Pinin promotes tumor progression via PI3K/AKT/CREB signaling pathway in prostate cancer

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Research

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Abstract

Background

Pinin (PNN), a desmosome associated protein, was demonstrated to be over-expressed and act as a tumor-promoting factor in ovarian cancer, hepatocellular carcinoma and colorectal cancer. However, the precise role of PNN in prostate cancer is still unknown.

Methods

The expression levels of PNN were assessed in prostate cancer by qRT-PCR, western blotting and immunohistochemical staining. The other proteins were quantified by western blotting. PNN-depleted cells were produced by infecting with lentivirus bearing short hairpin RNAs against PNN. PNN over-expression was performed by transfecting PNN expression vector. The proliferation of each cell line was assessed by MTS and colony formation assays. Tumors were induced on nude mice by injecting tumor cells subcutaneously. Apoptosis and cell cycle were evaluated by flow cytometry. Transwell and wound healing assay were performed to determined the ability of cell invasion and migration. The TCGA data were analyzed with GEPIA (Gene Expression Profiling Interactive Analysis) and GraphPad Prism.

Results

Here, we reported that PNN was upregulated in prostate cancer tissues and PNN expression was positively associated with Gleason score, tumor stage and tumor metastasis. PNN promoted cell growth and tumorigenicity *in vitro* and *in vivo*, and might modulate cell growth through driving G1/S transition via CDK6, CDK2, and Cyclin D1 in prostate cancer cells. Furthermore, PNN accelerated cell invasion, migration and EMT processes of prostate cancer cells accompanied with the up-regulation of MMP-2, MMP-9, N-cadherin, Vimentin and down-regulation of E-cadherin. Mechanism study demonstrated that the proliferation- and motility-promoting effects of PNN on prostate cancer cells dependent on the activation of PI3K/AKT/CREB signaling, which was reversed by AKT and CREB inhibitors.

Conclusions

Collectively, these findings indicated that PNN plays important roles in prostate cancer tumorigenesis and progression and it may be a potential therapeutic target for prostate cancer treatment.

Introduction

Prostate cancer (PCa) is the most common malignancy of the male urogenital system [1]. In the United States, the incidence of prostate cancer ranks first with accounting for more than 1 in 5 new diagnoses, and its mortality ranks second among all male malignant tumors in 2020 [2]. Although the incidence and

mortality of prostate cancer is lower in China, it increases rapidly in the past 20 years [3, 4]. When the cancerous cells are still confined within the prostate capsule, patients usually receive prostatectomy or radiation therapy and the outcome is well with the 5-yearr survival rate almost 99%. However, many patients are diagnosed after the cancer has spread and the 5-year survival rate of metastatic PCa is only 28% [5]. Although metastatic cancer has been focus of PCa, the mechanisms of PCa malignant progression are not fully understood.

Pinin (PNN), a desmosome associated protein, was found to locate at the cytoplasmic surface of the desmosome structure in corneal epithelia for the first time [6, 7]. The presence of PNN within the desmosome was correlated to highly organized, perpendicular bundles of keratin filaments, and primarily stabilized the intermediate fiber-desmosome composite structure and reinforcing epithelial cell to cell adhesion [8, 9]. Furthermore, PNN was found to widely distribute in the nuclear plaque region, which is involved in the transcription regulation of genes and the selective splicing of pre-mRNA and lncRNA [10–13]. Recent studies have found that PNN played important roles in various tumors. Down-regulation of PNN induced apoptosis in breast cancer MCF-7 cell [14]. PNN was over-expressed in ovarian cancer and PNN knockdown reduced the cell viability and tumorigenicity [15, 16]. Over-expression of PNN was found to promote cell survival, proliferation and migration via activation of ERK pathway in hepatocellular carcinoma and colorectal cancer [17, 18]. These results indicated that PNN may be a potential proto-oncogene. However, the role of PNN in prostate cancer is still unknown.

In this study, we revealed that up-regulated PNN was positively correlated with prostate cancer malignant progression. PNN over-expression promoted prostate cancer cell proliferation, invasion and migration by activating PI3K/AKT/CREB pathway. These findings demonstrated that PNN plays an important role in prostate cancer and it may be a valuable therapeutic target for prostate cancer.

Materials And Methods

1. **Tissue samples**

In the study, a total of 81 prostate cancer samples and 22 normal prostate samples were obtained from patients who underwent prostate biopsy in Department of Urology, Ningbo First Hospital (Ningbo, China) between 2012 and 2017. These samples were then formalin-fixed and paraffin-embedded followed by pathological diagnosis and immunohistochemical staining. The study protocol was approved by the Ethics Committee of Ningbo First Hospital and the information written consent was obtained from all the subjects prior to their participation in the study. The clinicopathological characteristics of patient samples were obtained from medical records within Ningbo First Hospital and were summarized in Table 1.

2. **Immunohistochemical staining**

Immunohistochemical staining (IHC) was performed on paraffin-embedded tissue sections to determine PNN levels in prostate cancer tissues and normal prostate samples using a staining kit (absin, Shanghai, China). Briefly, sections were deparaffinized with xylene and rehydrated with ethanol-aqueous solutions, then antigen retrieval was done by heating the slides for 15 min in a microwave oven in 10 mM citrate buffer (pH 6.0). After eliminating endogenous peroxidase activity using 3% H_2O_2 and blocking with 5% BSA, the sections were incubated with anti-PNN antibody (1:50, HPA001378, Sigma-Aldrich, Merck KGaA, Germany) overnight at 4°C and followed with secondary antibody. The sections were then incubated with Diaminobenzidine (DAB) and counterstained with Mayer's hematoxylin.

3. TCGA data analysis

The gene expression matrix and clinical phenotype of prostate cancer patients from TCGA were downloaded from UCSC (https://xenabrowser.net/datapages/), then PNN expression in prostate cancer was analyzed by GraphPad Prism 8.0. Kaplan-Meier survival curves, applied to analyze the effect of PNN expression on PCa patients' recurrence and survival, were analyzed with GEPIA (Gene Expression Profiling Interactive Analysis) [19].

4. Cell culture and cell transfection

Human prostate cancer cells DU145, 22Rv1, LNCaP clone FGC and PC-3, and human embryonic kidney cells 293T used in the study were purchased from American Type Culture Collection (ATCC, Manassas, VA, USA) and were cultured in MEM, RPMI 1640, F-12K or DMEM medium (Gibco, Thermo Fisher SCIENTIFIC, USA) containing 10% fetal bovine serum (PAN, Germany). All cell cultures were carried out in a humidified chamber at 37 °C with an atmosphere of 5% CO_2.

PNN expression vector pcDNA3.1-3xFlag-C-PNN (pcDNA3.1-PNN) and primer vector pcDNA3.1-3xFlag-C (pcDNA3.1) used in the study was purchased from YouBio (Changsha, Hunan, China). Lipofectamine™ 3000 reagent (Invitrogen, Thermo Fisher SCIENTIFIC, USA) was used to cell transfection following the manufacturer's instructions.

5. Lentivirus production and generation of stably PNN-knockdown PC-3 cells

The shRNAs targeted human PNN were obtained from GPP Web Portal (https://portals.broadinstitute.org/gpp/public/gene/search). The shRNAs sequences used in the study included shPNN #1 (5'-CCGACAGAAAGAGGTCTATAT-3'), shPNN #2 (5'-GAAGGTAGACGCATCGAATTT-3'), shPNN #3 (5'-GGTAGAGGACGTGGTAGTTTA-3') and a scramble shRNA (5'-CCTAAGGTTAAGTCGCCCTCG-3'). We cloned the shRNAs into pLKO.1-puro (Plasmid #8453, Addgene) at Age □ and EcoR □ to construct

pLKO.1-shPNN or pLKO.1-shSCR vectors. Three plasmids pCMV-dR8.2 dvpr (Plasmid #8455, Addgene), pCMV-VSV-G (Plasmid #8454, Addgene) and pLKO.1-shPNN or pLKO.1-shSCR were co-transfected into 293T cells and cultured for 72 h. Lentivirus-containing supernatants were then harvested using 0.45 μm sterilizing filter. Lentiviruses were then used to infect PC-3 cells and the infected cells were then selected by complete medium containing 2ug/ml puromycin to acquire stably PNN-knockdown PC-3 cells.

6. **Western blotting**

Tumor tissues and cells were lysed and protein was harvested with RIPA buffer (Solarbio, Beijing, China) supplemented with 1% protease inhibitor mix (Cell Signaling Technology, USA) and 1% phosphatase inhibitor mix (Sangon Biotech, Shanghai, China). Proteins were separated on SDS-PAGE gel, then transferred onto PVDF membranes (BIO-RAD, USA) followed with blocking by 5% non-fat milk. The membranes were incubated with the primary antibody at 4℃ overnight. The following primary antibodies were used: E-Cadherin, N-Cadherin, Vimentin, Fibronectin, GAPDH, MMP-2, MMP-9, CDK4, CDK6, CDK2, CyclinD1, CyclinE1, PI3K p110α, PI3K p110β, PI3K p110γ, PI3K p85, p-PI3K p85(Tyr458), AKT, p-AKT (Ser473), CREB and p-CREB (Ser133) were purchased from Cell Signaling Technology (USA), PNN antibody was obtained from Sigma-Aldrich (Merck KGaA, Germany). Then, membranes were incubated with HRP (horseradish peroxidase)-labeled secondary antibody (Boster, Wuhan, China) and detected by chemiluminescence.

7. **RNA extraction and quantitative real time-PCR (qRT-PCR)**

Total RNAs were extracted from prostate cancer cells using TRIzol Reagent (Invitrogen, Thermo Fisher SCIENTIFIC, USA). The RevertAid First Strand cDNA Synthesis Kit (Thermo Fisher SCIENTIFIC, USA) was used to synthesize cDNA. The cDNAs were amplified by qRT-PCR using SYBR Green PCR Master Mix (Roche, US) on a LightCycler480 system, and fold changes were calculated by relative quantification ($2^{-\Delta\Delta Ct}$). The PCR primers sequences were as follows: Forward primer: 5'-ACCCACTCCTCCACCTTTGAC-3' and Reverse primer: 5'-TGTTGCTGTAGCCAAATTCGTT-3' for GAPDH, Forward primer: 5'-CCTGTAAAGCAGTCTCAAGCC-3' and Reverse primer: 5'-CGAATGTTCTCATCCACGTTCT-3' for PNN.

8. **Transwell assay and wound healing assay**

The transwell assay was performed to determined the ability of cellular invasion and migration using 8 μm Transwell® Permeable Supports (Costar, Corning, Bedford, MA, USA). For cell migration assay, a suspension of cells (1×10^5 cells/well for PC-3 and 5×10^4 cells/well for DU145) in serum free basal medium was seeded to the upper chambers. The lower chambers were filled with growth media containing 10% FBS. After incubation at 37°C (24 h for DU145 cell and 48 h for PC-3 cell), the non-

invaded cells in upper chamber were removed and the invaded cells were fixed with 90% methyl alcohol, then stained with 0.1% crystal violet (Sigma-Aldrich, Merck KGaA, Germany). The invasion assay was performed using the same procedure with the following modifications: (i) the seeding density was 2×10^5 cells/well for PC-3 and 1×10^5 cells/well for DU145, (ii) the upper chambers were pre-coated with Matrigel® Matrix (Corning, Bedford, MA, USA), and (ﷺ) PC-3 and DU145 cells were all incubated for 48 h at 37°C.

The wound healing assay was performed to determine the cell motility. When the seeded cells reached 95% confluence in 24-well plate, a linear wound was created with a micropipette tip across the diameter of the well, and then PBS was used to rinse the non-adherent cells. The medium containing 0.5% FBS was added to allow cells to move into the gap without the influence of cell growth. Three different equidistant points of the scratched area were photographically measured and imaged by an inverted phase contrast microscope (Olympus, Japan) at 0 h and 24 h. Migration rate was calculated as the proportion of initial scratch distant of each sample using the mean distance between both borderline that remain cell-free after cell migration.

9. **MTS assay**

MTS assay was performed to determined cell proliferation using Cell Titer 96® Aqueous One Solution Reagent (MTS, Promega, Madison, USA) according to the manufacturer's protocol. In brief, a suspension of cells (2000 cells/well for DU145 and 4000 cells/well for PC-3) in 100 µl of growth media was seeded to 96-well plate,

Following incubation for 4, 24, 48, 72 and 96 h, 20 µl of MTS reagent was added to each well. The absorbance (OD value) was measured at 490 nm after incubation for another 2 h using iMark™ Microplate Reader (Bio-Rad, US).

10. **Cell cycle and apoptosis assay**

Cells were harvested by trypsinization and washed with PBS, then the cells were stained followed the Cell Cycle Staining Kit (MultiSciences, Hangzhou, China). After staining, cell cycle analysis was performed using a flow cytometer (Beckman Coulter, Fullerton, CA, USA).

Cell apoptosis was assessed using Annexin V-FITC/PI apoptosis kit (MultiSciences, Hangzhou, China). In brief, cells were harvested and washed with pre-cold PBS, then cells were stained with fluorescein

isothiocyanate (FITC)-conjugated Annexin V and PI followed with apoptosis analysis by Beckman flow cytometer.

11. **Tumorigenesis assay of tumor cells**

Colony formation assays and Xenograft model in nude mice were performed to detect the tumorigenicity of prostate cancer cells. For colony formation assays, PC-3 cells were counted and seeded in 6-well plate at a density of 1000 cells per well. After incubation for 14 days, the cells were fixed with 90% methyl alcohol for 15 min and then stained with 0.1% crystal violet (Sigma-Aldrich, Merck KGaA, Germany) for 15 min. The number of colonies consisting of more than 50 cells was counted.

Five-week-old male nude mice (BALB/C) (Shanghai laboratory animal center, China) were used as xenograft model with a protocol approved by the Institutional Animal Ethics Committee of Ningbo University. 4×10^6 stably PNN-knockdown PC-3 cells or PC-3/Control cells were injected subcutaneously into the flank of mouse (5 for each group) and tumor formation was monitored. On day 32 after inoculation, the nude mice were sacrificed to collect the tumors.The tumor volume was calculated with the formula $V = L*W^2/2$ (V, volume; L, length; W, width).

12. **Statistical analysis**

Statistical analyses were performed with SPSS software (SPSS Inc., Chicago, IL, USA). The correlation between PNN expression and the clinicopathological features was analyzed with chi-square test. Bivariate correlations between study variables were calculated using the Spearman's rank correlation coeffcient. Variance among the control and tested groups were analyzed using one-way ANOVA analysis followed by Dunnett post hoc test. Variance between two groups was assessed using student t test. The data were showed as Mean ± standard deviation (SD). $P < 0.05$ was considered statistically significant in all tests.

Results

1. **Over-expressed PNN correlates with malignant progression of prostate cancer**

Previous studies have demonstrated that PNN is up-regulated in colorectal cancer, hepatocellular carcinoma and ovarian cancer, promoting tumor cell growth and metastasis and inhibiting apoptosis [15-18]. Here, we firstly analyzed PNN expression using immunohistochemical staining in a cohort of 81

prostate cancer tissues and 22 normal prostate samples obtained by prostate biopsy. The results indicated that PNN was only expressed in 31.8% (7/22) normal prostate tissues at low levels (Table 1, Table 2, Figure 1A). However, PNN was positively expressed in 93.8% (76/81) prostate cancer samples, and a moderate to strong staining was observed in 39/81 tumor samples (Table 1, Table 2, Figure 1A). In addition, the results of 20 paired tumor-normal samples in the cohort showed that PNN is significantly up-regulated in tumors compared to their paired normal samples ($P < 0.001$) (Table 2).

Table 2: Correlation between PNN expression and clinicopathologic characteristics in prostate cancer patients

Characteristics	PNN Expression		χ^2	*P*
	Negative(%)	Positive (%)		
PNN expression in all samples				
Nomal vs Tumor			42.515	**< 0.001**
Normal	15 (68.2)	7 (31.8)		
Tumor	5 (6.2)	76 (93.8)		
PNN expression in pair-matched samples				
Nomal vs Tumor			18.027	**< 0.001**
Normal	14 (70.0)	6 (30.0)		
Tumor	1 (5.0)	19 (95.0)		

To better understand the significance of PNN expression in prostate cancer, a correlation analysis was performed between PNN expression and clinicopathological parameters. As shown in Table 3 and Table 4, PNN expression was positively correlated with Gleason score ($P < 0.01$), tumor stage ($P < 0.05$) and tumor metastasis ($P < 0.05$), but not PSA level and biochemical recurrence.

Table 3: Correlation between PNN expression and clinicopathologic characteristics in prostate cancer patients

Characteristics	PNN Expression		χ^2	*P*
	Negative and Low (%)	Moderate and High (%)		
PSA Level			2.021	0.364
<10	7 (63.6)	4 (36.4)		
10-50	20 (58.8)	14 (41.2)		
>50	16 (44.4)	20 (55.6)		
Gleason Score			7.546	**0.023**
<7	10 (76.9)	3 (23.1)		
=7	14 (66.7)	7 (33.3)		
>7	19 (40.4)	28 (59.6)		
Tumor Stage			4.941	**0.026**
□-□	33 (61.1)	21 (38.9)		
□-□	9 (34.6)	17 (65.4)		
Tumor Metastasis			4.357	**0.037**
No	23 (65.7)	12 (34.3)		
Yes	19 (42.2)	26 (57.8)		
Biochemical Recurrence			0.102	0.750
No	33 (54.1)	28 (45.9)		
Yes	10 (50.0)	10 (50.0)		

Table 4: Spearman analysis of correlation between PNN and clinicopathological features

Variables	PNN Expression	
	Spearman Correlation	*P*
PSA Level	0.156	0.164
Gleason Score	0.305	**0.006**
Tumor Stage	0.249	**0.026**
Tumor Metastasis	0.233	**0.037**
Biochemical Recurrence	-0.035	0.754

Meanwhile, we downloaded the gene expression matrix and clinical data of prostate cancer from TCGA database, and then analyzed PNN expression stratified by the clinicopathological parameters. As Figure 1B shown, PNN was up-regulated in tumors ($P < 0.001$), and its over-expression was correlated with tumor stage ($P < 0.01$), lymph nodal metastasis ($P < 0.001$), biochemical recurrence ($P < 0.01$) and Gleason score ($P < 0.001$). These results were basically consistent with our immunohistochemical staining results. Furthermore, to explore the relationship between PNN expression and the clinical prognosis of patients with prostate cancer, we determined the prognostic significance of PNN in TCGA cohort. The result of Kaplan-Meier analysis demonstrated that high PNN expression could predict significantly unfavorable PFS (progression-free survival) and OS (overall survival) (Figure 1C).

Collectively, these findings indicated that PNN is up-regulated in human prostate cancers and its over-expression correlates with prostate cancer malignant progression and poor prognosis.

2. **PNN has positive effects on cell growth and cell cycle in prostate cancer cells**

To address the biological importance of PNN, the expression of PNN in prostate cancer cells was detected. The results showed that PNN was up-regulated in PC-3 cells than the other cells both in protein and mRNA levels, however, LNCaP clone FGC (LNCaP) and DU145 cells showed lower PNN expression (Figure 2A, B). We overexpressed or stably depleted PNN in DU145 or PC-3 cells respectively (Figure 2C). As determined by MTS assay, PNN-depleted PC-3 cells displayed a slower growth rate than the controls (Figure 2D), whereas overexpression of PNN significantly promoted cell proliferation (Figure 2E). Similarly, colony formation assay showed that the ability of tumorigenicity was reduced in PNN-depleted PC-3 cells (Figure 2F).

Furthermore, we examined whether cell cycle and some important checkpoint molecules were also mediated by PNN in prostate cancer cells. Flow cytometry analysis showed that a marked elevation in the percentage of G0/G1 phase was observed in PC-3 cells with PNN depletion, which also displayed a

significant reduction of G1/S checkpoint molecules expression, including CDK6, CDK2, and Cyclin D1. Apoptosis assay was also performed and the results showed that PNN expression had no significant effect on PC-3 cell apoptosis (Figure 3C). Meanwhile, PNN-depletion also didn't trigger the activation of apoptotic effectors Caspase-3 and PARP (Figure 3D). Taken together, these findings demonstrate that PNN might modulate cell growth through G1/S transition via CDK6, CDK2, and Cyclin D1 in prostate cancer cells.

3. **PNN promotes the tumorigenesis of prostate cancer cell *in vivo***

Our data suggested that PNN positively regulates cell growth *in vitro* and drove us to further explore whether it plays an important role in the modulation of prostate cancer tumorigenesis and progression *in vivo*. To confirm the impact of PNN in prostate cancer, we performed an in vivo experiments with subcutaneous xeno-transplanted tumor models based on BALB/C nude mice. As shown in Figure 4A-E, mice bearing PNN-depleted PC-3 cells showed a drastic regression of tumor growth compared with the control mice. Furthermore, western blot assay revealed the reduction of expression of PNN and MCM2, a marker of proliferation, in tumors derived from PNN-depleted PC-3 cells (Figure 4F, E). Taken together, these findings demonstrated that PNN plays an important role in the tumorigenesis and progression of prostate cancer cells *in vivo*.

4. **PNN accelerates prostate cancer cell invasion and migration *in vitro***

Previous efforts reported that PNN facilitated metastasis of hepatocellular carcinoma and colorectal cancer [17, 18], it led to us to further explore the functions of PNN on cell invasion and migration in prostate cancer. As shown in Figure 5A, PNN depletion suppressed invasion of PC-3 cell (Figure 5A). Wound healing and transwell assays indicated that depletion of PNN also suppressed prostate cancer cell migration (Figure 5B, C). On the contrary, we found that up-regulation of PNN in DU145 cells accelerated cell migration and invasion (Figure 5D, E). Collectively, these findings reveal that PNN accelerates prostate cancer cell invasion and migration *in vitro*.

5. **PNN over-expression induces prostate cancer cell EMT**

Tumor cell invasion and migration are multistep processes which are finely regulated [20-22]. The epithelial-to-mesenchymal transition (EMT) has been identified as an important process of tumor cell invasion and migration [23-25]. Therefore, we determined the effects of PNN on EMT in prostate cancer cell. As shown in Figure 6A, the expression of epithelial cell marker E-cadherin was elevated, whereas expression of mesenchymal cell markers N-cadherin and Vimentin, as well as matrix metalloproteinase MMP-2 and MMP-9 were reduced in PNN-depleted PC-3 cell (Figure 6A). However, the opposite results were found in DU145 cells when PNN was overexpressed (Figure 6B). Moreover, we detected the expression of EMT-related proteins in tumors derived from control or PNN-depleted xenografts, similar results were observed (Figure 6C). During EMT, polarized epithelial cells rearrange cytoskeleton, dissolve the cell-cell junctions and convert into non-polarized mesenchymal cells [26-28]. Here we found that depletion of PNN changed the morphology from long, polygonal form to spindle appearances in PC-3 cells (Figure 6D). These results revealed that PNN has a positive effect on EMT process.

6. **PNN regulates prostate cancer cell proliferation and migration via PI3K/AKT/CREB signaling**

Because PI3K/AKT signaling pathway is one of the most important pathways which regulates cell survival, proliferation, metabolism as well as cytoskeletal reorganization in human cancers including prostate cancer [29-31], we determined the effects of PNN on PI3K/AKT signaling pathway. As shown in Figure 7A, the level of PI3K p110β, phosphorylated p85 (p-p85) and phosphorylated AKT (p-AKT) were all decreased in PNN-depleted cells. In contrast, they were increased in PNN-overexpressing DU145 cells (Figure 7A). Meanwhile, we observed that phosphorylated CREB was positively correlated with PNN levels (Figure 7A). CREB, a common downstream target of AKT, is a proto-oncogenic transcription factor, which generally regulates various cell functions by enhancing the expression of target genes [32, 33]. Our previous studies indicated that the over-expression and abnormal activation of CREB celebrate tumorigenesis and tumor migration [34, 35]. Therefore, we postulated that overexpression of PNN promotes prostate cancer progression through activating PI3K/AKT/CREB signaling axis.

To verify this hypothesis, small molecule inhibitors targeting AKT and CREB were utilized. The western blot assay showed that PNN overexpression-caused expression changes of p-CREB, E-Cad, N-Cad, and MCM2 could be rescued by small molecule inhibitor MK2206 targeting AKT in prostate cancer cells (Figure 7B). In addition, only the expression of E-Cad, N-Cad and MCM2, but not the p-AKT, were rescued by KG501 (CREB small molecule inhibitor) in PNN over-expressed prostate cancer cells (Figure 7B). Importantly, the MTS, transwell, and wound healing assays demonstrated that the PNN overexpression-caused cell phenotype changes also can be reversed by MK2206 and KG501 (Figure 8A-C).

Taken together, these results indicated that PNN modulates prostate cancer progression dependent on the activation of PI3K/AKT/CREB pathway.

Discussion

In the present study, we demonstrated that PNN was over-expressed in prostate cancer tissues and its over-expression was positively correlated with Gleason score, tumor stage and tumor metastasis (Fig. 1, Table 2–4). These findings suggest that PNN may play an important role in progression and metastasis in prostate cancer.

Furthermore, we found ectopic expression of PNN promoted prostate cancer cell proliferation *in vitro*, while knockdown of PNN inhibited proliferation *in vitro* and tumorigenesis *in vivo* (Fig. 2, 4). Cell cycle and apoptosis are the main events that affect cell growth. The experimental data displayed that PNN-silenced cell arrested at G0/G1 phase, and PNN knockdown distinctly repressed the expression of Cyclin D1, CDK2 and CDK6, which control the cell fate in G0/G1 phase and G1 to S transformation (Fig. 3). However, the effect of PNN expression on cell apoptosis was not significant in the study (Fig. 3). These results suggest that proliferation-promoting effect of PNN was through cell cycle control in prostate cancer.

Moreover, we found that over-expressed PNN accelerated prostate cancer cell invasion and migration *in vitro* (Fig. 5). Tumor cell invasion and migration, the major events in tumor progression, are multistep processes [36, 37]. It is well known that EMT had been demonstrated to be an important process of tumor cell invasion and migration. After EMT, tumor cells lose the polarity and gain motility, secrete matrix metalloproteinases to degrade extracellular matrix, then invade surrounding tissues and transfer to other organs [38, 39] In the study, we also found that PC-3 cell with down-regulation of PNN changed the morphology from long, polygonal form to spindle appearances (Fig. 6). Furthermore, up-regulation of PNN induced mesenchymal cell markers N-cadherin, Vimentin, Fibronectin and matrix metalloproteinase

MMP-2 and MMP-9 expression and suppressed epithelial cell marker E-cadherin. In addition, the opposite results were found in PNN silenced PC-3 cells (Fig. 6). These results revealed that altered PNN expression induced both morphological and molecular biological EMT. Therefore, we believed that PNN accelerated invasion and migration via inducing tumor cell EMT in prostate cancer.

PI3K/AKT signaling pathway is one of the most important pathways which regulates cell survival, proliferation, metabolism as well as cytoskeletal reorganization in human cancers including prostate cancer [29–31]. PI3K/AKT pathway has emerged as a noteworthy goal for cancer treatment. Lots of drugs that inhibit various components of this pathway have been approved or are now in clinical trials. PI3K inhibitors including Zydelig® (Idelalisib), Aliqopa® (Copanlisib) and Piqray® (Alpelisib) have been approved by FDA [40–45]. AKT phosphorylation inhibitors, Ipatasertib (GDC-0068) and Capivasertib (AZD5363) in phase Ⅱ clinical trials now on multiple tumors [46–49], are also considered a promising approach for cancer treatment.

In the study, we demonstrated that over-expression of PNN activated PI3K/AKT pathway. The phosphorylation of CREB, a common downstream target of AKT, positively changed with the level of PNN (Fig. 7). Moreover, inhibition of AKT and CREB activity reversed the effects of PNN on prostate cancer cell proliferation, invasion and migration (Fig. 7, Fig. 8). These findings suggested PNN accelerated prostate cancer cell proliferation, invasion and migration may via activating PI3K/AKT/CREB pathway.

Conclusions

Collectively, PNN was over-expressed in prostate cancer tissues and cells, and its over-expression indicated malignant progression. PNN promoted prostate cancer cell proliferation, invasion and migration via activating PI3K/AKT/CREB pathway. In conclusion, PNN is a potential proto-oncogene and a potential therapeutic target for prostate cancer treatment.

Abbreviations

PNN:pinin, desmosome associated protein; IHC: immunohistochemical staining; ATCC: American Type Culture Collection; TCGA: The Cancer Genome Atlas; DAB: Diaminobenzidine; GEPIA: Gene Expression Profiling Interactive Analysis; EMT: epithelial-to-mesenchymal transition; PCa: prostate cancer; PSA: prostate-specific antigen; PVDF: polyvinylidene fluoride; SDS-PAGE: sodium dodecyl sulfatepolyacrylamide gel electrophoresis; qRT-PCR: quantitative real-time PCR; PFS: progression-free survival; OS: overall survival

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of Ningbo First Hospital and the information written consent was obtained from all the subjects prior to their participation in the study. Tumor

xenograft model was approved by the Institutional Animal Ethics Committee of Ningbo University.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

QM, XYM, YYR, PW were responsible for the experimental design. XYM, HZZ, KJW and JFC contributed to the execution of experiments. XYM and QM prepared the manuscript. RS, JHJ performed prostate biopsy. QM, XYM and YYR participated in performing the data statistics. All authors have contributed to and approved the final manuscript.

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Table 1

Table 1: Clinicopathological characteristics of patient samples and expression of PNN in prostate cancer

Characteristics	Number of Patients	Percentage (%)
PSA Level (ng/ml)		
< 10	11	13.6
10-50	34	42.0
> 50	36	44.4
Gleason Score		
6	13	16.0
7	21	25.9
8	25	30.9
9	18	22.2
10	4	4.9
Tumor Stage		
	2	2.5
	52	64.2
	17	21.0
	9	11.1
Unknown	1	1.2
Tumor Metastasis		
Yes	45	55.6
No	35	43.2
Unknown	1	1.2
Biochemical recurrence		
Yes	20	24.7
No	61	75.3
PNN Expression in Tumors		
Negative	5	6.2
Low	38	46.9
Moderate	33	40.7
High	5	6.2
PNN Expression in Normal samples		
Negative	15	68.2
Low	7	31.8

Figures

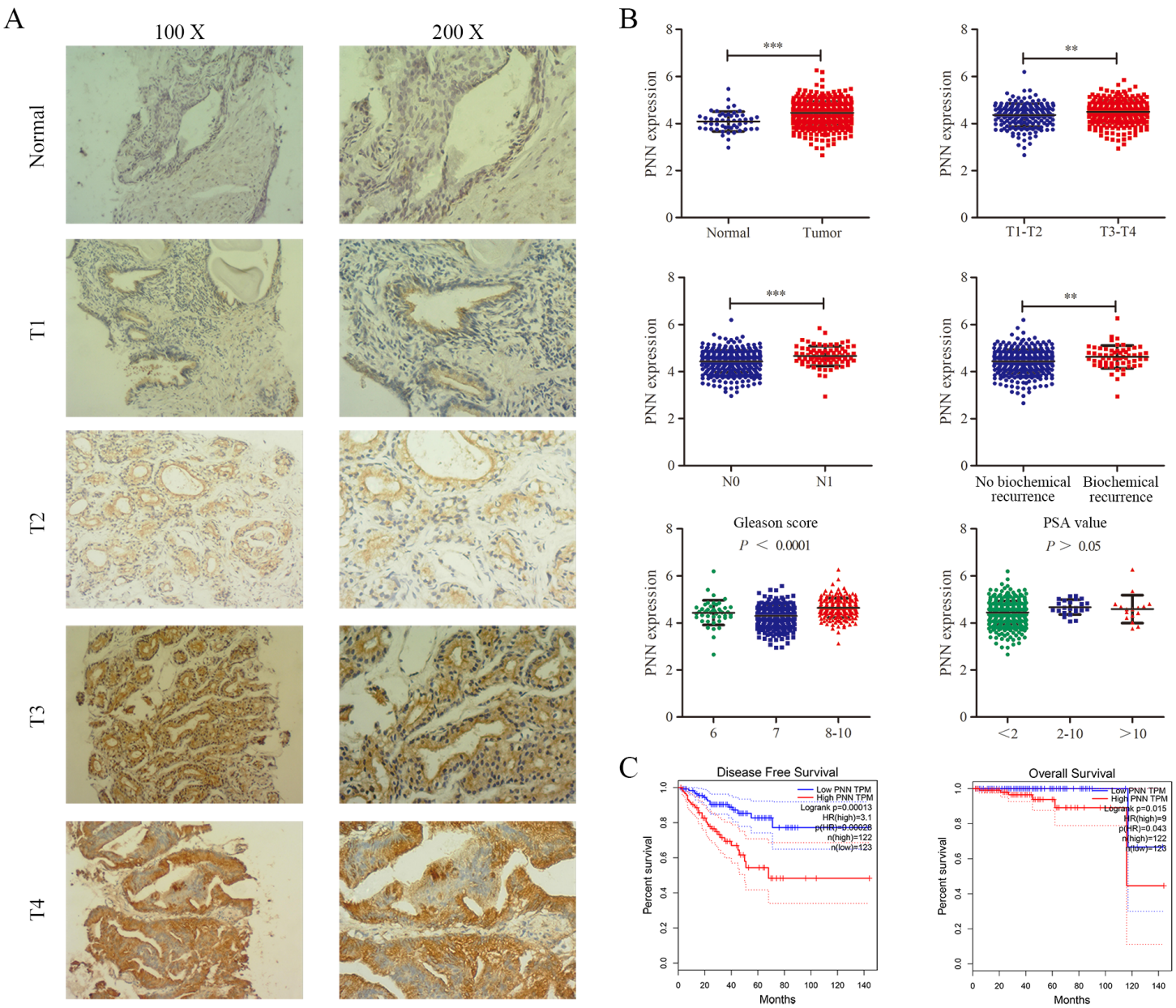

Figure 1

PNN is over-expressed in human prostate cancer A. PNN IHC staining. Representative images of immunohistochemical staining with PNN in normal prostate tissues and prostate cancer tissues. B. TCGA data analysis of prostate cancer. PNN was up-regulated in tumors, and its over-expression was correlated with tumor stage, lymph nodal metastasis, biochemical recurrence and Gleason score. C. The survival analysis based on the TCGA dateset. PNN over-expression indicated poor survival of prostate cancer patients.

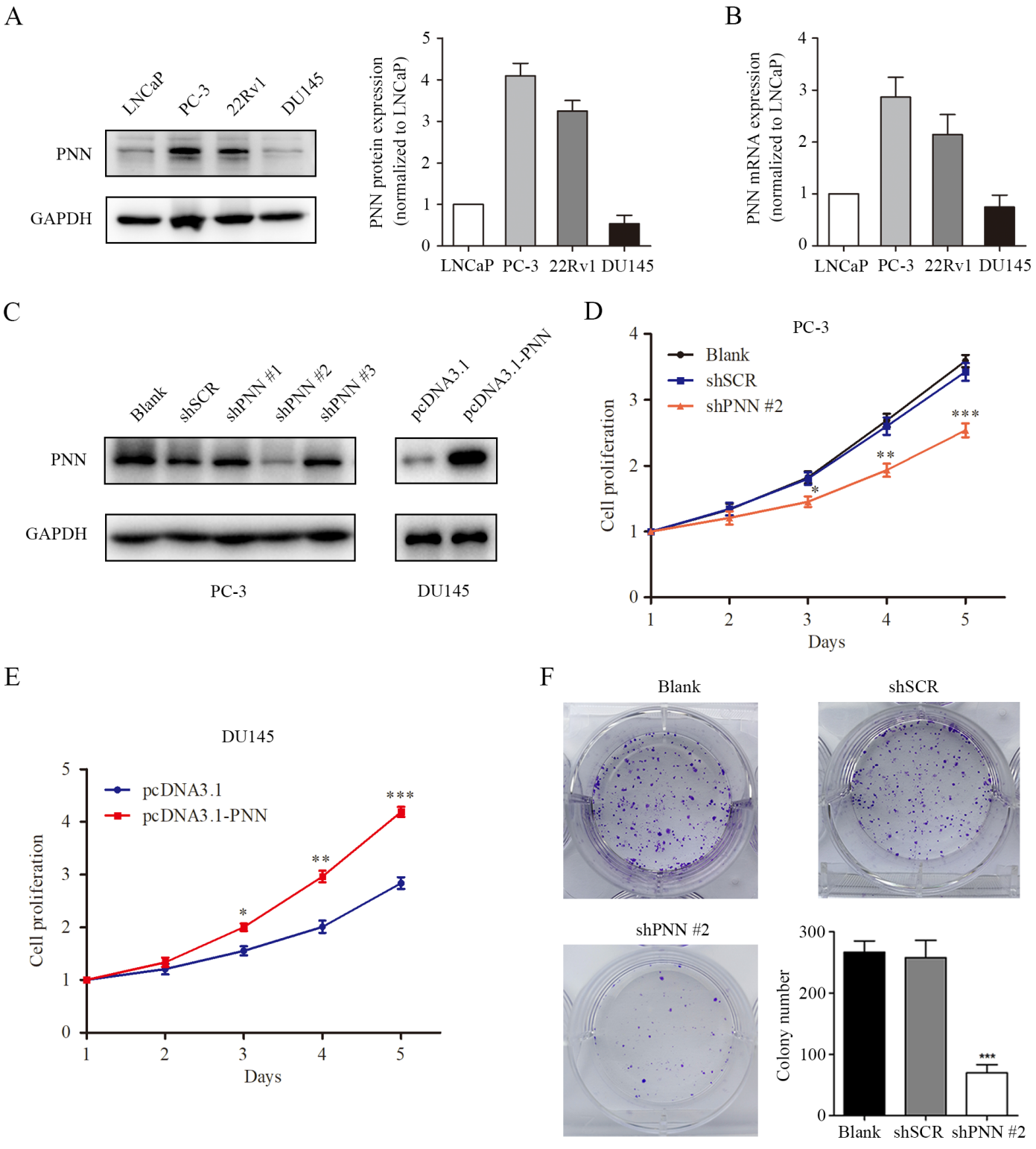

Figure 2

PNN promotes PCa cell proliferation in vitro A. PNN protein levels in prostate cancer cells. B. PNN mRNA expression in prostate cancer cells. C. Verification of PNN protein expression after prostate cancer cells infecting PNN-shRNA-lentivirus or transfecting with PNN over-expression vector (). D. Down-regulation of PNN repressed cell growth in PC-3 cells. E.PNN up-regulation showed proliferation-promoting effect DU145 cells. F. The tumorigenesis ability was reduced in PNN-silenced cells.

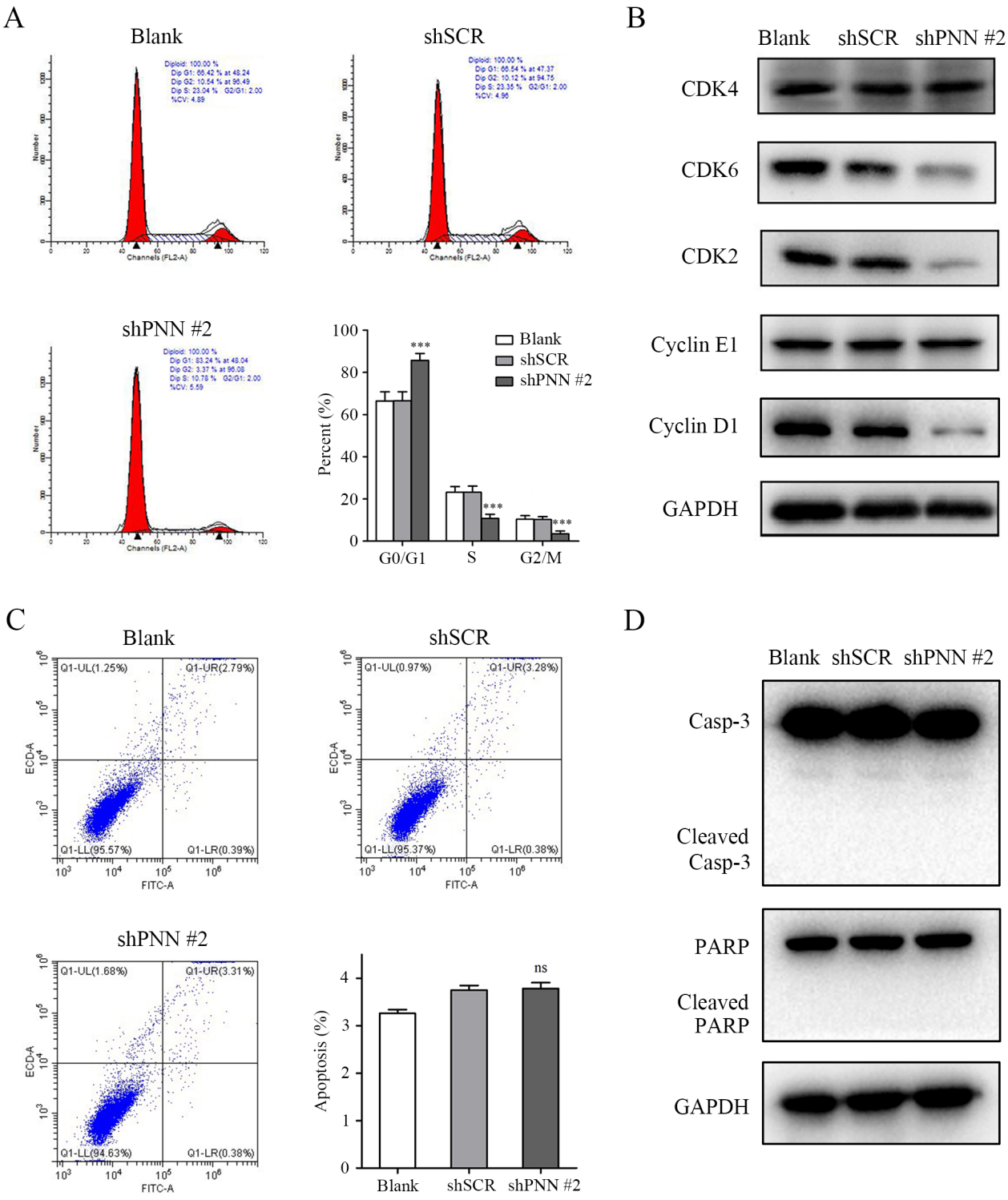

Figure 3

PNN modulates PCa cell growth through cell cycle control A.PNN knockdown induced PC-3 cell arrest at G0/G1 phase. B. Down-regulation of PNN decreased the expression of CDK2, CDK6 and Cyclin D1 in PC-3 cells. C.PNN showed less effect on PCa cell apoptosis. D. Apoptosis related proteins expression followed PNN knockdown.

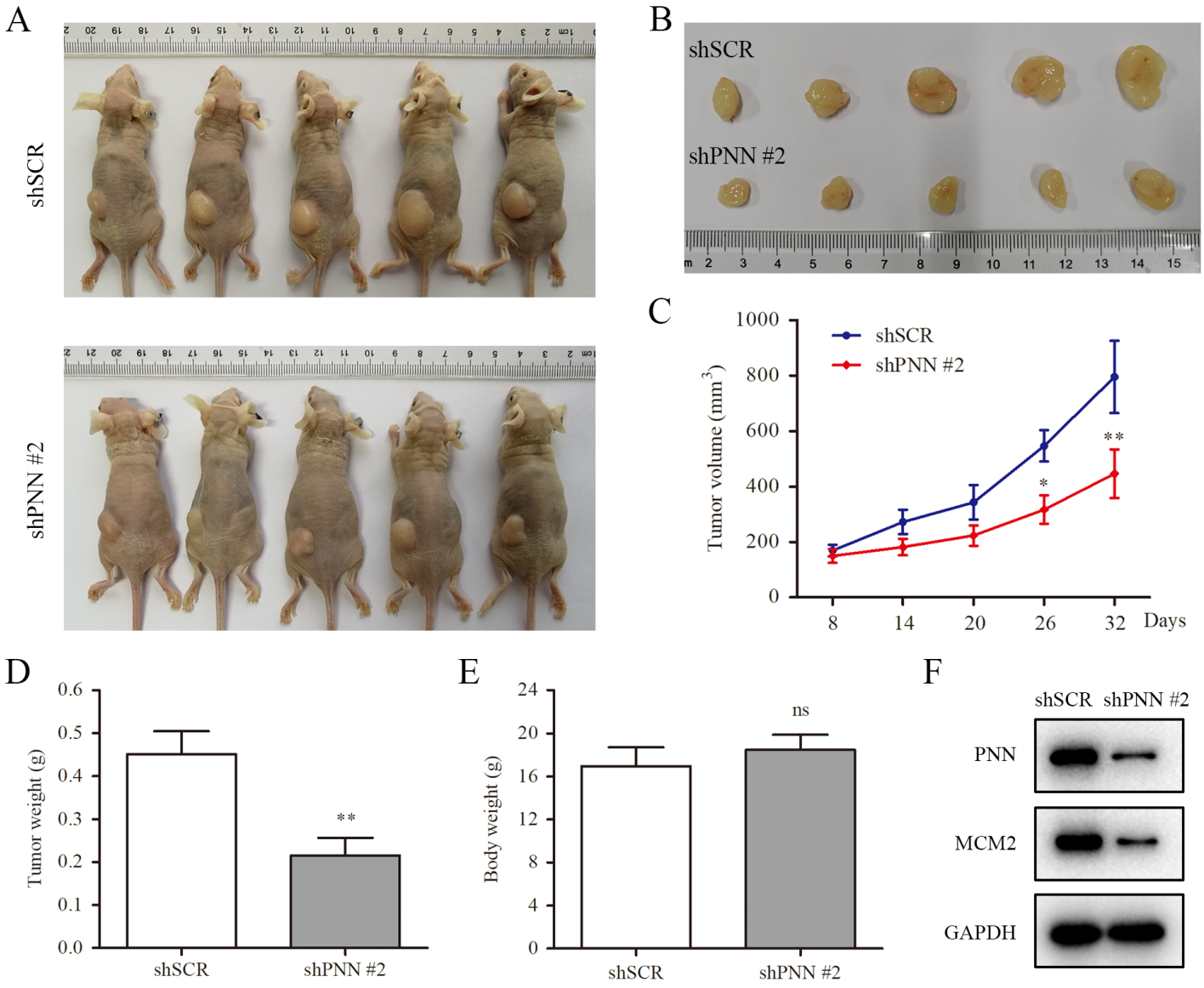

Figure 4

PNN modulates the tumorigenesis of prostate cancer cell in vivo A. Images of nude mice. B. Images of excised tumors from nude mice. C. Tumor growth curves. D. Average weight of xenograft tumor. E. PNN and MCM2 expression in tumors.

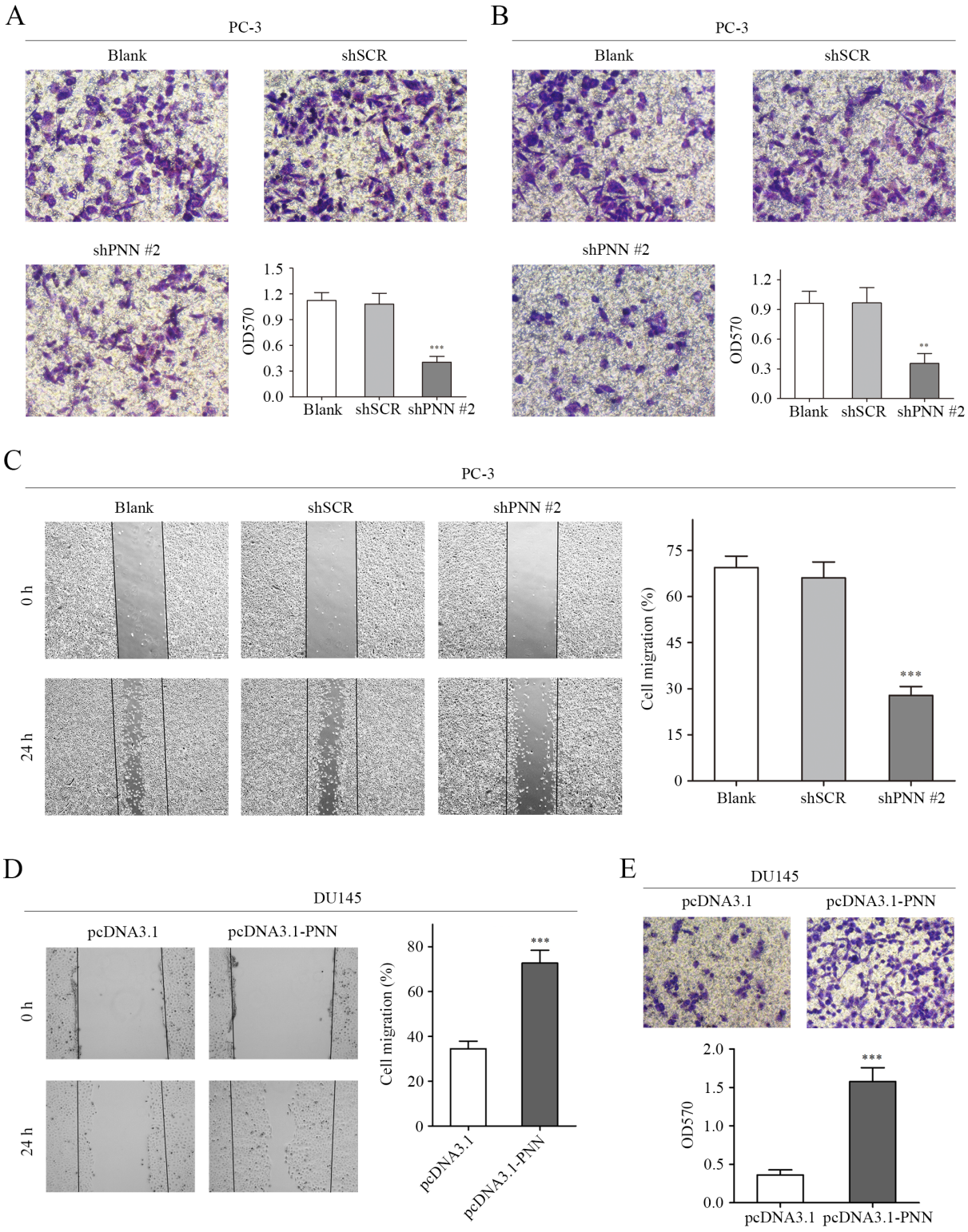

Figure 5

PNN accelerates prostate cancer cell invasion and migration in vitro A. Transwell assay covered with matrigel revealed that PNN down-regulation reduced the invasive ability of PC-3 cells. B and C. Down-regulation of PNN significantly suppressed prostate cancer cell migration in Wound healing assay and Transwell assay. D and E. Wound healing assay and Transwell assay demonstrated that up-regulation of PNN accelerated cell migration and invasion.

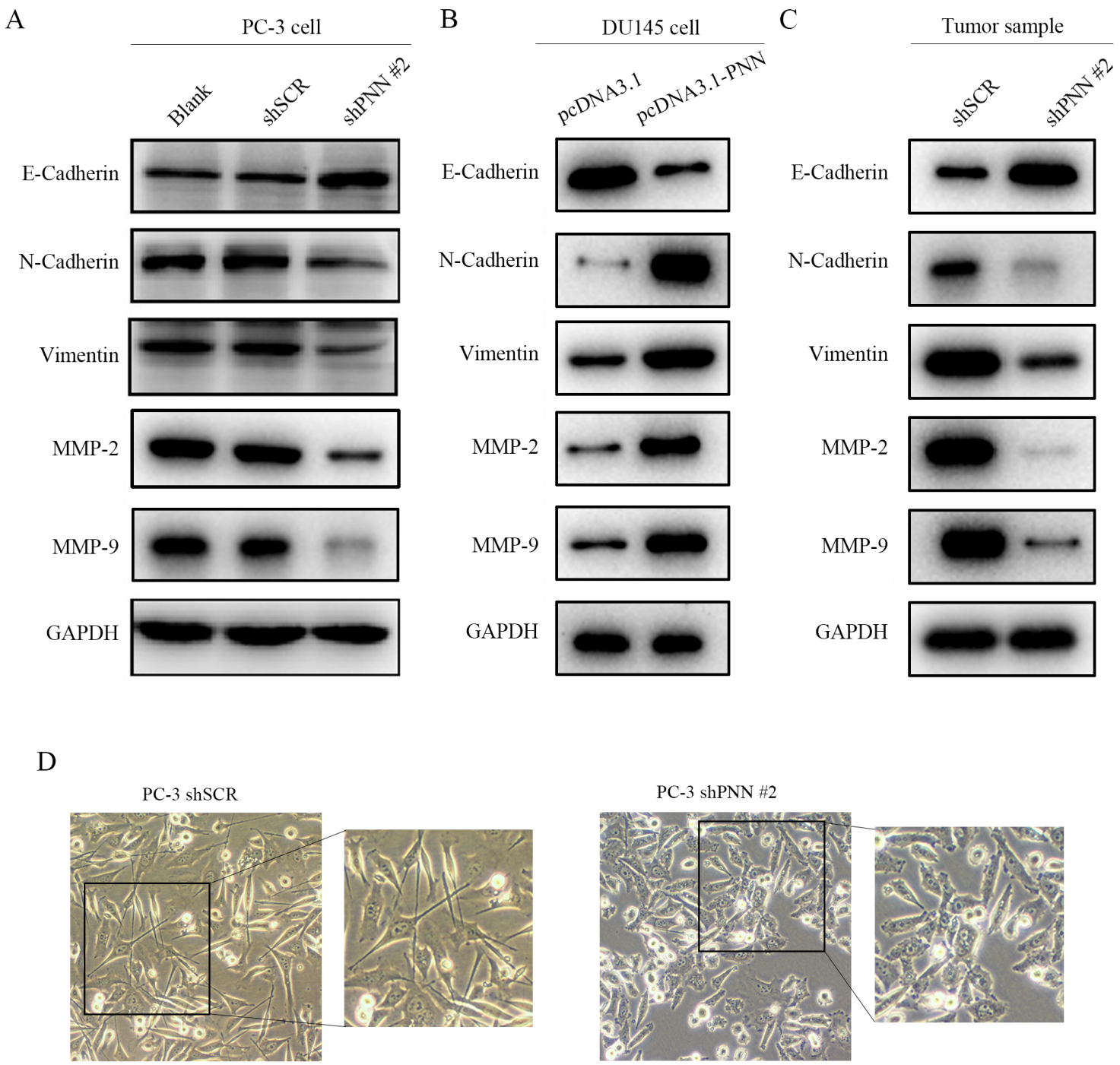

Figure 6

PNN over-expression induces prostate cancer cell EMT A and B. The expression levels of EMT related proteins in prostate cancer cells after altering PNN expression. C.EMT-related proteins level in tumors. D. Down-regulation of PNN induced PC-3 cell morphological changes.

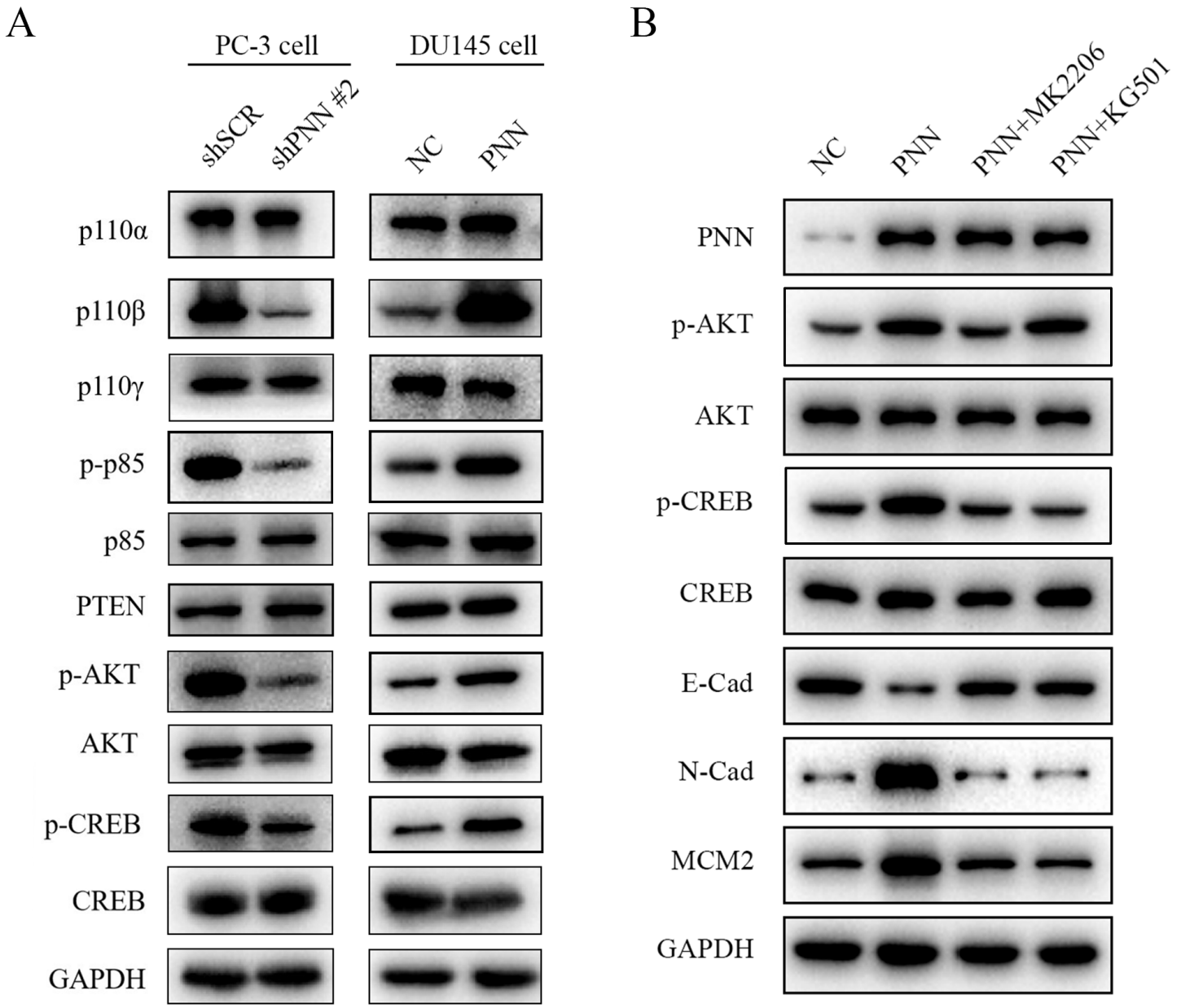

Figure 7

PNN positively regulates PI3K/AKT/CREB signaling in prostate cancer cells A. The activity and levels of proteins in PI3K/AKT/CREB pathway. B. PNN regulates prostate cancer progression via PI3K/AKT/CREB pathway on protein levels. The levels of AKT/CREB axis, EMT markers and cell growth related protein MCM2.

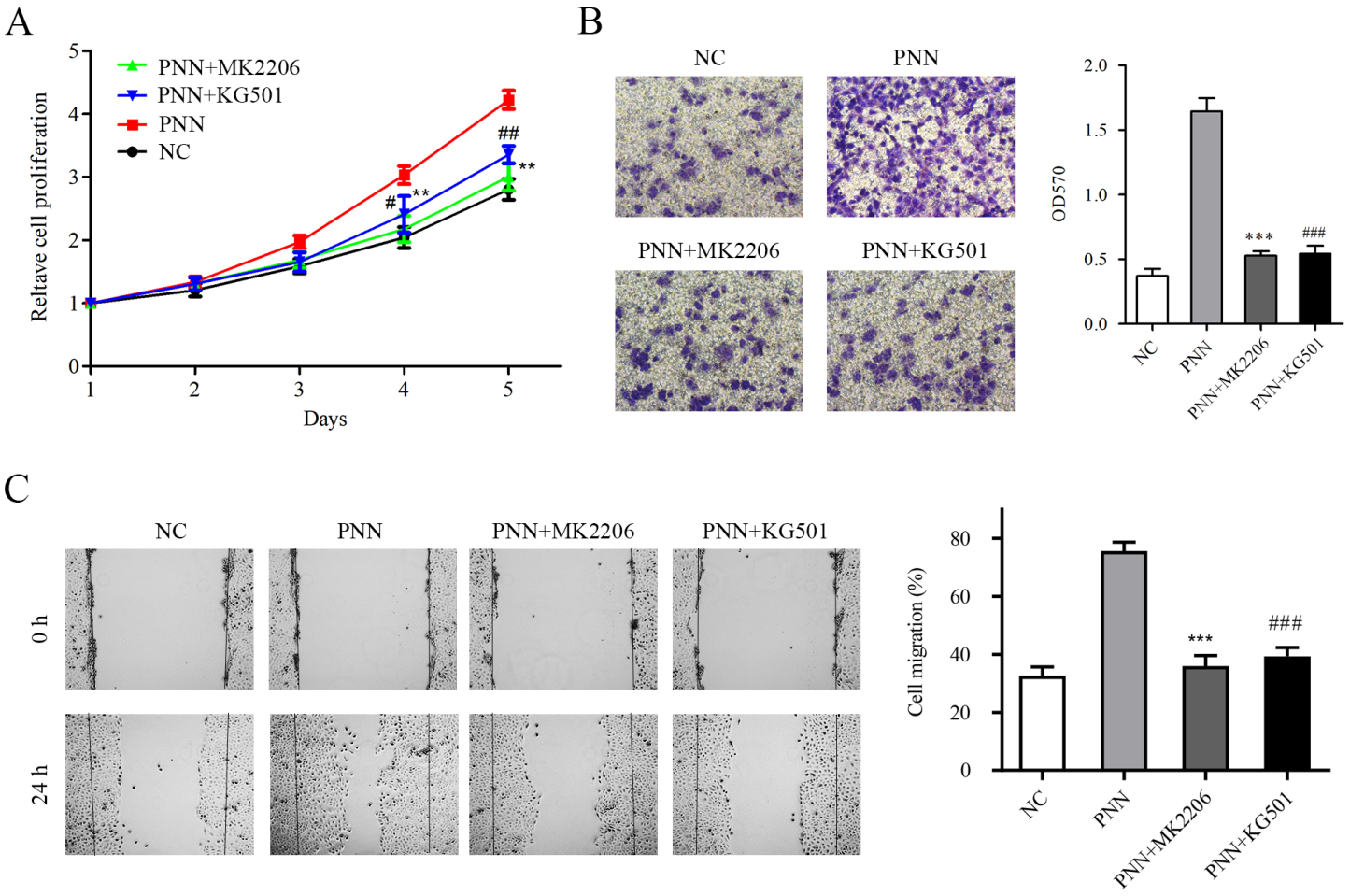

Figure 8

PNN regulates prostate cancer cell proliferation and migration via PI3K/AKT/CREB signaling A. AKT/CREB pathway was involved in PNN-mediated cell proliferation. B. Transwell assay revealed the role of AKT/CREB pathway on cell invasion in prostate cancer cells. C. Wound healing assay revealed the role of AKT/CREB pathway on cell migration in prostate cancer cells.