (**B**) CTEN expression in prostate cancer with Gleason score 7 (intensity ++). (**C**) CTEN expression in prostate cancer with Gleason score 8 (intensity +). (**D**) CTEN expression in prostate cancer with Gleason score 9 (intensity –).

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TABLE 1. Immunohistochemistry of CTEN in normal prostate and prostate cancer tissue on tissue microarray analysis

Clinicopathological features		CTEN Expression				Total Number
		(–)	(+)	(++)	(+++)	
Normal		0	1	2	13	16
Gleason score	6, 7	0	3	11	14	28
	8	2	4	5	1	12
	9, 10	11	15	4	2	32
Total number		13	23	22	30	88

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Fig. 1 Li et al.

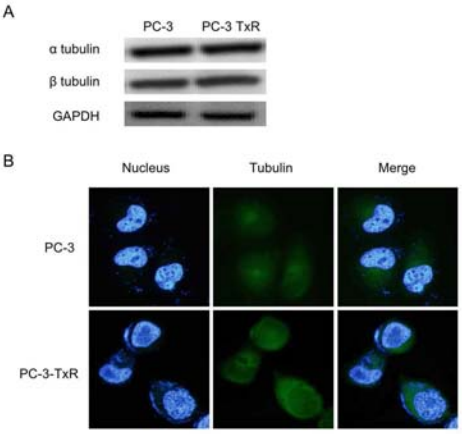

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Fig. 2 Li et al.

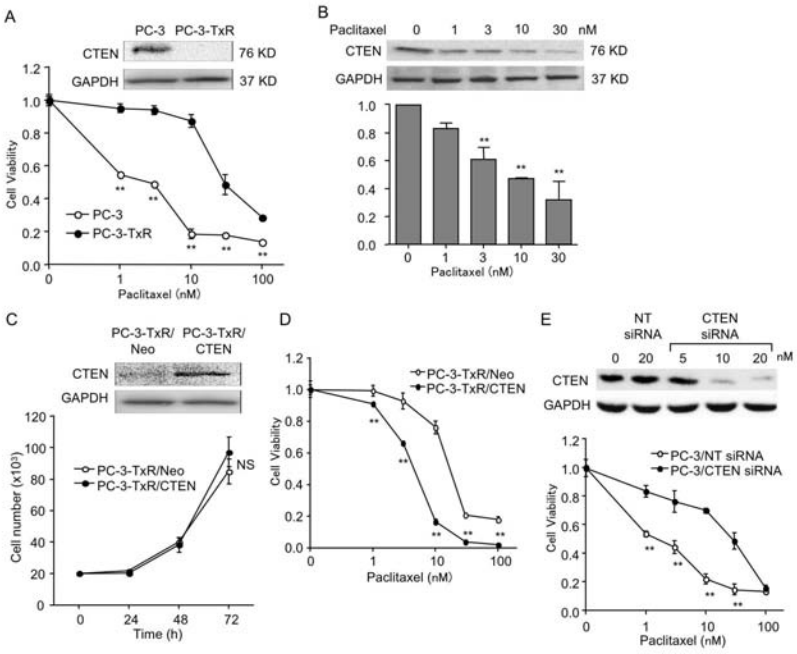

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Fig. 3 Li et al.

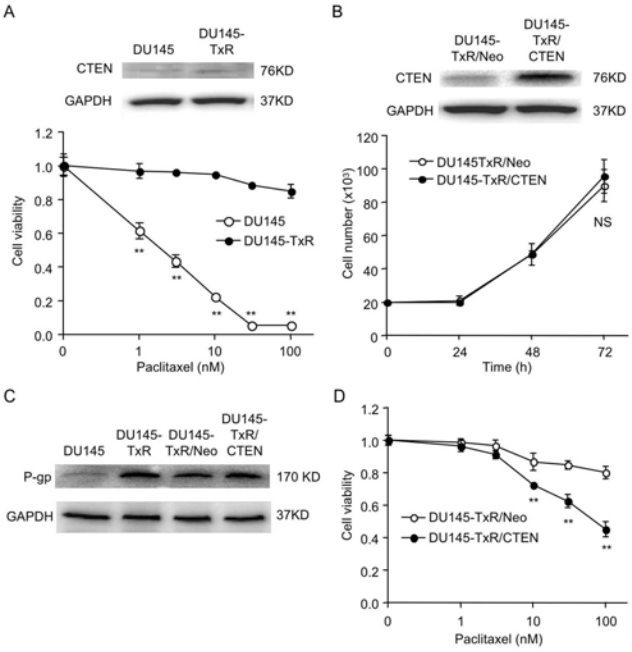

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Fig. 4 Li et al.

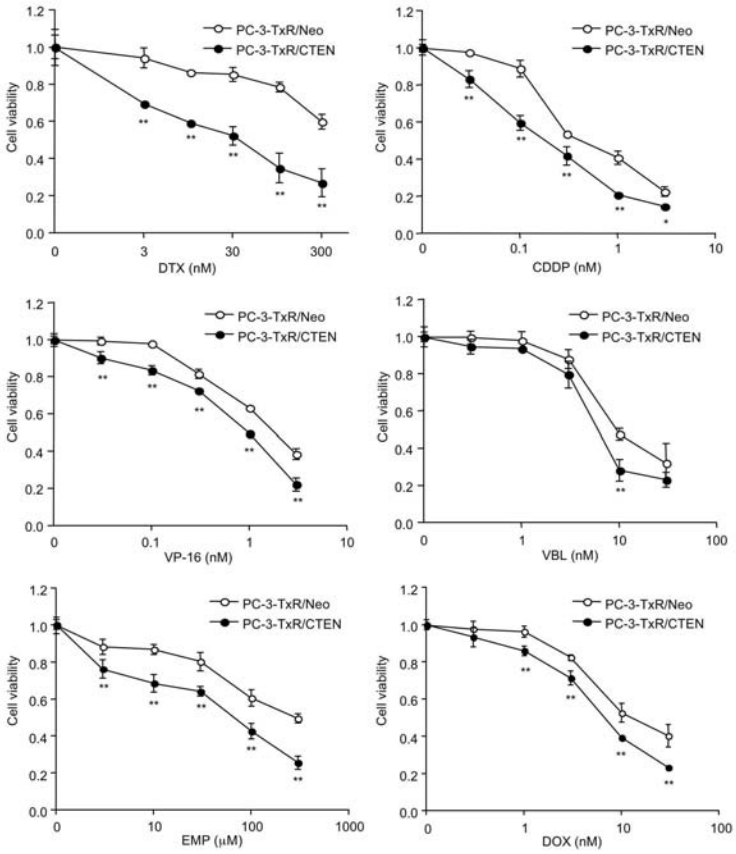

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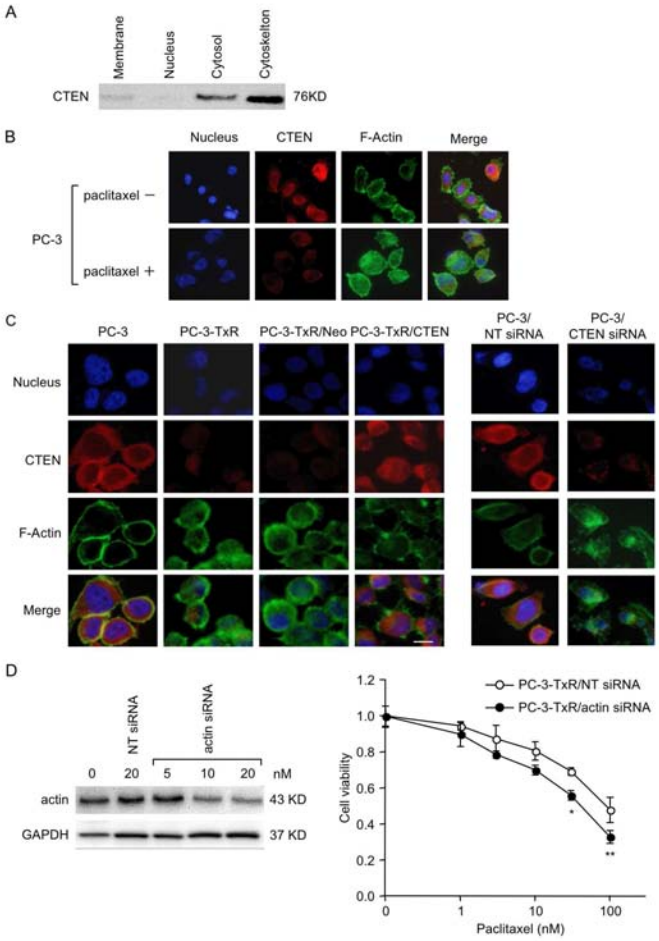
Fig. 5 Li et al.



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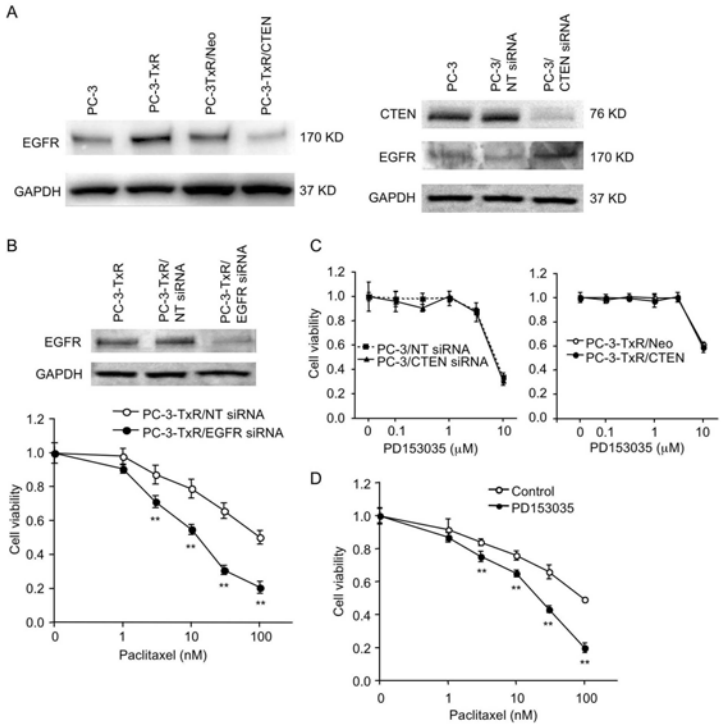

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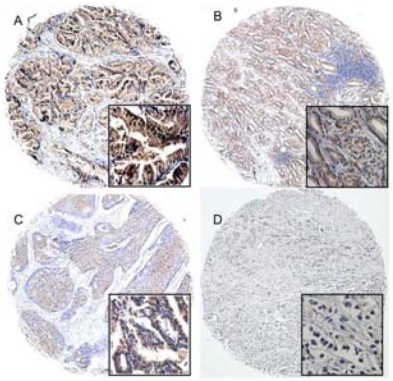

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