

Procaine Inhibits the Proliferation and Migration of Colon Cancer Cells Through Inactivation of the ERK/MAPK/FAK Pathways by Regulation of RhoA

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Colon cancer is one of the most lethal varieties of cancer. Chemotherapy remains as one of the principal treatment approaches for colon cancer. The anticancer activity of procaine (PCA), which is a local anesthetic drug, has been explored in different studies. In our study, we aimed to explore the anticancer effect of PCA on colon cancer and its underlying mechanism. The results showed that PCA significantly inhibited cell viability, increased the percentage of apoptotic cells, and decreased the expression level of RhoA in HCT116 cells in a dose-dependent manner ($p < 0.05$ or $p < 0.01$). Moreover, PCA increased the proportion of HCT116 cells in the G₁ phase as well as downregulated cyclin D1 and cyclin E expressions ($p < 0.05$). In addition, we found that PCA remarkably inhibited cell migration in HCT116 cells ($p < 0.01$). However, all these effects of PCA on cell proliferation, apoptosis, and migration were significantly reversed by PCA+pc-RhoA ($p < 0.05$ or $p < 0.01$). PCA also significantly decreased the levels of p-ERK, p-p38MAPK, and p-FAK, but PCA+pc-RhoA rescued these effects. Furthermore, the ERK inhibitor (PD098059), p38MAPK inhibitor (SB203580), and FAK inhibitor (Y15) reversed these results. These data indicate that PCA inhibited cell proliferation and migration but promoted apoptosis as well as inactivated the ERK/MAPK/FAK pathways by regulation of RhoA in HCT116 cells.

Key words: Colon cancer; HCT116; Procaine (PCA); RhoA; ERK/MAPK/FAK

INTRODUCTION

Colon cancer is considered to be one of the most common and lethal varieties of cancer worldwide¹. It is the third most common type of cancer after lung cancer and breast cancer¹⁻³. Colon cancer is the second most common cause for cancer-related deaths⁴. Colon cancer is primarily epithelial in nature, and mutations in different signaling pathways are mainly responsible for its origin¹. Many patients are diagnosed in the later stages of this disease: 35% in stage IV and 20%–50% in stage II or III⁵. Colon cancer metastasizes mainly to the liver and lung, and the 5-year survival rate is less than 10%⁵.

Currently, a variety of treatment modalities are available for the management of colon cancer⁶⁻⁸. These include surgery, chemotherapy, and radiotherapy, as well as newer treatment modalities like radiofrequency ablation, cryosurgery, and targeted drug therapy⁶⁻⁸. Chemotherapy is considered to be the preferred treatment option as it not only improves quality of life but is also convenient to administer⁹. However, conventional chemotherapeutic drugs often

fail to achieve the desirable effects as only a small amount of the drug reaches the disease site. Hence, a search for newer drugs for the management of colon cancer is of utmost importance¹⁰. An understanding of the underlying molecular mechanisms plays an important role in the identification of novel drug targets.

Studies have already established the implicating role of secreted Wingless (Wnt) type ligands in tumorigenesis and the aberrant methylation of the promoter region of WIF-1 (Wnt inhibitory factor). This is known to be one of the important ways of epigenetic silencing in cancer. Procaine (PCA), a local anesthetic drug mainly used in oral surgeries especially during tooth extraction, is known to be an inhibitor of DNA methylation and thereby suggests a protective role in lung cancer^{4,11}. The antitumor activity of PCA, mainly in combination with cisplatin, has been established in different studies¹¹⁻¹⁶.

RhoA is a member of the Rho family of GTPases, which is a relatively small family of G proteins. This family is mainly responsible for the regulation of certain

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physiological functions like cell movement, dynamics of actin, transcription of a number of genes, and progression of the cell cycle. Several studies have reported a high expression of RhoA in different malignant tumors and also described its active role in different signaling pathways that are implicated in tumorigenesis. Suppression of the Rho pathway has improved the outcomes in different varieties of cancers like hepatocellular, gastric, colon, and lung cancers¹⁷⁻²¹.

Therefore, in this study we explored the underlying mechanism of the action of PCA as an anticancer drug along with exploration of its role in the regulation of RhoA in colon cancer.

MATERIALS AND METHODS

Cell Culture and Treatment

Human colon carcinoma (HCT116) cells were purchased from the American Type Culture Collection (ATCC; Manassas, VA, USA). HCT116 cells were cultured in McCoy's 5A, and the medium was supplemented with 10% heat-inactivated fetal bovine serum (FBS; Sigma-Aldrich, St. Louis, MO, USA), 1% penicillin/streptomycin (100 µg/ml; PAA Laboratories, Westborough, MA, USA), and 1% amphotericin B (250 µg/ml; PAA Laboratories). Cells were plated at a density of 5.0×10^5 cells/100-mm dish and cultured for 24 h, followed by culture with PCA hydrochloride (Sigma-Aldrich) at corresponding concentrations (0.5, 1, 1.5, and 2 µM). Culture medium with or without the drug was changed every 24 h.

Plasmid Transfection

A RhoA expression vector (pc-RhoA) was constructed by subcloning the full-length wild-type RhoA coding sequence into pcDNA3.1 (+) and was confirmed by sequencing. The empty construct pcDNA3.1 was transfected as a control. Cell transfections were conducted using Lipofectamine 3000 reagent (Invitrogen, Grand Island, NY, USA) following the manufacturer's protocol.

CCK-8 Assay

HCT116 cells were seeded into 96-well plates with 5,000 cells/well. Cell viability was assessed by a cell counting kit-8 (CCK-8; Dojindo Molecular Technologies, Gaithersburg, MD, USA). Briefly, after transfection for 48 h, the 10-µl CCK-8 solution was added to the culture medium, and the cultures were incubated for 1 h at 37°C in humidified 95% air and 5% CO₂. The absorbance was measured at 450 nm using a microplate reader (Bio-Rad, Hercules, CA, USA).

Apoptosis Assay

Apoptosis analysis was performed to identify and quantify the apoptotic cells using Annexin-V-FITC/propidium iodide (PI) apoptosis detection kit (Beijing

Biosea Biotechnology, Beijing, P.R. China). The cells (1.0×10^5 cells/well) were seeded into six-well plates. Treated cells were washed twice with cold phosphate-buffered saline (PBS) and resuspended in a buffer. The adherent and floating cells were combined and treated according to the manufacturer's instructions and measured with a flow cytometer (Beckman Coulter, Schaumburg, IL, USA) to differentiate apoptotic cells (annexin V⁺ and PI⁻) from necrotic cells (annexin V⁺ and PI⁺).

Cell Cycle Assay

For analysis of the cell cycle, cells with different treatments were trypsinized, washed twice in PBS, and fixed overnight at -20°C in 300 µl of PBS and 700 µl of ethanol. The fixed cells were spun down gently in 200 µl of extraction buffer (0.1% Triton X-100, 45 mM Na₂HPO₄, and 2.5 mM sodium citrate) at 37°C for 20 min and then stained with PI (BD Biosciences, San Jose, CA, USA) (50 µg/ml) containing 50 µg/ml RNase A for 30 min at 37°C in the dark, and subsequently analyzed by FACS. The experiment was repeated at least three times, and the data were analyzed using the CellQuestk and ModFitk software.

Migration Assay

Cell migration was determined using a modified two-chamber migration assay with a pore size of 8 µm. For the migration assay, HCT116 cells suspended in 200 µl of serum-free medium were seeded onto the upper compartment of a 24-well Transwell culture chamber, and 600 µl of complete medium was added to the lower compartment. After 12 h of incubation at 37°C, cells were fixed with methanol. Cells that did not migrate were removed from the upper surface of the filter carefully with a cotton swab. Traversed cells on the lower side of the filter were stained with crystal violet and counted.

Quantitative Real-Time PCR (qRT-PCR)

Total RNA was isolated from transfected cells using TRIzol reagent (Invitrogen) and treated with DNaseI (Promega, Madison, WI, USA). Reverse transcription was performed using the MultiScribe RT Kit (Applied Biosystems, Foster City, CA, USA) and random hexamers or oligo (dT). The reverse transcription conditions were 10 min at 25°C, 30 min at 48°C, and a final step of 5 min at 95°C. The sequences of the primers were as follows: RhoA, 5'-AGA GGT GTA TGT GCC CAC AGT-3' (forward) and 5'-CTT CGG AAT GAT GAG CAC AC-3' (reverse); GAPDH, 5'-GCA CCG TCA AGG CTG AGA AC-3' (forward) and 5'-TGG TGA AGA CGC CAG TGG A-3' (reverse).

Western Blotting

The protein used for Western blotting was extracted using RIPA lysis buffer (Beyotime Biotechnology,

Shanghai, P.R. China) supplemented with protease inhibitors (Roche, Guangzhou, P.R. China). The proteins were quantified using the BCA™ Protein Assay Kit (Pierce, Appleton, WI, USA). The Western blot system was established using a Bio-Rad Bis-Tris Gel system according to the manufacturer's instructions. Primary antibodies of RhoA (ab86297), p53 (ab131442), p21 (ab219811), BCL-2-associated X (Bax; ab32503), B-cell lymphoma 2 (Bcl-2; ab32124), cyclin D1 (ab61758), cyclin E (ab88259), p-AKT (Thr308; ab38449), extracellular signal-regulated kinase (ERK; ab214362), t-ERK (ab196883), phosphorylated (p)-p38MAPK (ab4822), t-p38MAPK (ab31828), p-FAK (ab39967), t-FAK (ab61113) and GAPDH (ab8245; Abcam, Cambridge, UK), p-AKT (Ser473, P4112; Sigma-Aldrich), and t-AKT (#4691; Cell signaling Technology, Danvers, MA, USA) were used for chromatin immunoprecipitation. Primary antibodies were prepared in 5% blocking buffer at a dilution of 1:1,000. Primary antibodies were incubated with the membrane at 4°C overnight, followed by washing and incubation with a secondary antibody marked by horseradish peroxidase for 1 h at room temperature. After rinsing, the polyvinylidene difluoride (PVDF) membrane carried blots and antibodies were transferred into the Bio-Rad ChemiDoc™ XRS system, and then 200 µl of Immobilon Western Chemiluminescent HRP Substrate (Millipore, Boston, MA, USA) was added to cover the membrane surface. The signals were captured, and the intensity of the bands was quantified using Image Lab™ Software (Bio-Rad, Shanghai, P.R. China).

Statistical Analysis

All experiments were repeated three times. The results of multiple experiments are presented as mean±SD. Statistical analyses were performed using GraphPad 6.0 statistical software (GraphPad Software, San Diego, CA, USA). The values of *p* were calculated using one-way analysis of variance (ANOVA). A value of *p*<0.05 was considered to indicate a statistically significant result.

RESULTS

PCA Inhibited Cell Viability and Promoted Apoptosis in HCT116 Cells

HCT116 cells were exposed to increasing concentrations of PCA, ranging between 0.5 and 2 µM. Results revealed that cell viability of HCT116 cells was significantly decreased at 1.5 and 2 µM PCA (*p*<0.05 or *p*<0.01) (Fig. 1A). The percentage of apoptotic cells was significantly increased following exposure to different concentrations of PCA: 1, 1.5, and 2 µM (*p*<0.05 or *p*<0.01) (Fig. 1B). These data indicate that PCA inhibits cell viability but promotes apoptosis in a dose-dependent manner.

PCA Inhibited the Expression of RhoA in HCT116 Cells

qRT-PCR assay was used to analyze the expression levels of RhoA after exposure to different concentrations of PCA. RhoA mRNA expression was significantly decreased following exposure to increasing concentrations of PCA: 1, 1.5, and 2 µM (*p*<0.05 or *p*<0.01) (Fig. 2A). However, there was no obvious difference at 0.5 µM PCA. Furthermore, Western blot analysis revealed that the expression of RhoA protein was decreased following exposure to PCA in a dose-dependent manner (Fig. 2B). The results demonstrate that PCA can suppress

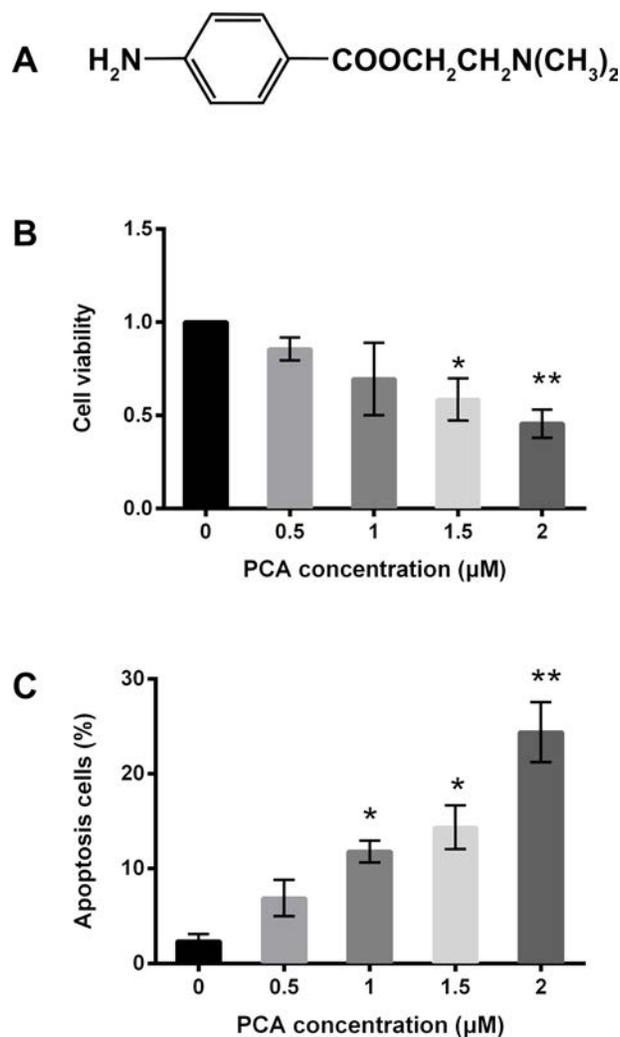


Figure 1. Procaine (PCA) inhibited cell viability and promoted apoptosis in HCT116 cells. (A) The molecular structural formula of PCA. (B) PCA significantly inhibited cell viability at the concentrations of 1.5 and 2 µM. (C) PCA significantly promoted cell apoptosis at the concentrations of 1, 1.5, and 2 µM. **p*<0.05, ***p*<0.01.

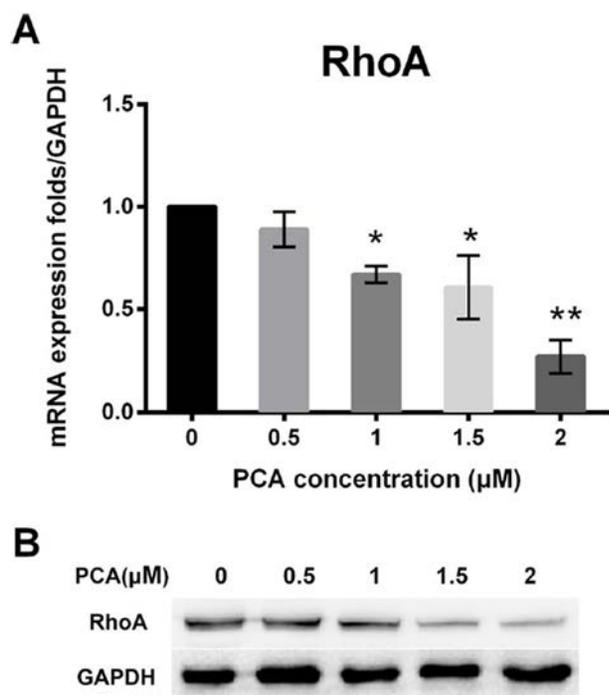


Figure 2. PCA inhibited the expression of RhoA in HCT116 cells. (A) PCA inhibited the mRNA expression level of RhoA at the concentrations of 1, 1.5, and 2 μM . (B) PCA inhibited the protein expression level of RhoA at the concentrations of 1, 1.5, and 2 μM . * $p < 0.05$, ** $p < 0.01$.

RhoA expression in a dose-dependent manner. Thus, 2 μM PCA was used for further investigations.

RhoA Overexpression Upregulated RhoA Expression in HCT116 Cells

The expression levels of RhoA were assessed in HCT116 cells following transfection with RhoA expression vector (pc-RhoA group of cells) and control group of cells (HCT116 cells transfected with empty construct pcDNA3.1). The expression of RhoA was significantly higher in the pc-RhoA group compared to the control group ($p < 0.05$) (Fig. 3A). Western blot analysis revealed consistent results with qRT-PCR in that the expression of RhoA was higher in the pc-RhoA group compared to the control group (Fig. 3B). The results indicate that the transfection efficiency of pc-RhoA is high and can be used for further study.

PCA Inhibited Cell Viability and Promoted Apoptosis by Regulation of RhoA

The cell viability assay revealed that cotransfecting with PCA and RhoA overexpression (PCA+pc-RhoA) significantly promoted cell viability compared to the HCT116 group of cells that were transfected with empty construct pcDNA3.1 and PCA (PCA+pcDNA3.1)

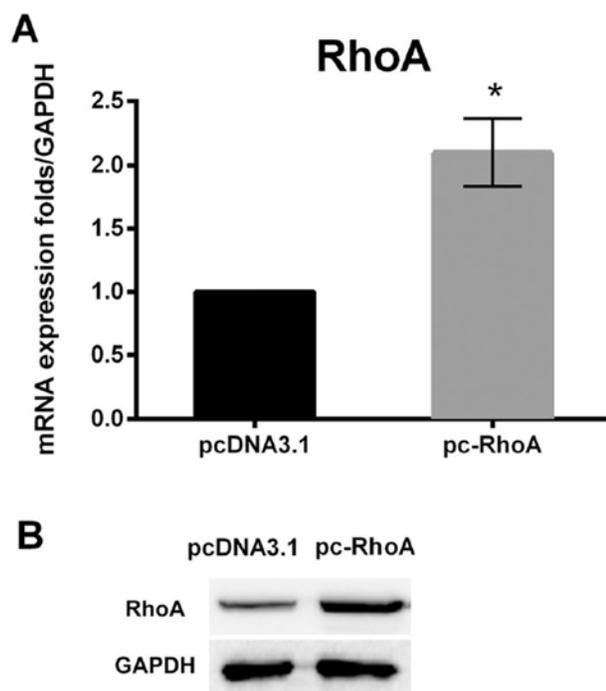


Figure 3. RhoA overexpression upregulated RhoA expression in HCT116 cells. (A) The level of RhoA mRNA was significantly upregulated by pc-RhoA. (B) The level of RhoA protein was significantly upregulated by pc-RhoA. * $p < 0.05$.

(Fig. 4A). The apoptosis assay revealed that the percentage of apoptotic cells was significantly increased in HCT116 cells treated with PCA, whereas cotransfection with PCA and RhoA overexpression significantly decreased the percentage of apoptotic cells compared to the control group ($p < 0.05$ or $p < 0.01$) (Fig. 4B). In addition, the qRT-PCR results revealed that PCA significantly upregulated the mRNA expressions of p53, p21, and proapoptotic factor Bax but downregulated Bcl-2 expression compared with the control ($p < 0.05$). However, cotransfection with PCA and RhoA overexpression abolished the regulatory effect of PCA on expressions of these four factors ($p < 0.05$) (Fig. 4C). In terms of the protein levels of p53, p21, Bax, and Bcl-2, the Western blot assay showed a coinciding result (Fig. 4D). These results imply that PCA inhibits cell viability but promotes apoptosis by regulation of RhoA.

PCA Arrested the Cell Cycle at the G₁ Stage and Suppressed Cell Migration by Regulating RhoA

The cell cycle assay revealed that PCA prominently increased the proportion of HCT116 cells in the G₁ phase when compared with its control ($p < 0.05$) (Fig. 5A). Moreover, the qRT-PCR and Western blot assays showed that PCA downregulated the cell cycle-related factors of cyclin D1 and cyclin E expressions. However, these effects were reversed by transfection with RhoA overexpression

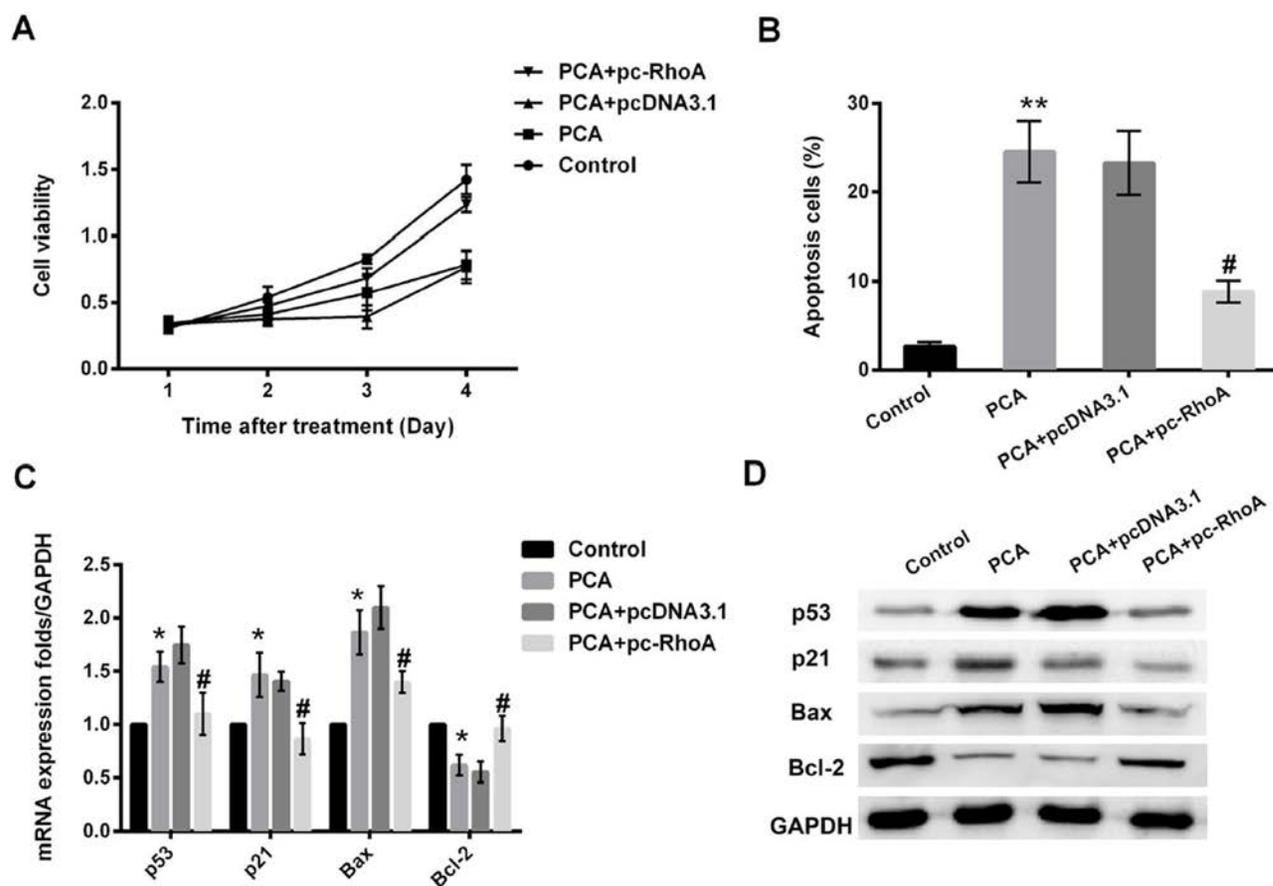


Figure 4. PCA inhibited cell viability and promoted apoptosis by regulating RhoA. (A) PCA+pc-RhoA remarkably promoted cell viability compared to PCA+pcDNA3.1. (B) PCA+pc-RhoA remarkably inhibited cell apoptosis compared to PCA+pcDNA3.1. (C) PCA+pc-RhoA downregulated p53, p21, and Bax mRNA expressions and upregulated Bcl-2 mRNA expression compared to PCA+pcDNA3.1. (D) PCA+pc-RhoA downregulated p53, p21, and Bax protein expressions and upregulated Bcl-2 protein expression compared to PCA+pcDNA3.1. * $p < 0.05$, ** $p < 0.01$ for PCA compared with the control; # $p < 0.05$ for PCA+pc-RhoA compared with PCA+pcDNA3.1.

($p < 0.05$) (Fig. 5B and C). In addition, PCA remarkably inhibited cell migration in HCT116 cells compared to its control ($p < 0.01$). However, these effects were also reversed by transfection with RhoA overexpression (Fig. 5D). These data indicate that PCA might arrest the cell cycle at the G_1 phase and suppress cell migration by regulating RhoA.

PCA Inactivated the ERK/MAPK/FAK Signal Pathways by Regulating RhoA

In the AKT signal pathway, the expression levels of p-AKT (p473) and p-AKT (p308) were similar in different groups of control cells, PCA, PCA+pc-DNA3.1, and PCA+RhoA (Fig. 6A). Consistent results were obtained by Western blot analysis (Fig. 6B). In the ERK, MAPK, and FAK signaling pathways, the expression levels of p-ERK, p-p38MAPK, and p-FAK were significantly decreased by PCA compared to their corresponding

control (all $p < 0.05$). Cotransfection with PCA and RhoA overexpression obviously improved the expression levels of p-ERK, p-p38MAPK, and p-FAK factors compared to PCA together with the empty construct pcDNA3.1 groups (all $p < 0.05$). Simultaneously, the activation effect was reversed by inhibitors of ERK1/2 (PD098059), p38MAPK (SB203580), and FAK (Y15). The expression levels of t-ERK, t-p38MAPK, and t-FAK showed no significant changes in the different groups. Consistent results were obtained by Western blot analysis (Fig. 6C–H). These data show that PCA can inactivate the ERK/MAPK/FAK signaling pathways by regulating RhoA.

DISCUSSION

Several studies have explored the anticancer effects of the local anesthetic agent PCA in different types of cancers^{11–16}. Viale et al. explored the role of the

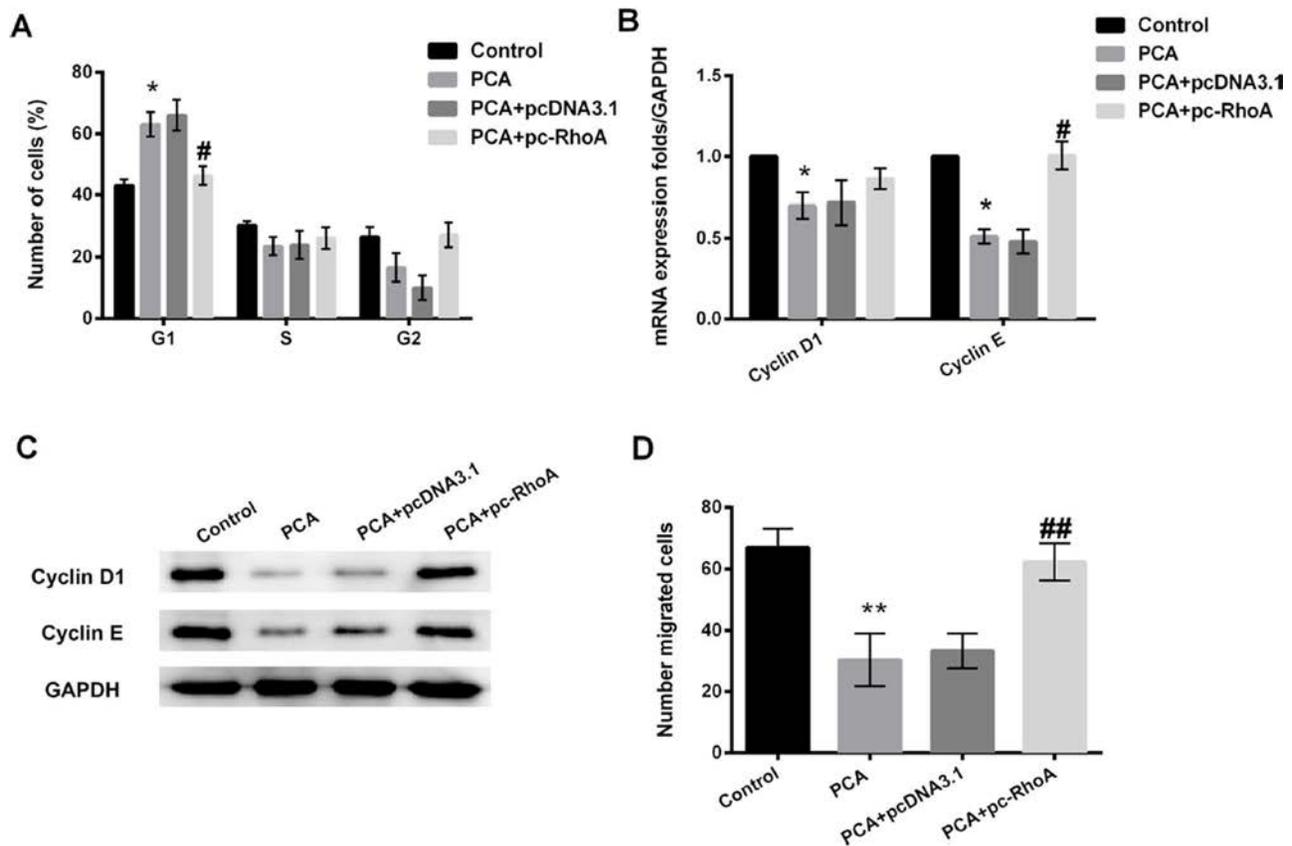


Figure 5. PCA arrested the cell cycle at the G_1 stage and suppressed cell migration by regulating RhoA. (A) PCA increased the proportion of HCT116 cells in the G_1 phase when compared with the control. (B) PCA downregulated the expressions of cyclin D1 and cyclin E mRNAs. (C) PCA reduced the expressions of cyclin D1 and cyclin E proteins. (D) PCA remarkably inhibited cell migration in HCT116 cells compared to the control. * $p < 0.05$, ** $p < 0.01$ for PCA compared to control; # $p < 0.05$ for PCA+pc-RhoA compared with PCA+pcDNA3.1; ## $p < 0.01$ for PCA+pc-RhoA compared with PCA+pcDNA3.1.

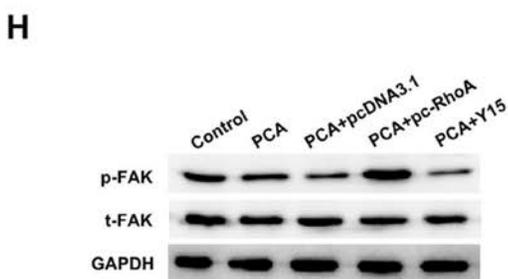
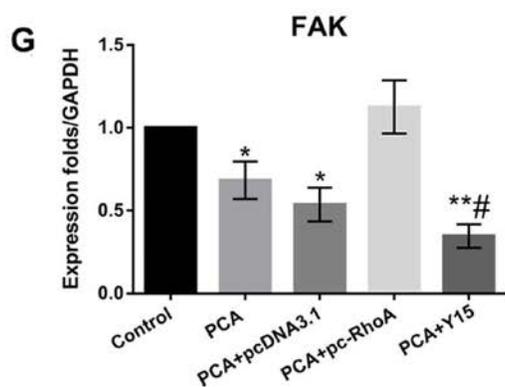
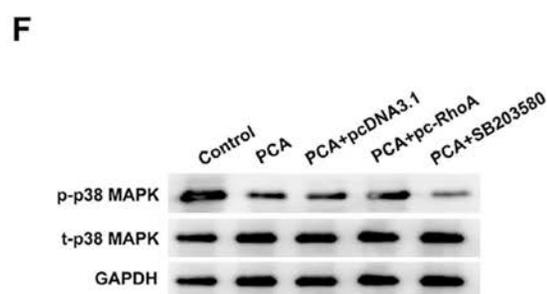
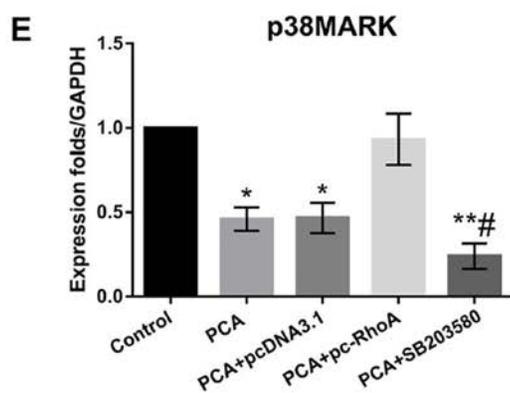
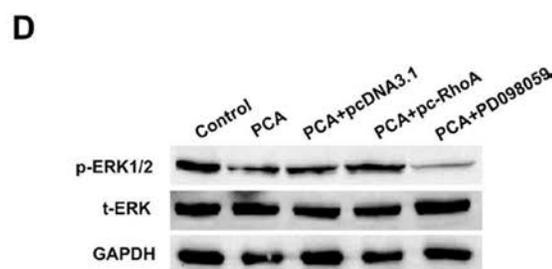
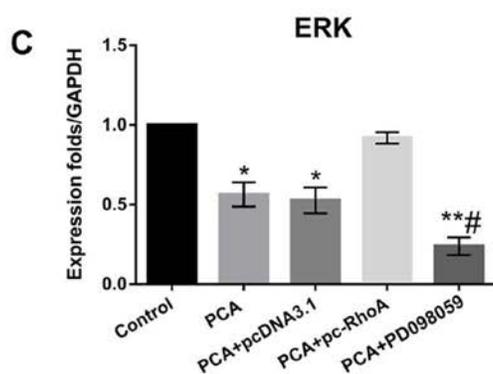
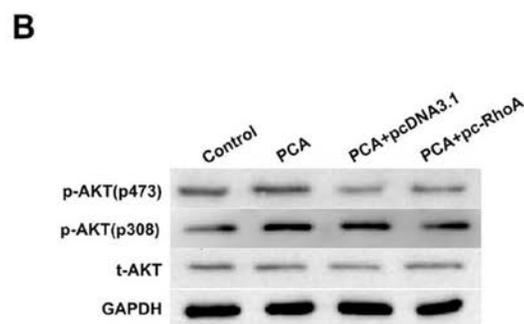
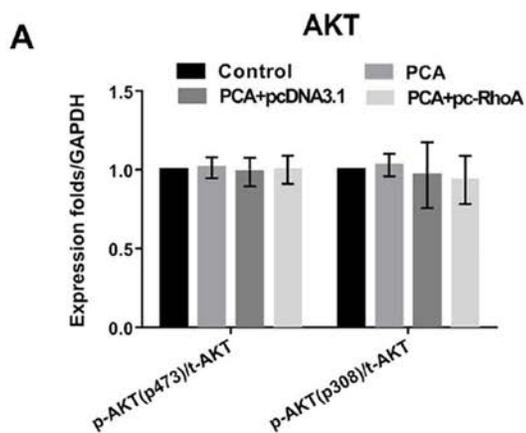
cisplatin-PCA combination complex *cis*-diamminechloro-[2-(diethylamino) ethyl 4-amino-benzoate, N4]-chloride platinum (II) monohydrochloride monohydrate (DPR) with other anticancer drugs in ovarian cell lines¹³. They demonstrated that DPR, when combined with other conventional anticancer drugs like 5-fluorouracil, doxorubicin, mitomycin C, and cisplatin, showed a synergistic effect in human and murine ovarian cancer cells¹³. Similarly, Pastrone et al. also demonstrated that cisplatin-PCA combined with DPR, when administered with other anticancer drugs like mitomycin C, demonstrated therapeutic advantages over treatment with mitomycin C alone²². Sabit et al. explored the role of PCA alone and in combination with other chemotherapeutic drugs in colon

cancer⁴. They demonstrated that PCA with carboplatin was the most effective treatment⁴. In this study, we have demonstrated that PCA significantly decreased cell viability but increased apoptosis in a dose-dependent manner in HCT116 cells. Similar to our findings, Sabit et al. also showed that PCA treatment decreased the cell viability of HCT116 cells in a dose-dependent manner and also when administered alone and in combination with other anticancer drugs⁴.

RhoA is a family of GTPases. Several studies have demonstrated a high expression of RhoA in different cancer cells, such as colon, lung, ovarian, gastric, and liver cancers¹⁸⁻²¹. In terms of colon cancer, several studies have reported that the expression of RhoA in colon

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Figure 6. PCA inactivated the ERK/MAPK/FAK signaling pathways by regulating RhoA. (A) PCA had no effect on the AKT pathway. (B) PCA had no effect on the expression of AKT pathway-associated proteins. (C-H) mRNA and protein levels of the ERK p38MAPK and FAK pathway-associated factors were increased by PCA+pc-RhoA, but the activation effect was reversed by inhibitors of ERK1/2 (PD098059), p38MAPK (SB203580), and FAK (Y15). * $p < 0.05$, ** $p < 0.01$ when compared with the control group, # $p < 0.05$ when compared with the PCA group.



cancer was higher compared to their corresponding control group of cells²³. Also, the incidence of lymphatic metastasis was much higher in colon cancer patients with an increased expression of RhoA. The activity of RhoA was correlated with lymph node metastasis in human colorectal cancer²³.

Yao et al. demonstrated that α -tocopherol ether-linked acetic acid (α -TEA) inhibited cell proliferation, migration, and invasion in colon cancer via downregulation of the activity of RhoA¹⁹. Li et al. also demonstrated that miR-126 suppressed colon cancer proliferation and migration by suppressing the RhoA signaling pathway²⁰. In our study, we found that the expression of RhoA was significantly increased in HCT116 cells following exposure to PCA in a dose-dependent manner. Moreover, we found that PCA treatment decreased cell viability, promoted apoptosis, arrested the cell cycle at the G₁ stage, and suppressed cell migration in HCT116 cells by regulating RhoA. Similar to our findings, several studies have shown that PCA suppressed cell proliferation, promoted apoptosis, and arrested the cell cycle, especially in lung cancer^{14,15}.

The role of inactivating the AKT, ERK, MAPK, and FAK signaling pathways in the suppression of colon cancer progression has been explored in different studies^{24–26}. Zhang et al. described in their study that the anticancer role of miR-218 in colon cancer was mediated via suppression of the AKT pathway²⁴. Gupta et al. also demonstrated that pharmacological inhibition of the MAPK pathway reduced the growth of tumor cells in colon tumors²⁵. Song et al. demonstrated that the tissue inhibitor matrix metalloproteinase 1 (TIMP1) plays a vital role in colon cancer progression²⁶. They also demonstrated that the FAK-PI3K/AKT and MAPK signaling pathways facilitate TIMP1-induced cell proliferation, metastasis, and antiapoptotic effects in colon cancer cells. In addition, several studies have reported that inhibiting ERK, MAPK, and FAK could be involved in cell proliferation, apoptosis, and metastasis. For example, it has been proven that the FAK inhibitor (Y15) inhibits cell viability and promotes detachment and apoptosis in colon cancer²⁷. Similar to previous studies, our results demonstrate that PCA+RhoA can activate ERK, p38MAPK, and FAK. However, the activation effects are reversed by inhibitors of ERK1/2 (PD098059), p38MAPK (SB203580), and FAK (Y15).

In conclusion, our study demonstrates that PCA inhibits cell proliferation and migration, promotes apoptosis, and inactivates the ERK, p38MAPK, and FAK pathways by regulating RhoA in HCT116 cells. These data provide a new insight in the treatment of colon cancer. Further studies are required to explore the anticancer properties of PCA in colon cancer.

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