Original Article

Physcion inhibits the metastatic potential of human colorectal cancer SW620 cells *in vitro* by suppressing the transcription factor SOX2

Yan-tao HAN, Xue-hong CHEN*, Hui GAO, Jun-li YE, Chun-bo WANG

Medical College of Qingdao University, Qingdao 266071, China

Aim: Physcion, an anthraquinone derivative, exhibits hepatoprotective, anti-inflammatory, anti-microbial and anti-cancer activities. In this study we examined whether and how physcion inhibited metastatic potential of human colorectal cancer cells *in vitro*.
Methods: Human colorectal cancer cell line SW620 was tested. Cell migration and invasion were assessed using a wound healing and Transwell assay, respectively. The expression levels of transcription factor SOX2 in the cells were modulated with shRNA targeting SOX2 and SOX2 overexpressing plasmid. The expression of target molecules involved in epithelial-mesenchymal transition (EMT) process and the signaling pathways was determined with Western blots or qRT-PCR. ROS levels were measured using DCF-DA.
Results: Physcion (2.5, 5 mol/L) did not affect the cell viability, but dose-dependently inhibited the cell adhesion, migration and invasion. Physcion also inhibited the EMT process in the cells, as evidenced by the increased epithelial marker E-cadherin expression, and by decreased expression of mesenchymal markers N-cadherin, vimentin, fibronectin and α-SMA, as well as transcriptional repressors Snail, Slug and Twist. Physcion suppressed the expression of SOX2, whereas overexpression of SOX2 abrogated the inhibition of physcion on metastatic behaviors. Physcion markedly increased ROS production and phosphorylation of AMPK and GSK3β in the cells, whereas the AMPK inhibitor compound C or the ROS inhibitor NAC abolished the inhibition of physcion on metastatic behaviors.
Conclusion: Physcion inhibits the metastatic potential of human colorectal cancer cells *in vitro* via activating ROS/AMPK/GSK3β signaling pathways and suppressing SOX2.

Keywords: physcion; anthraquinone; human colorectal cancer cell line SW620; metastasis; EMT process; SOX2; ROS; AMPK; GSK3β

Introduction

Colorectal cancer (CRC) is one of leading causes of cancer-related death in the world[1]. Clinical studies showed that in most patients, colorectal cancer has metastasized, which indicates that the development of metastasis is a major determinant of survival[2]. These facts suggest that the discovery and development of a safe and effective drug aimed to suppress metastasis may potentially enhance the therapeutic outcome for patients with CRC.

Cancer metastasis is a highly coordinated sequential process that includes the invasion of cancer cells into the surrounding tissue, survival in the circulatory system, penetration of the walls of lymphatic and/or blood vessels, and the growth of a macroscopic secondary tumor in distant organs[3]. Given the high aggressiveness of CRC, many efforts have been made

to identify the factors involved in metastasis, which can later serve as targets for chemotherapy. Sex determining region Y box 2(SOX2) encodes a protein consisting of 317 amino acids and belongs to the SOX (SRY-related high mobility group box) family of transcription factors[4]. SOX2 plays a pivotal role in the maintenance of the self-renewal and pluripotency of embryonic stem cells and in the production of induced pluripotent stem cells[5, 6]. Interestingly, strong SOX2 expression is associated with many types of human solid tumors, including lung cancer, breast cancer, ovarian carcinoma, pancreatic carcinoma and esophageal carcinoma[7]. Furthermore, recent studies have shown that SOX2 is involved in the biological behaviors of a variety of human malignancies, including proliferation[8], apoptosis[9, 10], and invasion and metastasis[7]. In terms of CRC, the increased expression of SOX2 is associated with distant metastases and lymph-node metastases in right-sided CRC[11]. A later study by Han *et al* further demonstrated that silencing SOX2 induces a mesenchymal-epithelial transition and that SOX2 expression predicted liver and lymph node

metastasis of CRC patients [12]. Given the important functional role of SOX2 in metastasis, SOX2 has the potential to be a target for novel therapeutic agents.

Recently, natural products have been used in the chemotherapy of cancer and have shown promising therapeutic effects with no harm to normal tissues. Physcion, an anthraquinone derivative that has been isolated and characterized from both terrestrial and marine sources, has also been widely used as a mild laxative[13, 14]. In addition, physcion has a variety of pharmacological properties, including hepatoprotective, anti-inflammatory and anti-microbial activities[15-17]. Moreover, recent studies have shown that physcion exerted an antiproliferative effect *in vitro* in a variety of human malignancies, including cervical cancer, lung cancer, leukemia, breast cancer and colon cancer[18-20]. However, the effect of physcion on metastatic behavior has never been investigated. In this study, we used CRC cells as a model to assess the effects of physcion on metastatic potential and the underlying mechanisms. This study demonstrates an effect of physcion on cancer metastasis and has identified SOX2 as the target of its action by inducing AMPK activation.

Materials and methods

Cell lines and cultures

SW620 cells were obtained from the American Type Culture Collection (ATCC, Rockville, MD, USA). Cells were grown in RPMI-1640 medium (HyClone, Waltham, MA, USA) containing 10% fetal bovine serum (HyClone, Waltham, MA, USA) and 1% antibiotics (100 mg/L of streptomycin and 100 U/mL of penicillin) at 37 °C in a 5% CO_2 atmosphere. Cells were suspended using trypsin-EDTA (HyClone, Waltham, MA, USA) and plated at a density of 1.5×10^5/mL, every 48 h.

Cytotoxicity assay

In vitro cytotoxicity was determined in a MTT assay (Sigma, St Louis, MO, USA). Briefly, cells were plated at a density of 5×10^3 cells/well in 96-well culture plates. After treatment, 20 µL of MTT solution (5 mg/mL in PBS) was added to each well and incubated for 2 h. MTT formazan was dissolved in 150 µL of DMSO, and the absorbance was measured at 595 nm using an ELISA reader (Tecan Group Ltd, Männedorf, Switzerland).

Adhesion assay

Following treatment, the cells were plated (1×10^3 cells/well) in fibronectin-coated (1 µg/mL, Sigma-Aldrich) wells in a 96-well plate, followed by 1 h incubation at 37 °C in 5% CO_2. Adherent cells were fixed with 3.7% paraformaldehyde for 10 min and stained with a 0.2% crystal violet/20% methanol (*w/v*) solution. The stain was eluted, and absorbance was measured at 540 nm.

Wound healing assay

Each well of a 24-well tissue culture plate was seeded with cells to a final density of 1×10^5 cells per well, and these cells were maintained at 37 °C and 5% CO_2 for 24 h to permit cell adhesion and form a confluent monolayer. These confluent monolayers were then scored with a sterile pipette tip to leave a scratch of approximately 0.4-0.5 mm in width. The cell surface was then washed with serum-free culture medium three times to remove dislodged cells. Wound closure was monitored by collecting digitized images at 0, 24, 36 and 48 h after the scratch was performed. Digitized images were captured with an inverted microscope (Motic China Group Co, Xiamen, China) and a digital camera (Nikon, Tokyo, Japan). The digitized images were then analyzed using ImageJ software.

Invasion assay

For cell invasion assays, 24-well transwells coated with matrigel (8-µm pore size; BD Biosciences, San Jose, California) were used following a standard protocol. Equal numbers (1×10^5) of cells were plated into separate wells. Cells were starved overnight in serum-free medium, trypsinized and washed three times in DMEM containing 1% FBS. A total of 1×10^5 cells were then resuspended in 500 µL DMEM containing 1% FBS and added to the upper chamber, and MEM with 10% FBS was added to the lower chamber as a chemoattractant. For the control, medium containing 1% FBS was added to the lower chamber. After 24 h of incubation, matrigel and the cells remaining in the upper chamber were removed with cotton swabs. The cells on the lower surface of the membrane were fixed in formaldehyde and stained with hematoxylin staining solution. Cells in at least five random microscopic fields (magnification, 200×) were counted and photographed.

Quantitative RT-PCR (qRT-PCR)

Total RNA was extracted from cells using the RNA Simple Total RNA Kit (TIANGEN Co, Beijing, China), and 3 µg of RNA was converted into cDNA using the High Capacity cDNA Archive Kit (Applied Biosystems, Foster City, CA, USA). The primers were synthesized based on published sequences[21]. For each PCR reaction, a master mix that included SYBR GREEN MasterMix (Solarbio Co, Beijing, China), forward primer, reverse primer, and 10 ng of template cDNA was prepared. The PCR conditions were 5 min at 95°C, followed by 40 cycles of 95°C for 30 s, 60°C for 30 s, and 72°C for 30 s. The data were analyzed using the comparative ΔCt method (ABPrism software, Applied Biosystems, Foster City, CA, USA), with GAPDH serving as an internal normalization control.

Generation of plasmid constructs and establishment of SOX2-overexpressing cell lines

To generate SOX2-overexpressing vectors, CDS region of SOX2 coding sequences were obtained by RT-PCR and cloned into the pCMV vector (Beyotime Institute of Biotechnology, Shanghai, China) as previously described[22]. The resulting plasmid was named pCMV-SOX2. SW620 cells were transfected with pCMV-SOX2 vector to induce enforced SOX2 expression or pCMV vector to generate stable clones expressing SOX2 constitutively as a control, and the resulting cell lines were named SW620/pCMV-SOX2 and SW620/pCMV, respectively. Two days after transfection, G418 solution was added to the cells

for the selection of stable clones (SW620/pCMV-SOX2 and SW620/pCMV cells). Stable clones were selected and maintained in medium containing G418. The overexpression of SOX2 was verified by qRT-PCR and Western blot analysis.

Silencing SOX2 in CRC cells

The shRNA oligonucleotides for SOX2 gene knockdown were designed and synthesized as previously described[23]. Two different shRNA sequences and one scramble sequence as a control were subcloned into plasmid vector pGCsi-H1 following manufacturer's instructions. These recombinant vectors were designated as p-shRNA1, p-shRNA2 and p-shRNA-control. The SW620 cells in the logarithmic growth phase were seeded in 6-well plates at a density of 3×10^5 cells per well, incubated overnight and then transfected with p-shRNA1, p-shRNA2 or p-shRNA-control using Lipofectamine 2000 transfection reagent (Invitrogen, CA, USA) according to the manufacturer's protocol. Transfected cells were incubated for another 48 h, and the transfection efficiency was examined under fluorescence microscopy. The stable transfection cell clones, designated as SW620/shRNA1, SW620/shRNA2 and SW620/shRNA-control, were verified by qRT-PCR and Western blot analysis.

Detection of intracellular ROS

The intracellular ROS levels were measured using the oxidation-sensitive fluorescent dye 2,7-dichlorodihydrofluorescein diacetate (DCF-DA) (Invitrogen, USA). Briefly, after being washed once with PBS, treated cells were incubated with 20 µmol/L of DCF-DA in serum-free RPMI-1640 medium at 37°C for 30 min before analysis.

Western blot analysis

Following treatment, cells were harvested from flasks and lysed with ice-cold lysis buffer (50 mmol/L 2-amino-2-hydroxymethyl-propane-1,3-diol-hydrochloric acid (Tris-HCl), pH 7.4, 150 mmol/L sodium chloride, 1 mmol/L magnesium chloride, 100 µg/mL of phenylmethanesulfonylfluoride (PMSF) and 1% Triton X-100) for 30 min on ice. Cell lysate was then collected after centrifugation at 15000×*g* for 5 min at 4 °C. Equal amounts (50 µg) of lysate proteins were separated on 10% SDS-PAGE gels and transferred onto PVDF membranes (Millipore, MA, USA). Proteins were probed with specific antibodies following a standard protocol. The primary antibodies used were a rabbit polyclonal antibody to SOX2 (Sigma, St Louis, MO, USA), rabbit polyclonal antibodies against N-cadherin, E-cadherin, vimentin, fibronectin, α-SMA, Snail, Slug, Twist, AMPKα, phospho-AMPKα (Thr172), GSK3β and phospho-GSK3β (Ser9) (Cell Signaling Technology, Beverly, MA, USA), and a rabbit polyclonal antibody to β-actin as a gel loading control. After another wash with TBST, secondary antibody was added and incubated for 2 h. The blots were washed with TBST before the signals were detected using chemiluminescent substrate (KPL, Guildford, UK). BandScan software (Glyko, Novato, CA, USA) was used to quantify the blot density.

Statistical analysis

All statistical analyses were performed using SPSS statistical software. Values were presented as the mean±SD. Statistical comparisons were performed using a one-way ANOVA. Tukey's *post hoc* test was used for multiple group comparisons and Student's *t*-test was used for single comparisons. *P*<0.05 was considered statistically significant.

Results

Effect of physcion on SW620 cell viability, adhesion, migration and invasion

To ensure that the concentrations of physcion to be used for cell adhesion and migration assays are not harmful to the cells, we used an MTT assay to examine the effect of 1.25 to 10 µmol/L physcion exposure for 24 and 48 h on the viability of cells. As shown in Figure 1A, compared with the untreated control cells, cell viability was not significantly changed in cells that were treated with physcion at concentrations of 1.25 to 5 µmol/L. Thus, we used physcion concentrations of 2.5 and 5 µmol/L in all subsequent experiments. Furthermore, we investigated whether physcion could inhibit the cell adhesion, migration, and invasive properties of SW620 cells. A cell adhesion assay was performed using fibronectin as an adhesion substrate. As shown in Figure 1B, physcion-treated SW620 cells (2.5 and 5 µmol/L) showed a significant decrease in adhesion to fibronectin compared with cells treated with vehicle. Next, we examined the effect of physcion on cell migration and invasion in SW620 cells. As shown in Figure 1C, physcion suppressed cell migration at all three tested time points. Physcion at 2.5 µmol/L showed inhibitory effect on cell migration only at 36 and 48 h. In contrast, physcion at 5 µmol/L was able to inhibit cell migration at all tested time points. Then, the effect of physcion on cell invasion was determined in a Transwell assay. As shown in Figure 1D, physcion also exhibited inhibitory effects on cell invasion, and physcion at 2.5 and 5 µmol/L significantly suppressed cell invasion. The cell viability of SW620 cells at the concentrations and times tested was not affected by physcion (Figure 1A), thus confirming that the inhibitory effect on SW620 cell motility was not due to a cytotoxic effect of physcion. Taken together, our data confirm the inhibitory effects of physcion on the migration potential of SW620 cells.

Physcion inhibits epithelial-mesenchymal transition (EMT) process in SW620 cells

EMT is crucial step in cancer metastasis. Thus, we examined the effect of physcion on the EMT process to further evaluate the suppressive effect of physcion on the metastatic potential of CRC cells. As shown in Figure 2A, treatment with physcion in SW620 cells resulted in changes in morphological features that were characterized by a scattered distribution of cells in the culture and a spindle- or star-like morphology of the cells. The epithelial marker E-cadherin, and mesenchymal markers N-cadherin, vimentin, fibronectin and α-SMA were examined to support the role of physcion in regulating the EMT process. Our results showed that the mRNA level of E-cadherin was
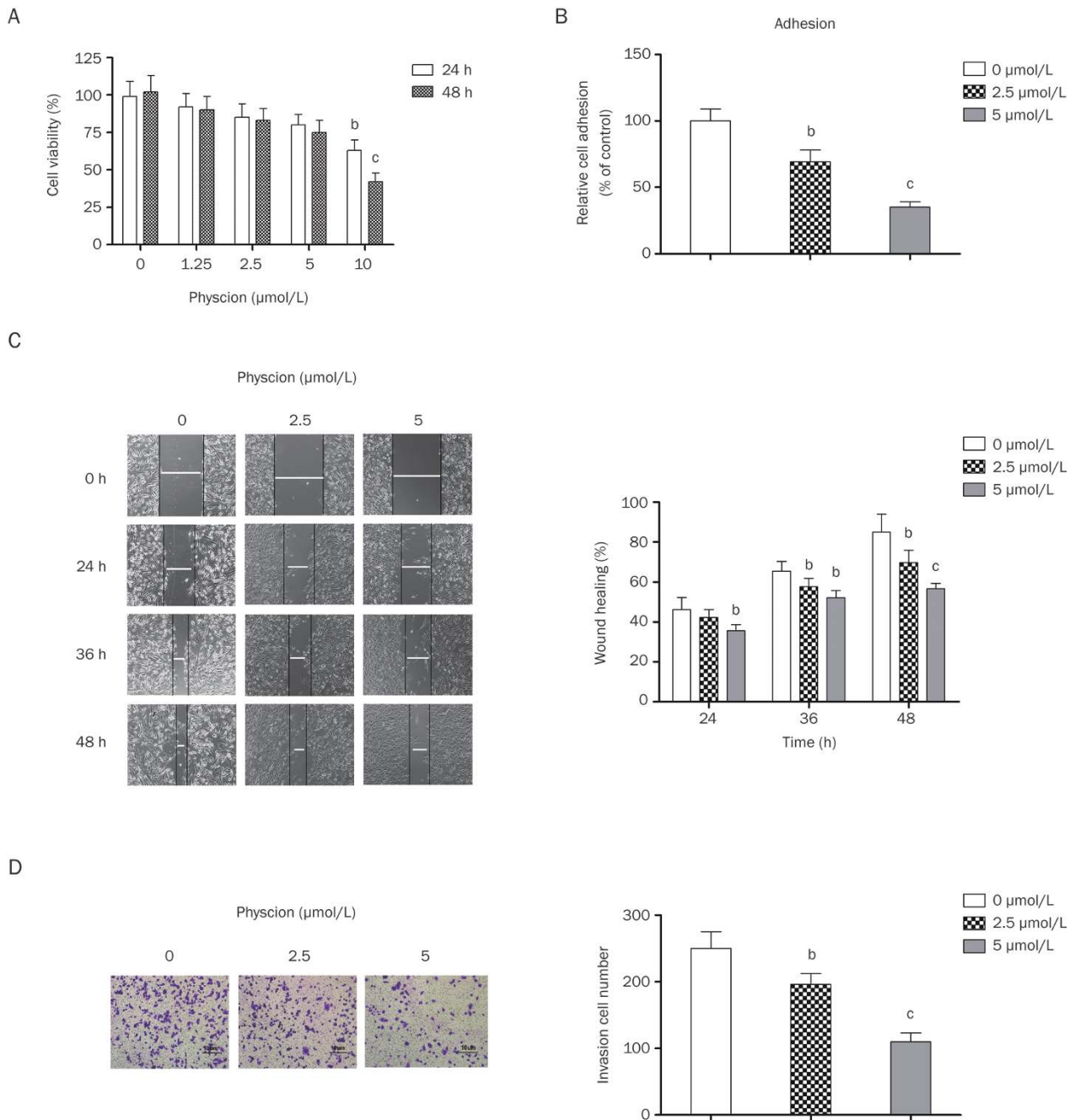
Figure 1. Effect of physcion on SW620 cell viability and metastasis. (A) Cell cytotoxicity was estimated in a MTT assay. (B) Physcion suppressed cell adhesion. (C) Physcion inhibited cell migration. (D) Physcion inhibited cell invasion. SW620 cells were incubated with physcion at the indicated concentrations for 24 h. Mean±SD. *n*=3. [b]$P<0.05$, [c]$P<0.01$ *vs* vehicle.

upregulated by physcion and that 5 μmol/L physcion showed a more profound promoting effect on E-cadherin expression (Figure 2B). Moreover, as shown in Figure 2C, physcion treatment led to an increase in E-cadherin protein expression and a decrease in N-cadherin, vimentin, fibronectin and α-SMA.

Transcriptional repressors Snail, Slug and Twist regulate the expression of mesenchymal and epithelial markers and,

hence, play a critical role in EMT [24]. Therefore, to completely understand the mechanism of physcion's action, the effect of physcion on these regulatory molecules was examined. As shown in Figure 2D and 2E, upon treatment with physcion, the expression of these transcriptional repressors was inhibited at both the protein and mRNA levels. Taken together, the results indicate that physcion exerted an inhibitory effect on
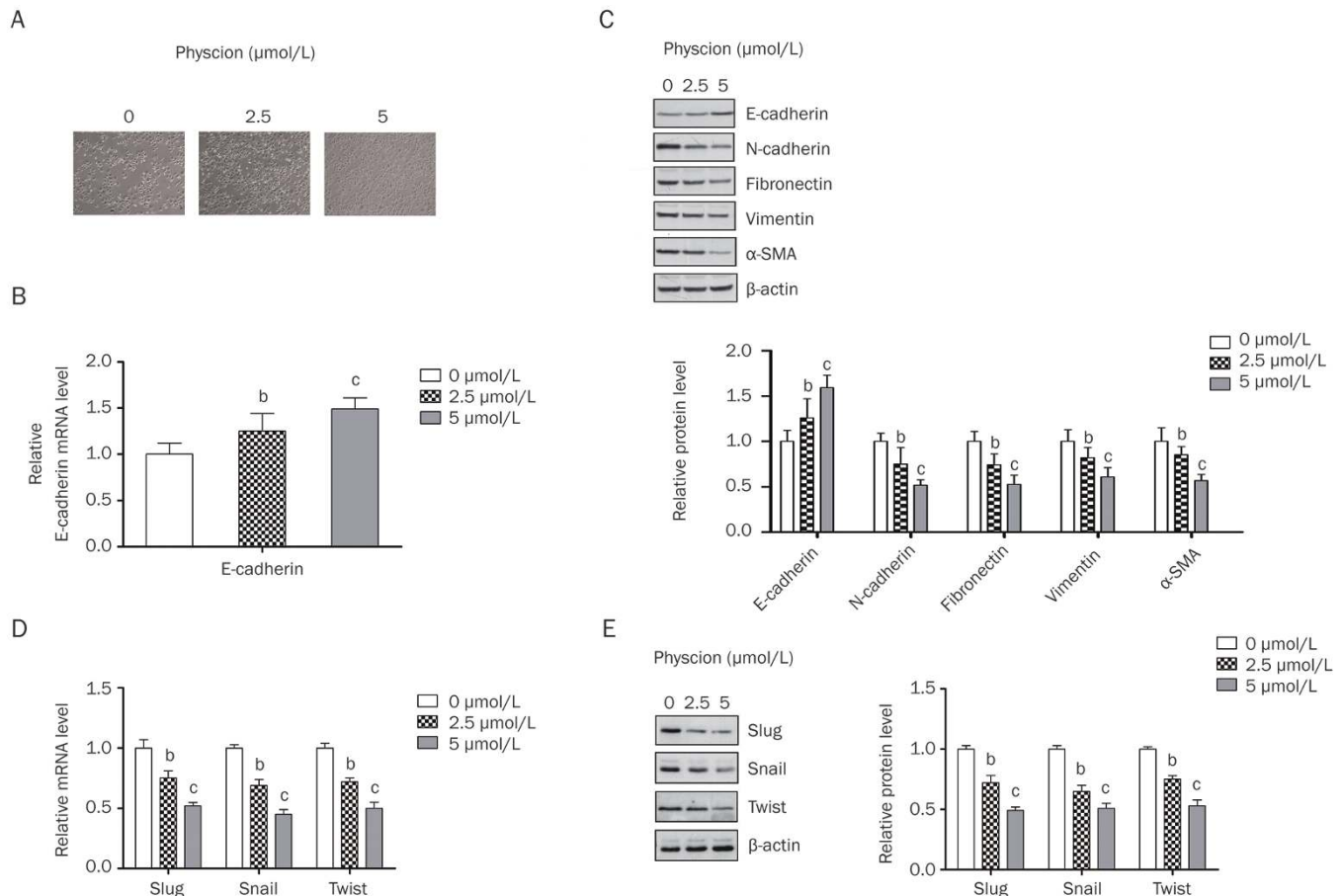
Figure 2. Effect of physcion on EMT of SW620 cells. SW620 cells were incubated with physcion at the indicated concentrations for 24 h. (A) Physcion treatment caused morphological changes in SW620 cells. (B) Physcion regulated the mRNA expression of E-cadherin. (C) Physcion regulated the expression of EMT markers. (D) Physcion modulated the expression of transcriptional repressors Snail, Slug and Twist at the mRNA level. (E) Physcion modulated the expression of transcriptional repressors Snail, Slug and Twist at the protein level. Mean±SD. n=3. [b]P<0.05, [c]P<0.01 *vs* vehicle.

EMT in CRC cells.

Suppression of SOX2 is involved in physcion-induced inhibition of metastatic potential of SW620 cells

A few studies have shown that SOX2 plays an important functional role in the metastasis of cancer, including CRC[12]. Therefore, we asked whether SOX2 was involved in the suppressive effects of physcion on the metastatic potential of CRC cells. As shown in Figure 3A and 3B, physcion downregulated the expression of SOX2 in SW620 cells at both the mRNA and protein levels. Next, to explore the role of SOX2 in the physcion-induced inhibition of cell migration and invasion, SW620 cells were transfected with a SOX2-overexpressing plasmid (the overexpression of SOX2 is demonstrated in Supplementary Figure 1A). As shown in Figure 3C, the suppressive effects of physcion on cell migration was significantly attenuated in SW620 cells that were transfected with SOX2-overexpressing plasmid. Next, shRNA targeting SOX2 was used as a positive control to silence SOX2 to further demonstrate the involvement of SOX2 in cell migratory behavior in SW620 cells (the knockdown of SOX2 is demonstrated in Supplementary

Figure 1B). As shown in Figure 3C, the suppression of SOX2 by shRNA resulted in a significant decrease in cell migration, which was similar to the effect of physcion treatment and supported the role of SOX2 in mediating cell migration. Similar results were obtained in a Transwell assay. As shown in Figure 3D, treatment with either physcion or shRNA targeting SOX2 significantly decreased the number of invading cells, whereas the inhibitory effect of physcion on cell invasion was significantly abrogated in SOX2-overexpressing SW620 cells.

Involvement of SOX2 in the modulatory effect of physcion on EMT

To further demonstrate the involvement of SOX2 modulation by physcion in the suppressive effect of physcion on the metastatic potential of SW620 cells, the levels of EMT markers and transcriptional repressors were examined. As shown in Figure 4A, the mRNA expression levels of the epithelial marker E-cadherin were significantly upregulated by physcion treatment and SOX2 shRNA compared with SW620 cells treated with vehicle. Similar results were obtained when the protein level of E-cadherin was examined (Figure 4B). In contrast, the
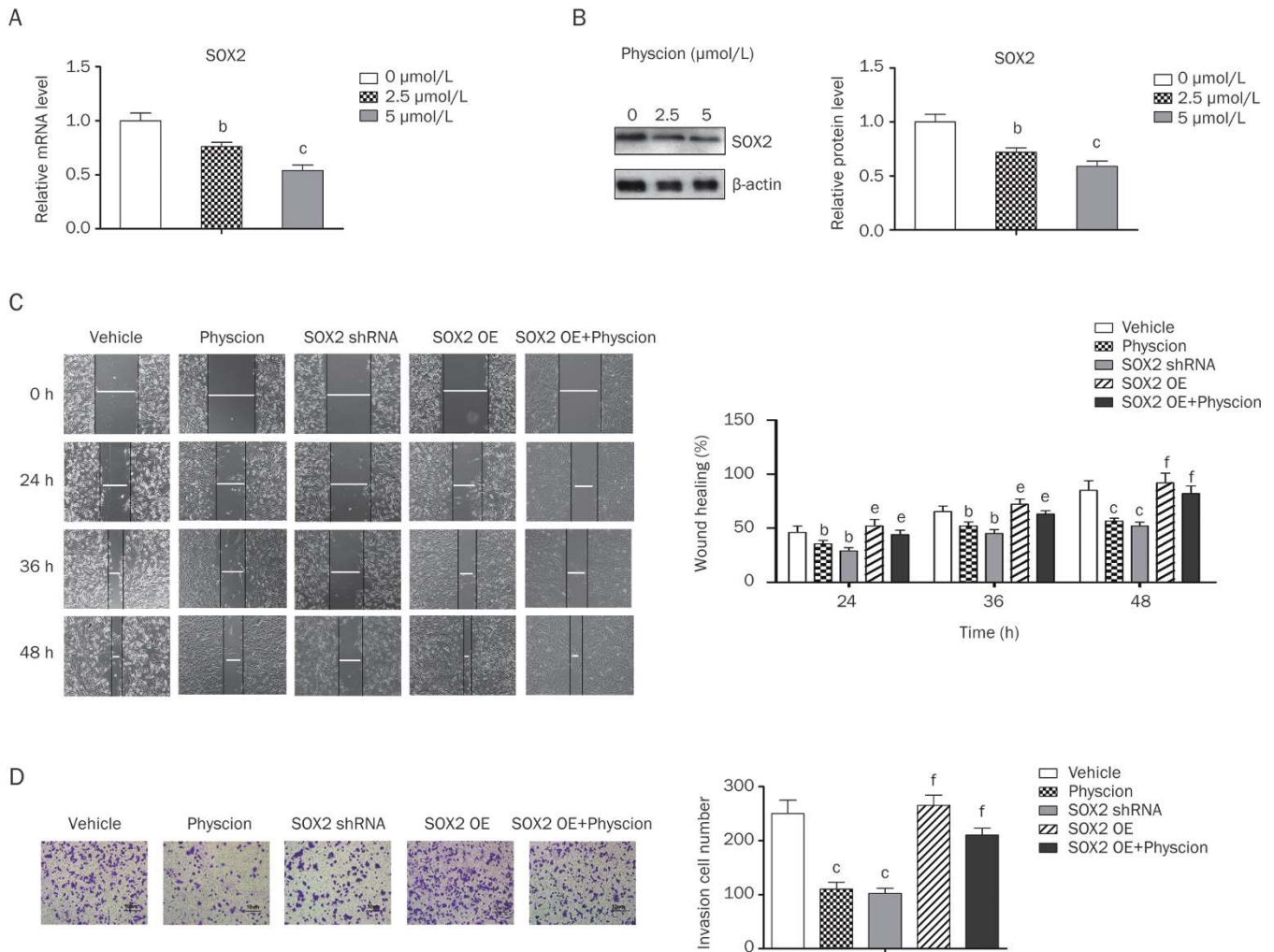
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Figure 3. Involvement of SOX2 in the modulatory effect of physcion on cell migration and invasion. SW620 cells were incubated with physcion at the indicated concentrations (or 5 µmol/L if not marked) for 24 h. (A) Physcion suppressed the SOX2 mRNA expression. (B) Physcion suppressed the SOX2 protein expression. (C) Silencing SOX2 inhibited cell migration, whereas the suppressive effect of physcion on cell migration was significantly abolished in SOX2-overexpressing SW620 cells. (D) Silencing SOX2 inhibited cell invasion, while the suppressive effect of physcion on cell invasion was significantly abrogated in SOX2-overexpressing SW620 cells. Mean±SD. *n*=3. $^bP<0.05$, $^cP<0.01$ *vs* vehicle. $^eP<0.05$, $^fP<0.01$ *vs* physcion.

expression levels of the mesenchymal markers N-cadherin, fibronectin, vimentin and α-SMA were all significantly down-regulated by treatment with either physcion or shRNA targeting SOX2 compared with SW620 cells treated with vehicle (Figure 4B). More importantly, the expression of the EMT markers induced by physcion treatment was significantly changed in SOX2-overexpressing SW620 cells. As shown in Figure 4C and 4D, in terms of the expression levels of the transcriptional repressors Slug, Snail and Twist, physcion treatment showed similar effect as that of shRNA targeting SOX2, which served as a positive control. In contrast, the effect of physcion on the expression levels of these molecules was almost completely reversed by SOX2 overexpression in SW620 cells. Taken together, these results indicate the involvement of SOX2 modulation in the inhibitory effect of physcion on metastatic potential in SW620 cells.

Physcion suppresses SOX2 expression via ROS/AMPK/GSK3β signaling

SOX2 expression can be modulated via several signaling pathways. The crucial role of AMPK/GSK3β signaling in modulating SOX2 expression has been evidenced[25]. Therefore, we attempted to investigate whether physcion modulated the SOX2 levels by targeting the AMPK signaling pathway. As shown in Figure 5A, physcion treatment resulted in the increased phosphorylation of AMPK but did not change the total AMPK level. The increased phosphorylation of GSK3β was also observed in cells treated with physcion. Next, we examined the involvement of AMPK/GSK3β signaling in the modulatory effect of physcion on SOX2 expression. As shown in Figure 5B, AICAR (AMPK activator) or LiCl (GSK3β inhibitor) was used as a positive control, and both caused the inhibition of SOX2 expression, which was similar to the effect
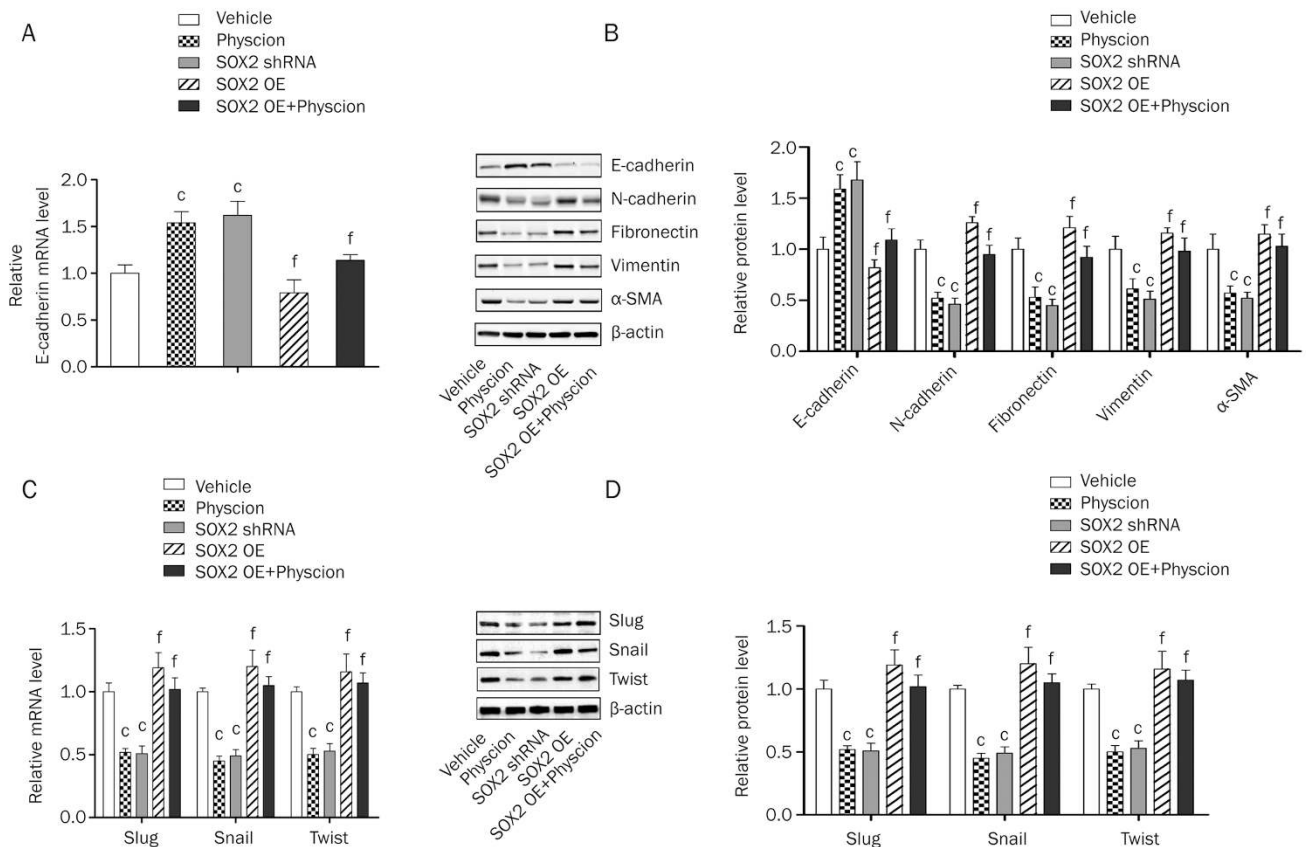
Figure 4. Involvement of SOX2 in the modulatory effect of physcion on EMT. SW620 cells were incubated with 5 µmol/L physcion for 24 h. (A) Silencing SOX2 resulted in an increase in the mRNA level of E-cadherin, whereas the increase in physcion-induced E-cadherin mRNA level was abolished by SOX2 overexpression. (B) Silencing SOX2 suppressed EMT, and the suppressive effects of physcion on EMT was significantly abrogated in SOX2-overexpressing SW620 cells. (C) Silencing SOX2 suppressed the transcriptional repressors Snail, Slug and Twist at the mRNA level, whereas the suppressing effect of physcion on these genes was significantly abrogated in SOX2-overexpressing SW620 cells. (D) Silencing SOX2 suppressed the transcriptional repressors Snail, Slug and Twist at the protein level, and the suppressive effect of physcion on these proteins was significantly abrogated in SOX2-overexpressing SW620 cells. Mean±SD. *n*=3. [b]$P<0.05$, [c]$P<0.01$ *vs* vehicle. [e]$P<0.05$, [f]$P<0.01$ *vs* physcion.

of physcion. In contrast, the AMPK inhibitor compound C significantly abolished the modulatory effect of physcion on SOX2. Collectively, our results showed that physcion regulated the expression of SOX2 by modulating AMPK/GSK3β signaling.

Next, we examined the mechanism by which physcion activated AMPK signaling. AMPK is a metabolic checkpoint protein that is activated by metabolic stress and the xenobiotic compounds that cause energy imbalance[26], including ROS generation[27]. Considering the chemical structures of physcion[20], we postulated that physcion activated AMPK signaling by inducing intracellular ROS generation. As shown in Figure 5C, physcion at concentrations of both 2.5 and 5 µmol/L caused a significant accumulation of intracellular ROS. Next, ROS activator $CoCl_2$ and inhibitor NAC were used to demonstrate the role of ROS in the physcion-induced activation of AMPK signaling. As shown in Figure 5D, an increase in the ROS level by $CoCl_2$ resulted in the activation of AMPK/GSK3β signaling, similar to physcion. Treatment with both physcion and NAC almost completely abrogated the

activation of AMPK signaling by physcion. Collectively, these results showed that physcion modulated SOX2 expression via ROS/AMPK/GSK3β signaling.

ROS/AMPK/GSK3β signaling is critical for the physcion-induced inhibition of the metastatic potential of SW620 cells

To further support our aforementioned findings, we examined the role of ROS/AMPK/GSK3β signaling in physcion-induced inhibition of the metastatic potential of SW620 cells. As shown in Figure 6A, AMPK activator AICAR, ROS activator $CoCl_2$ and GSK3β inhibitor LiCl significantly inhibited cell migration, thus suggesting a regulatory role for ROS/AMPK/GSK3β signaling in cell migration behavior. In contrast, the AMPK inhibitor compound C and the ROS inhibitor NAC significantly abolished the suppressive effect of physcion on cell migration, which confirmed that the inhibitory effect of physcion on cell migration was mediated, at least partly, through ROS/AMPK/GSK3β signaling. Similar effects were observed when cell invasion was examined, as shown in Figure 6B. Moreover, the inhibitory effect of physcion on EMT
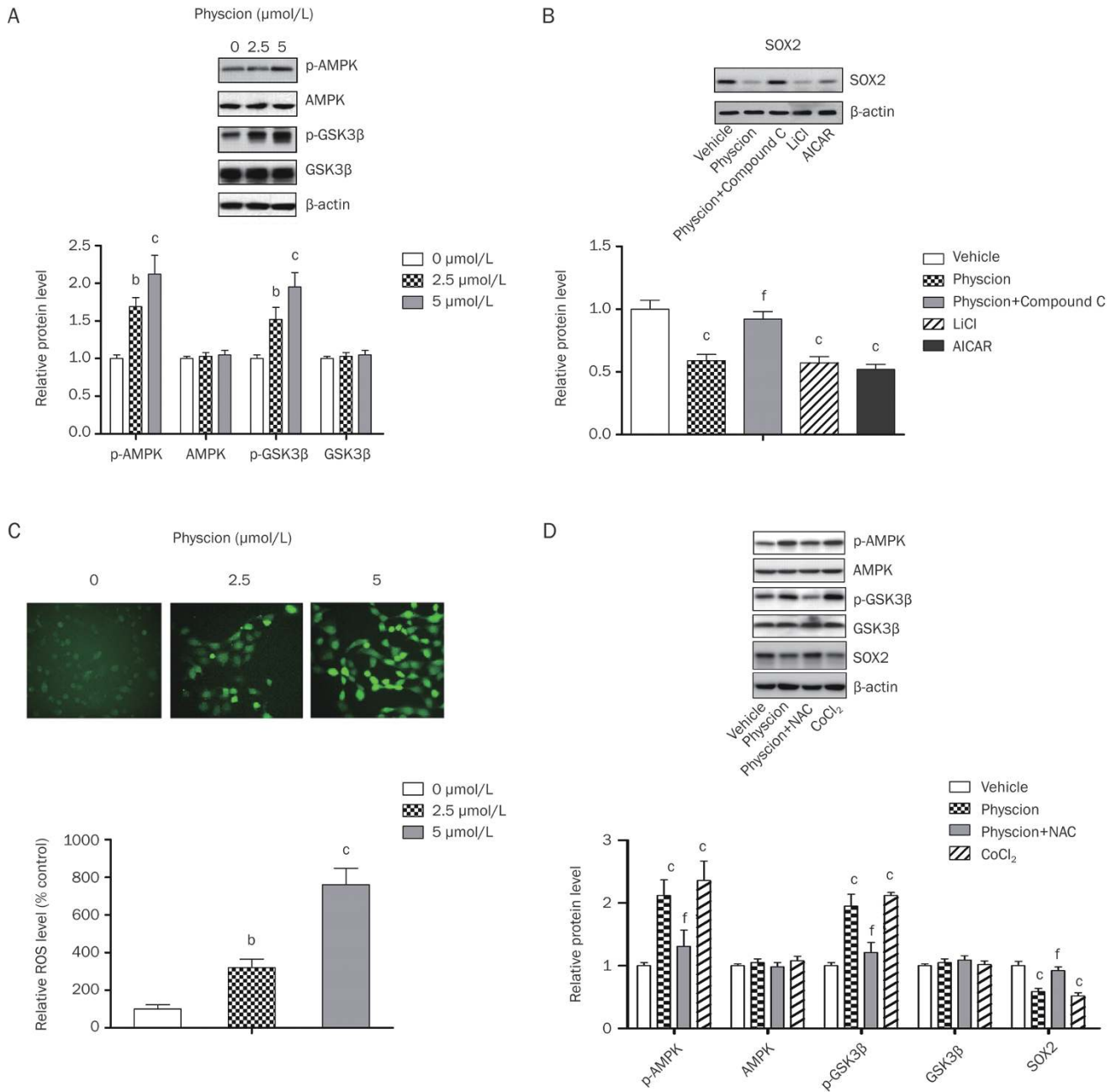
Figure 5. Involvement of ROS/AMPK/GSK3β signaling in the modulatory effect of physcion on SOX2. SW620 cells were incubated with physcion at the indicated concentrations (or 5 μmol/L if not marked) for 24 h. (A) Physcion activated AMPK/GSK3β signaling. (B) Physcion modulated expression of SOX2 via AMPK/GSK3β signaling. (C) Physcion induced intracellular ROS accumulation. (D) Physcion activated AMPK/GSK3β signaling via generating ROS. The concentrations of AICAR, Compound C, LiCl, NAC and CoCl2 were 5 mmol/L, 10 μmol/L, 10 mmol/L, 5 mmol/L and 100 μmol/L, respectively. Mean±SD. *n*=3. $^bP<0.05$, $^cP<0.01$ *vs* vehicle. $^eP<0.05$, $^fP<0.01$ *vs* physcion.

in SW620 cells was abrogated by compound C and NAC, as indicated by changes in the expression levels of two key EMT markers: E-cadherin and N-cadherin (Figure 6C). Combined with the aforementioned results, our results suggest that physcion caused the generation of intracellular ROS, which in turn caused the activation of AMPK/GSK3β signaling and the subsequent suppression of SOX2 levels, resulting in the inhibition of the metastatic potential of the CRC cell line SW620.

Discussion

Physcion, a naturally occurring anthraquinone derivative, has been widely used as a mild laxative. Moreover, physcion displays anti-cancer effects *in vitro*[18-20]. However, the effect of physcion on the metastatic potential of cancer has never been explored. This study investigated the effect of physcion on the metastatic potential of the CRC cell line SW620. Our data clearly demonstrate that physcion is an effective inhibitor of
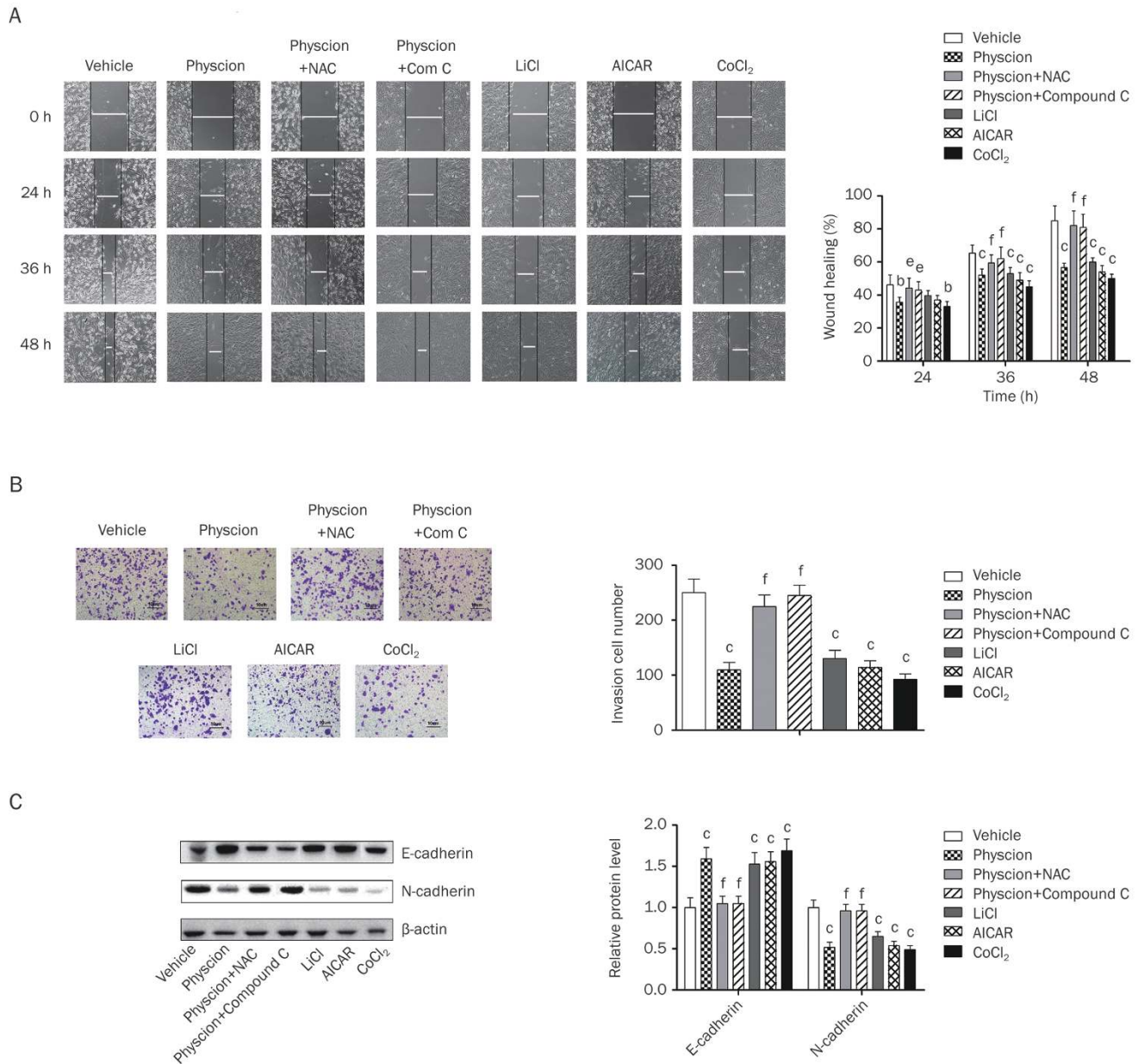
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Figure 6. Physcion suppresses metastatic behaviors in SW620 cells via modulating ROS/AMPK/GSK3β signaling. SW620 cells were incubated with 5 μmol/L physcion for 24 h. (A) ROS/AMPK activator and a GSK3β inhibitor mimicked the suppressive effect of physcion on cell migration, whereas ROS/AMPK inhibitor abolished the suppressive effect of physcion on cell migration. (B) ROS/AMPK activator and GSK3β inhibitor mimicked the suppressive effect of physcion on cell invasion, whereas ROS/AMPK inhibitor abrogated the inhibitory effect of physcion on cell invasion. (C) ROS/AMPK activator and GSK3β inhibitor mimicked the suppressing effect of physcion on EMT, whereas ROS/AMPK inhibitor abolished the suppressive effect of physcion on EMT. The concentrations of AICAR, Compound C, LiCl, NAC and $CoCl_2$ were 5 mmol/L, 10 μmol/L, 10 mmol/L, 5 mmol/L and 100 μmol/L, respectively. Mean±SD. n=3. [b]$P<0.05$, [c]$P<0.01$ vs vehicle. [e]$P<0.05$, [f]$P<0.01$ vs physcion.

the metastatic potential of CRC cells. In addition, the expression of SOX2, which was mediated by ROS/AMPK/GSK3β pathway, was important for the suppressive effect of physcion on the adhesion, migration, invasion and EMT of SW620 cells.

First identified in 1994, SOX2 was initially found to play a crucial role in the maintenance of self-renewal or pluripotency of the embryonic stem cells[5, 6]. Later studies showed that the aberrant expression of SOX2 was associated with a variety of

human tumors, including those of the lung, pancreatic, breast, cervical, hepatocellular and head/neck[8, 21, 28-30]. However, the pattern of SOX2 expression and its correlation with clinical/pathological outcomes of various cancers are highly controversial. In renal cell carcinoma and gastric cancer, the expression of SOX2 is reduced[31, 32], and the relationship between SOX2 expression and a favorable prognosis in non-small cell lung cancer, gastric cancer and renal cell carcinoma has been

established[31-33]. In contrast, other studies have related SOX2 expression to poor clinical outcomes, including cancer recurrence, and lymph node and distant metastasis in a variety of human malignancies[34, 35]. The role of SOX2 in tumorigenesis likely depends on the histological and organizational origin of the cells. In the case of cancer, the role of SOX2 in cancer progression has been controversial. The functional role of SOX2 in CRC was first reported by Fang *et al* in 2010, who used RT-PCR and immunohistochemical staining to show that SOX2 is overexpressed in CRC tissues compared with normal adjacent tissues[36]. Their results were supported by a later study, which showed that increased expression of SOX2 is associated with distant metastases and lymph-node metastases in right-sided CRC[11]. Han's group also found that silencing SOX2 induced EMT and that SOX2 expression predicted liver and lymph node metastasis in CRC patients[12]. Consistent with these previous studies, evidence from the present study showed that physcion suppressed metastatic potential by downregulating SOX2 expression, thus supporting the promotional role of SOX2 in CRC metastasis. However, a subsequent study has identified that autophagy induced by SOX2 enhanced cellular senescence by upregulating tumor suppressors or senescence factors, including p16, p21 and phosphorylated p53 in colon adenocarcinoma cells[37]. Given the use of different CRC cell lines in the above study and different manipulation methods, the role of SOX2 in cancer progression or metastasis might depend on the specific cell type and is probably related to the constitutive expression level of SOX2.

Because AMPK signaling is a pivot point between cell survival and apoptosis, it has been considered a beneficial target for cancer therapy[38]. Recent evidence has also linked AMPK signaling to cancer metastasis. For example, the activation of CaMKKβ-AMPK induced by lysophosphatidic acid increases tumor metastasis in ovarian cancer through dynamic cytoskeletal rearrangements[39]. However, AMPK activation by metformin inhibits the migration and invasion of melanoma cells[40]. Moreover, a recent study showed that metformin reverses EMT via the activation of AMPK in human breast cancer cells[41]. Accordingly, it seems that the role of AMPK in cell metastatic potential may be dependent on the type of stimulus or the cell that is used in the assay. In our study, physcion was shown to significantly increase AMPK phosphorylation, and this activation downregulated SOX2 expression, which suppressed the metastatic potential of CRC cell SW620. Based on our results, we postulated that AMPK activation by physcion was a negative regulator of CRC metastasis. GSK3β, a multifunctional serine/threonine kinase, is an important regulator of cell survival that may act as an anti- or pro- apoptotic factor in a cell-specific manner. Full GSK3β activity generally requires phosphorylation at tyrosine 216 (Tyr216), whereas phosphorylation at serine 9 (Ser9) inhibits its activity. Regarding the role of GSK3β in CRC metastasis, early studies have established that the decreased phosphorylation of GSK3β was associated with the inhibition of migration in colon cancer cells[42]. However, two recent studies revealed that GSK3β

inhibition correlated with a reversal of the EMT process in colon cancer cells[43, 44]. Moreover, Zhao *et al* reported that inhibition of GSK3β via activating AMPK exerted an anti-tumor effect in osteosarcoma[25]. In the present study, we demonstrated that cells treated with AMPK activators showed an increased phosphorylation of GSK3β, which suggests that physcion treatment could inactivate GSK3β through the activation of AMPK and exert an inhibitory effect on the metastatic potential of CRC cells. Further research will fully reveal the role of GSK3β in CRC metastasis.

A number of studies have shown that increased oxidative stress and ROS production are associated with many metastatic human tumors[45]. However, differential effects of ROS on cell migration and invasion have been reported, which suggests that the role of ROS in the metastatic behavior of cancer cells depends on the dose, type of ROS (superoxide, hydroxyl radical or hydrogen peroxide) and tissue type[46]. For example, the hydroxyl radical has a promotional role, and superoxide and hydrogen peroxide play inhibitory roles in lung carcinoma cells[47]. In contrast, ROS generation induced by natural compounds, such as berberine[27], butein[48], and salidroside[49], all seem to exhibit inhibitory action against the metastatic potential of cancer cells, although different signaling pathways were activated by ROS generation. The results from the present study also show that physcion-induced ROS generation stimulates AMPK signaling and inhibits the metastatic potential of CRC cells. Previous studies have noted that AMPK is activated by exogenous hydrogen peroxide[50]; hence, we proposed that physcion might activate AMPK by inducing the generation of hydrogen peroxide, which is consistent with the inhibitory effect of hydrogen peroxide on cell migration and invasion of lung carcinoma cells, as reported by Luanpitpong *et al*[47].

In conclusion, the results from this study identified a major role of physcion-induced SOX2 downregulation in the attenuation of the metastatic potential of CRC cells by activating ROS/AMPK/GSK3β signaling. Our study highlights the potential of physcion in the development of beneficial agents for use in combination with other anti-tumor or anti-metastatic drugs in the treatment of CRC, although more studies, including preclinical and clinical data, need to be collected.

Author contribution
Xue-hong CHEN and Yan-tao HAN designed research; Yan-tao HAN, Xue-hong CHEN, Hui GAO and Jun-li YE performed research; Chun-bo WANG analyzed data; Hui GAO and Jun-li YE contributed new analytical tools and reagents; Yan-tao HAN and Xue-hong CHEN wrote the paper.

Supplementary information
Supplementary information is available at Acta Pharmaco-

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