

SB-T-121205, a next-generation taxane, enhances apoptosis and inhibits migration/invasion in MCF-7/PTX cells

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Abstract. Breast cancer is the leading cause of cancer death among women. Paclitaxel, a mitotic inhibitor, is highly effective in the treatment of breast cancer. However, development of resistance to paclitaxel limits its clinical use. Identifying new compounds and new strategies that are effective against breast cancer, in particular drug-resistant cancer, is of great importance. The aim of the present study was to explore the potential of a next-generation taxoid, SB-T-121205, in modulating the proliferation, migration and invasion of paclitaxel-resistant human breast cancer cells (MCF-7/PTX) and further evaluate the underlying molecular mechanisms. The results of MTT assay showed that SB-T-121205 has much higher potency to human breast cancer cells (MCF-7/S, MCF-7/PTX and MDA-MB-453 cells) than paclitaxel, while that the non-tumorigenic human bronchial epithelial cells (BEAS-2B) were slightly less sensitive to SB-T-121205 than paclitaxel. Flow cytometry and western blot methods revealed that SB-T-121205

induced cell cycle arrest at the G2/M phase and apoptosis in MCF-7/PTX cells through accelerating mitochondrial apoptotic pathway, resulting in reduction of Bcl-2/Bax ratio, as well as elevation of caspase-3, caspase-9, and poly(ADP-ribose) polymerase (PARP) levels. Moreover, SB-T-121205 changed epithelial-mesenchymal transition (EMT) property, and suppressed migration and invasion abilities of MCF-7/PTX cells. Additionally, SB-T-121205 exerted antitumor activity by inhibiting the transgelin 2 and PI3K/Akt pathway. These findings indicate that SB-T-121205 is a potent antitumor agent that promotes apoptosis and also reduces migration/invasion abilities of MCF-7/PTX cells by restraining the activity of transgelin 2 and PI3K/Akt, as well as mitochondrial apoptotic pathway. Such results suggest a potential clinical value of SB-T-121205 in breast cancer treatment.

Introduction

Breast cancer is the most frequently diagnosed cancer and the leading cause of cancer-related mortality among females worldwide (1). Currently, standard therapies for breast cancer patients include surgery, radiotherapy and chemotherapy, which plays an irreplaceable role (2). Paclitaxel (PTX; Fig. 1A), a first-line therapeutic agent used clinically to treat breast cancer, exerts its antitumor activity by promoting the polymerization of tubulin and stabilizing the resulting microtubules, causing cell cycle arrest at the G2/M phase that leads to apoptotic death of cancer cells (3). However, paclitaxel resistance often occurs after a period of treatment, causing a serious problem in chemotherapy (4). Accumulated studies manifest that there are several major mechanisms for paclitaxel resistance, including point mutations in β -tubulin, alterations in the expression of β -tubulin isotypes, particularly the β -III tubulin isoform, overexpression of ATP-binding cassette transporters and suppression of apoptosis. More importantly, the drug-resistance to chemotherapy may eventually result in mortality of cancer patients due to tumor metastasis (5,6). It is therefore highly desirable to develop novel agents with

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Abbreviations: PTX, paclitaxel; PI3K/Akt, phosphatidylinositol 3 kinase/serine-threonine kinase; EMT, epithelial-mesenchymal transition

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minimum side-effects and improved activity against various tumors, especially against drug-resistant human breast cancer.

In the last decades, a number of taxanes have been designed and synthesized based on the structure of the first-generation taxanes, paclitaxel and docetaxel. Many of these new taxanes exhibited strong antitumor activity against paclitaxel-resistant tumor xenografts. For instance, Roh *et al* (7) found two of the 3'-*N*-acyl-paclitaxel analogues, in which the phenyl group of 3'-*N*-benzoyl was replaced with 1-cyclopentenyl (1k) and 1-cyclohexenyl (1n), displayed seven times higher cytotoxicity than paclitaxel against doxorubicin-resistant breast cancer cells. It was also reported that another taxane, Lx2-32c, was active against paclitaxel-resistant breast cancer cells (MX-1/T) through intrinsic apoptosis signaling pathway, and exhibited efficacy against its tumor xenografts in nude mice, which suggests the potential of Lx2-32c to be a promising drug candidate (8). TPI-287, a new microtubule stabilizer, showed cytotoxicity similar to that of paclitaxel in breast cancer cells and efficacy against primary breast tumor xenografts in an animal model. Also, it was found to significantly decrease metastatic colonization of breast cancer in the brain (9). Moreover, Ojima *et al* (10) developed a series of novel second-generation taxanes with systematic modifications at the C2, C10, C3' and C3'N positions. For example, among these new-generation taxanes synthesized and assayed, SB-T-1214 and SB-T-121303, exhibited significantly lower IC₅₀ values, 9.00±0.77 nM and 3.65±0.21 nM, respectively for paclitaxel-resistant ovarian cancer cells than paclitaxel (532.95±3.18 nM). Such results clearly warrant further exploitation of next-generation taxanes with superior potency, efficacy and pharmacological properties against breast cancer.

Transgelin 2 is reported to be implicated in tumorigenesis, boosting tumor progression and promoting metastases (11). Additionally, abnormal expression of transgelin 2 was discovered in lung, gastric and colorectal cancer (12-14). We previously reported that transgelin 2 expression was extremely high in paclitaxel-resistant human breast cancer cells (MCF-7/PTX) compared to breast cancer drug-sensitive cells by proteomics analysis (15). Knockdown of transgelin 2 via small interfering RNA sensitized MCF-7/PTX cells to paclitaxel, and suppressed their migration/invasion abilities, suggesting that transgelin 2 might be a new biomarker for breast cancer (16). On the other hand, aberrant activation of the phosphatidylinositol 3 kinase/serine-threonine kinase (PI3K/Akt) pathway contributes to chemo-resistance, tumor metastasis and poor prognosis (17,18). Notably, we reported that the PI3K/Akt pathway was activated in MCF-7/PTX cells and the *TAGLN2*-knockdown inhibited the PI3K/Akt pathway, suggesting that the PI3K/Akt pathway would be critical to breast cancer progression (19).

We confirmed that the MCF-7/PTX cells, developed by our laboratory for the assay used, were highly resistant to paclitaxel and exhibited strong migration/invasion capacities (20,21). In the present study, eight novel next-generation taxanes were screened by MTT assay. Among these taxanes, SB-T-121205 (Fig. 1B) was found to be highly potent against the paclitaxel-resistant MCF-7/PTX cells. Subsequently, the effect of SB-T-121205 on cell apoptosis, epithelial-mesenchymal transition (EMT) property, migration and invasion

was assessed in MCF-7/PTX cells, along with the underlying molecular mechanisms. Our data indicated that SB-T-121205 exerted its high potency against MCF-7/PTX cells through activation of the transgelin 2 and PI3K/Akt pathway, which suggests that SB-T-121205 would serve as an efficacious drug candidate for breast cancer treatment.

Materials and methods

Chemicals and antibodies. In the present study, the anticancer activity of SB-T-121205 was assessed using paclitaxel as the positive control. Paclitaxel was purchased from Nanjing Sike Pharmaceutical, Co., Ltd. (Nanjing, China). All taxanes were kindly provided by Dr Changwei Wang, the laboratory of Professor Iwao Ojima at Stony Brook University. 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) was obtained from Sigma-Aldrich (St. Louis, MO, USA). Annexin-V-FLUOS staining kit was obtained from Invitrogen (Waltham, MA, USA). The primary rabbit monoclonal antibodies against N-cadherin, and GSK-3β were acquired from Abcam (Cambridge, MA, USA). The primary rabbit monoclonal antibodies against E-cadherin, phosphatase and tensin homologue deleted on chromosome ten (PTEN), Akt, phospho-Akt (p-Akt), p-GSK-3β and Snail were purchased from Cell Signaling Technology (Danvers, MA, USA). The rabbit polyclonal antibodies against caspase-3, caspase-9 and poly(ADP-ribose) polymerase (PARP) were also obtained from Cell Signaling Technology. The rabbit polyclonal antibodies against vimentin and transgelin 2 were from GeneTex, Inc. (Irvine, CA, USA). The rabbit monoclonal antibodies against Bcl-2 and Bax were acquired from Epitomics (Burlingame, CA, USA). The rabbit polyclonal anti-β-actin antibody was obtained from Beijing Bo Aosen Biotechnology Co., Ltd. (Beijing, China). Horseradish-peroxidase-conjugated goat anti-rabbit IgG was from CW Biotech (Beijing, China).

Cell lines and cell culture. The human breast cancer cell lines, MCF-7/S and MDA-MB-453, and non-tumorigenic human bronchial epithelial cell line (BEAS-2B) were obtained from the Cell Bank of Shanghai, Institute of Biochemistry and Cell Biology, Chinese Academy of Sciences. MCF-7/PTX cell line was successfully established as previously described (16) with the concentration of 30 nM paclitaxel. The cells were grown in RPMI-1640 medium (Gibco, Carlsbad, CA, USA) supplemented with 10% fetal bovine serum (FBS; Thermo Fisher Scientific, Waltham, MA, USA) and 1% penicillin (Harbin Pharmaceutical Group, Co., Ltd., Harbin, China)/streptomycin (North China Pharmaceutical Group, Co., Ltd., Shijiazhuang, China) at 37°C in a humidified atmosphere of 5% CO₂. Cells in exponential phase growth were observed under inverted light microscope (Olympus Corp., Tokyo, Japan).

MTT assay. Cells at 5x10⁵/ml density were seeded into 96-well plates (Corning, Inc., Corning, NY, USA) with 100 μl medium for the duration indicated. After 72 h, 20 μl of MTT (5 mg/ml) was added into each well and incubated at 37°C for 4 h. Then, 150 μl of dimethyl sulfoxide (DMSO) was added into each well for dissolving the formazan for 15 min. The absorbance was tested at 490 nm on a microplate reader (BioTek Instruments,

Inc., Winooski, VT, USA). The 50% growth inhibitory concentration (IC₅₀) of drug was calculated to evaluate the drug sensitivity. Each experiment was repeated three times.

Flow cytometry assay. For cell cycle assay, cells were exposed to paclitaxel (600 nM) or SB-T-121205 (10 or 20 nM) for 48 h and then harvested. After three washes with cold phosphate-buffered saline (PBS), cells were fixed with 70% cold ethanol at 4°C overnight. The next day, cells were washed with cold PBS and suspended in a 500 µl staining solution of propidium iodide (PI; Sigma-Aldric) staining solution at 37°C for 30 min without light. The samples were tested using FACSCanto™ II flow cytometry (Becton Dickinson, Franklin Lakes, NJ, USA).

For cell apoptosis analysis, cells with different treatments after 48 h were collected, washed and were resuspended with cold PBS. Then, the cells were double stained with Annexin V-FITC and PI at 37°C for 20 min from light with an Annexin-V-FLUOS staining kit in accordance with the manufacturer's instructions. The stained cells were analyzed using FACSCanto™ II flow cytometry. Annexin V⁺/PI⁻ were regarded as early apoptotic cells and Annexin V⁺/PI⁺ were late apoptotic cells. Experiments were repeated in triplicate, independently.

Western blot assay. Cells with different treatments were lysed in RIPA buffer containing protease inhibitor (Roche, Basel, Switzerland) on ice. Then, equal amount of protein lysates were electrophoretically separated by 10% sodium dodecyl sulfate polyacrylamide gelelectrophoresis (SDS-PAGE; Beyotime Institute of Biotechnology, Beijing, China) and transferred to polyvinylidene fluoride (PVDF) membranes (Millipore, Billerica, MA, USA). After blocking with 5% non-fat dried milk for 2 h, the membranes were incubated with diluted antibodies N-cadherin (1:1,000, ab76011), E-cadherin (1:1,000, #3195), vimentin (1:500, GTX100619), PTEN (1:1,000, #9188), Akt (1:1,000, #4691), p-Akt (1:800, #4060), GSK-3β (1:1,000, ab32391), p-GSK-3β (1:1,000, #9322), Bcl-2 (1:2,500, #1017-1), Bax (1:2,500, #1063-1), caspase-3 (1:800, #9662), caspase-9 (1:800, #9502), PARP (1:800, #9542), Snail (1:1,000, #3879), transgelin 2 (1:2,000, GTX115082) and β-actin (1:800, bs-0061R) overnight at 4°C. After incubation with a horseradish peroxidase-conjugated secondary antibody (1:25,000, cat. no. CW0103), for 2 h at 37°C, the protein bands were detected using the SuperSignal West Pico kit (Thermo Fisher Scientific). All western blot experiments were repeated at least three times.

Mammosphere formation assay. Mammosphere culture was carried out in a serum-free DMEM/F-12 (Gibco) supplemented with 2% B27 (Gibco), 20 µg/l human epidermal growth factor (PeproTech, Rocky Hill, NJ, USA), 10 µg/l human basic fibroblast growth factor (PeproTech), and 5 mg/l insulin (Jiangsu Wanbang Biochemical Pharmaceutical, Co., Ltd., Xuzhou, China). Single cells prepared from mechanical and enzymatic dissociation were plated in 6-well ultralow attachment plates (Corning) at 1x10⁴/ml density in culture. Single cell status was confirmed under microscope. After 14 days, the number of mammospheres was counted under an inverted light microscope. Experiments were repeated in triplicate, independently.

Table I. The effect of paclitaxel and new-generation taxanes on cell viability in MCF-7/PTX cells.^a

Taxane	IC ₅₀ (nM)	Taxane	IC ₅₀ (nM)
SB-T-1214	80.50±7.62	SB-T-121303	21.67±2.25
SB-T-101141	66.66±5.59	SB-T-12301	54.59±4.61
SB-T-121205	19.01±2.03	SB-T-121405	34.90±2.97
SB-T-121605	31.43±2.84	SB-T-1230105	119.05±9.68
Paclitaxel	2290.87±125.18		

^aCell were treated with various concentrations of taxanes and IC₅₀ values were calculated. Data were presented as mean ± SD from three independent experiments.

Wound healing scratch assay. Cells (5x10⁵/ml) were seeded in 6-well plate until confluent. Cells were serum-starved overnight and an artificial scratch wound was created. The cells were then maintained in serum-free culture at 37°C in a humidified atmosphere of 5% CO₂. Migration photos were captured at 0, 24 and 48 h after scratching. Experiments were repeated in triplicate independently. Percent wound closure was calculated using the following equation: percent wound closure (%) = [1-(L_t/L₀)] x 100%.

Transwell invasion assay. The invasiveness of cells was evaluated by a Boyden chamber method. The polycarbonate filters (8 µm pore size; Corning) were coated with Matrigel Matrix (BD Biosciences, San Jose, CA, USA) and incubated at 37°C for 5 h. Next, 5x10⁵ cells suspended in 200 µl serum-free RPMI-1640 were added into the upper chamber, while 800 µl of complete media was added to the lower chamber. After 48 h, cells migrated through Matrigel and adhered onto the lower chamber was fixed in 4% paraformaldehyde for 30 min, stained with 0.1% crystal violet (Beyotime Institute of Biotechnology) and counted by fluorescent microscopy (Olympus). Each invasion assay was repeated in three independent experiments.

Statistical analysis. Statistical analysis was performed using one-way ANOVA. All values were expressed as mean ± standard deviation (SD) from triplicate experiments performed in a parallel manner. P<0.05 were considered statistically significant.

Results

The intrinsic cytotoxicity of SB-T-121205 on cancer and normal cells. The intrinsic cytotoxicity of the eight novel taxanes against MCF-7/PTX cells were measured by MTT assay. Treating cells with these taxanes for 72 h significantly inhibited cell growth. Among these taxanes examined, SB-T-121205 showed the highest inhibition. We therefore, chose SB-T-121205 for further study. After 72 h of exposure, SB-T-121205 obviously restrained growth of MCF-7/PTX cells with an IC₅₀ value of 19.01±2.03 nM, which was two orders of magnitude lower than paclitaxel (2290.87±125.18 nM) (16) (Table I and Fig. 1C and D). The molecular formula of

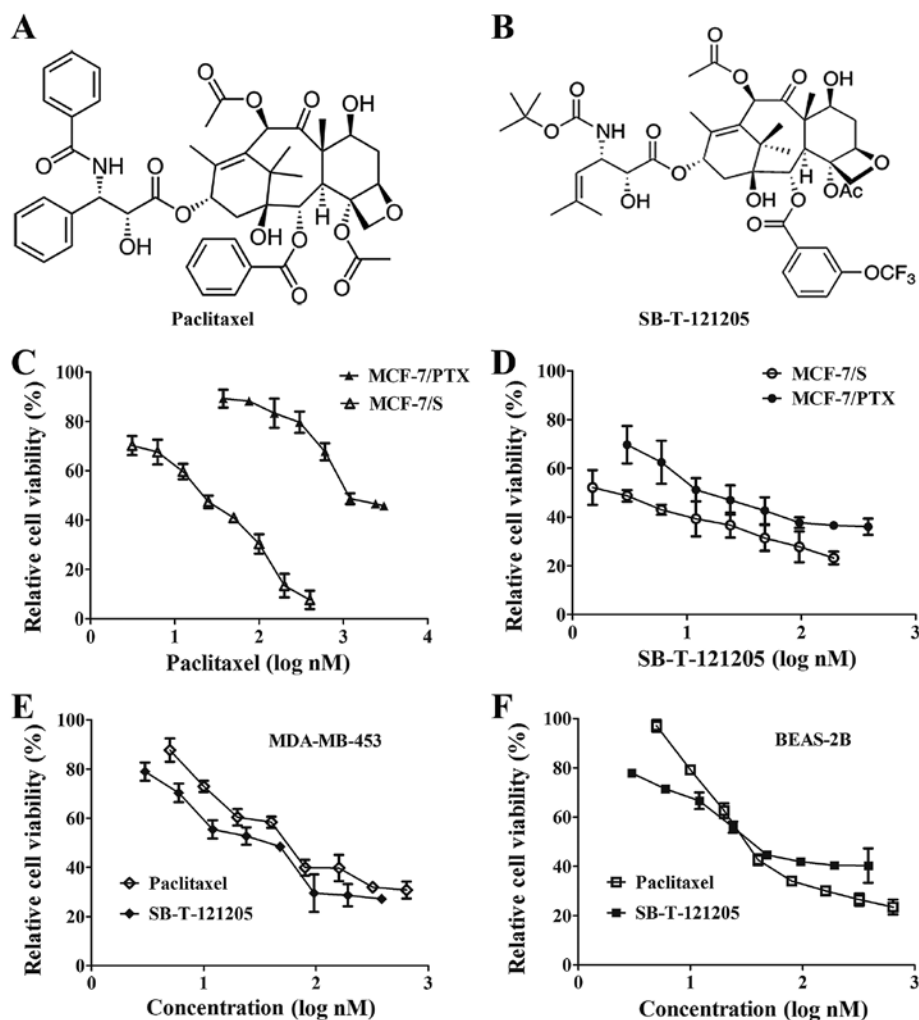


Figure 1. Effects of paclitaxel and SB-T-121205 on cell viability. The chemical structures of (A) paclitaxel and (B) SB-T-121205. MCF-7/PTX cells and MCF-7/S cells were treated with (C) paclitaxel or (D) SB-T-121205 for 72 h at a range of concentrations, and relative cell viability was determined by MTT assay. In the same manner, (E) MDA-MB-453 cells were treated with paclitaxel or SB-T-121205, and relative cell viability was determined. In the same manner, (F) BEAS-2B cells were treated with paclitaxel or SB-T-121205 and relative cell viability was determined.

SB-T-121205 is $C_{44}H_{56}F_3NO_{16}$ with molecular weight 911.91. Moreover, the effect of SB-T-121205 on the proliferation of parental MCF-7/S cells was examined and the result showed SB-T-121205 inhibited the cell growth with the IC_{50} value of 2.14 ± 0.32 nM, which was ~ 10 times lower than that of paclitaxel (20.0 ± 0.9 nM) (16) (Fig. 1C and D).

We examined the cell growth inhibitory effect of SB-T-121205 on MDA-MB-453 cells. SB-T-121205 was found to have slightly lower IC_{50} value (38.67 ± 3.58 nM) than paclitaxel (IC_{50} 54.62 ± 3.28 nM) (Fig. 1E). We also examined the cytotoxicity of paclitaxel and SB-T-121205 against non-tumorigenic BEAS-2B human bronchial epithelial cells. Treating BEAS-2B cells with different concentration of paclitaxel or SB-T-121205 revealed that BEAS-2B cells are slightly less sensitive to SB-T-121205 (IC_{50} 59.80 ± 1.89 nM) than paclitaxel (IC_{50} 54.57 ± 2.10 nM) (Fig. 1F). Thus, for the treatment of MCF7/S and MCF7/PTX and MDA-MB-453 cancer cells, SB-T-121205 has much wider therapeutic index than paclitaxel.

SB-T-121205 induces apoptosis and G2/M arrest in MCF-7/PTX cells. To confirm whether SB-T-121205 triggered apoptosis of MCF-7/PTX cells, we carried out Annexin V

and PI double staining followed by flow cytometric analysis. MCF-7/PTX cells were incubated with paclitaxel alone or SB-T-121205 alone for 48 h. As shown in Fig 2A, paclitaxel (600 nM) and SB-T-121205 (10 or 20 nM) indeed increased cell apoptosis rates that reached 33.48, 31.78 and 39.81%, respectively (Fig. 2A). Since the concentration used for paclitaxel is 30–60 times higher than that of SB-T-121205, SB-T-121205 is far better than paclitaxel in promoting cell apoptosis. In brief, it is confirmed that SB-T-121205 has the ability to induce apoptosis in MCF-7/PTX cells.

To further investigate the mechanisms that SB-T-121205 inhibits the cancer cell growth, the MCF-7/PTX cells were exposed to various concentrations of SB-T-121205 for 48 h, and then cell cycle analysis was performed. Compared with the control group, paclitaxel (600 nM) markedly elevated the number of cells in G2/M phase in MCF-7/PTX cells and the proportion of MCF-7/PTX cells in G2/M phase increased from 24.84 to 92.06%. SB-T-121205 at low concentrations (10, 20 and 40 nM) also increased the percentage of cells in G2/M phase in a dose-dependent manner from 26.23% (10 nM) to 52.77% (40 nM) (Fig. 2B). The results confirmed that SB-T-121205 arrests the mitosis of MCF-7/PTX cells at

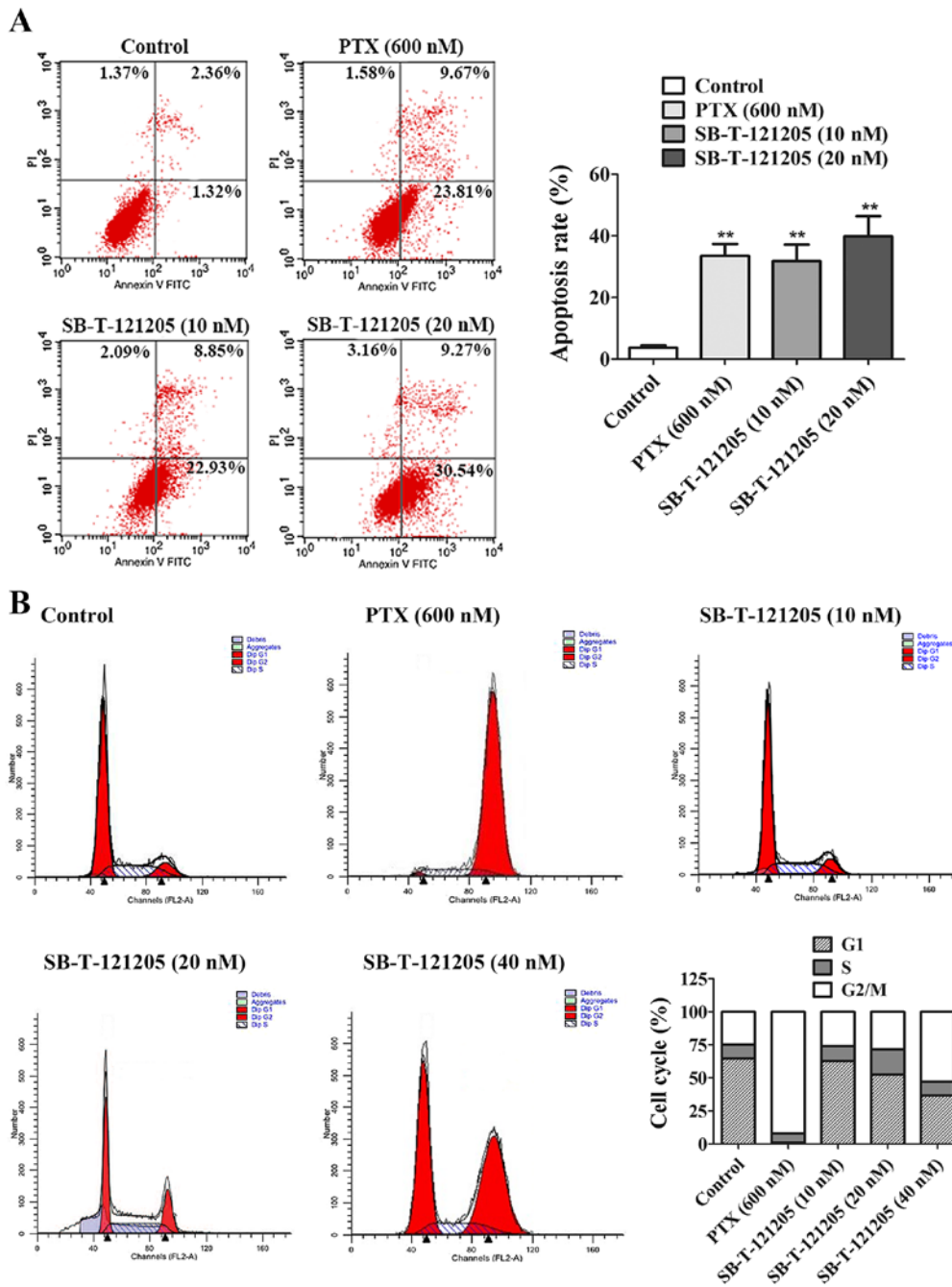


Figure 2. SB-T-121205 induces cell apoptosis and cell cycle distribution in MCF-7/PTX cells. (A) Treatment with paclitaxel alone (600 nM) or SB-T-121205 (10 and 20 nM) for 48 h, apoptosis in MCF-7/PTX cells was determined by flow cytometry. (B) Cell cycle distribution of MCF-7/PTX cells after treatment with paclitaxel or SB-T-121205 for 48 h was examined. Data were presented as proportion of cells in G1, S and G2/M phases of the cell cycle. Data are shown as mean \pm SD from three experiments, **P<0.01 vs. control group.

the G2/M phase of the cell cycle in a manner similar to other known taxanes.

SB-T-121205 suppresses the EMT property of MCF-7/PTX cells.

It is well known that EMT is a critical event in the development of cancers (22). To further examine whether SB-T-121205 could alter the EMT property of MCF-7/PTX cells, mammosphere formation and western blot assays were performed. As Fig. 3A shows, SB-T-121205 exposure triggered morphological changes in the MCF-7/PTX cells from elongated shape to cobblestone shape (Fig. 3A), which is a characteristic EMT morphology. After treated with SB-T-121205, the mammosphere forming

ability of MCF-7/PTX cells was decreased (Fig. 3B). In addition, a low concentration (20 nM) of SB-T-121205 distinctly increased the expression of epithelial marker E-cadherin, whereas the levels of mesenchymal markers N-cadherin and vimentin were reduced (Fig. 3C). However, the effect of high concentration (600 nM) of paclitaxel was inferior to that of the low concentration of SB-T-121205. Thus, SB-T-121205 possesses much higher potency than paclitaxel for suppression of EMT in MCF-7/PTX cells.

SB-T-121205 inhibits migration and invasion in MCF-7/PTX and MDA-MB-453 cells. Tumor migration and invasion are

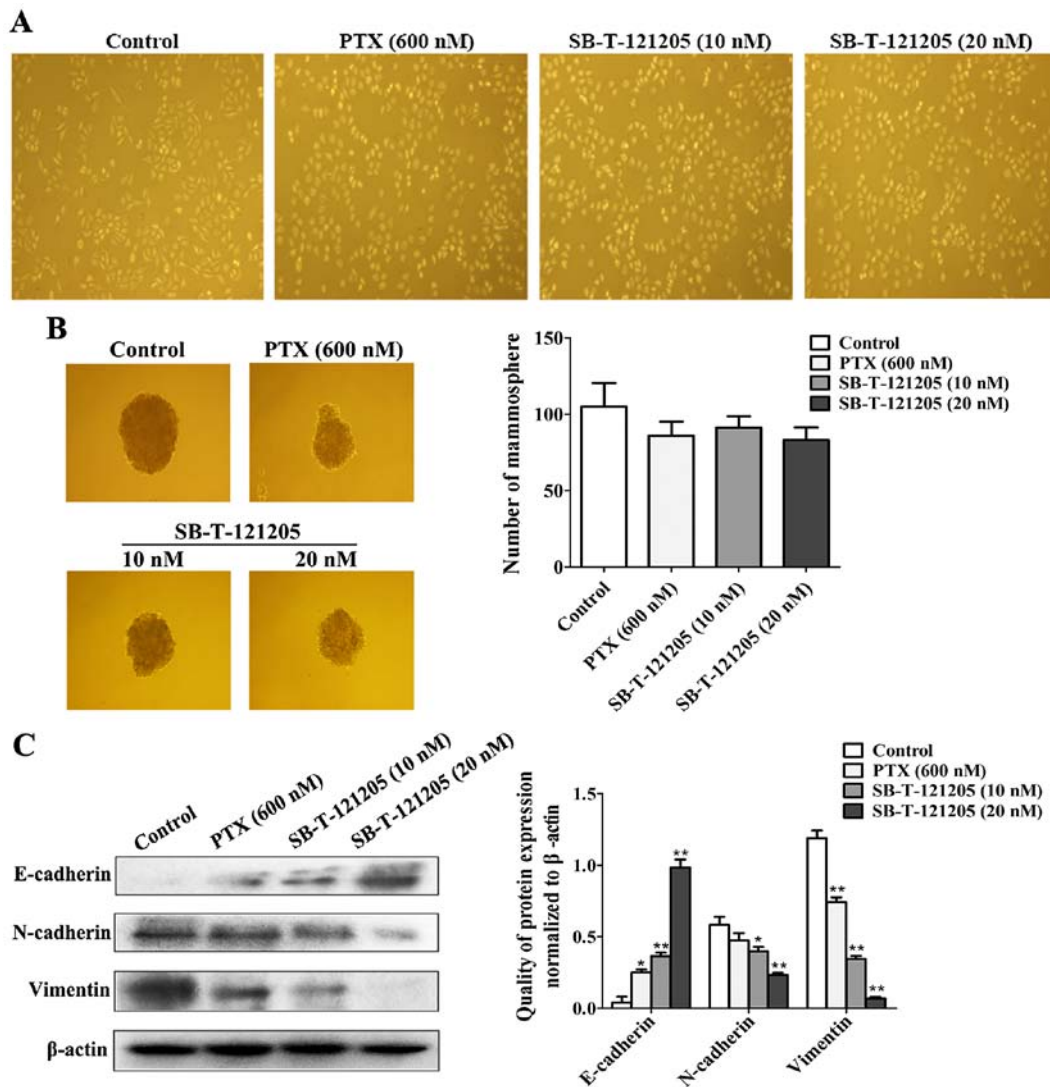


Figure 3. SB-T-121205 inhibits the EMT process in MCF-7/PTX cells. (A) Cell morphology observed by microscopy in MCF-7/PTX cells treated with paclitaxel alone or SB-T-121205 alone (original magnification, x100). (B) The effect of paclitaxel or SB-T-121205 on mammosphere forming ability of MCF-7/PTX cells was examined (original magnification, x100). (C) Expression of E-cadherin, N-cadherin and vimentin after treated with paclitaxel or SB-T-121205, was measured by western blot analysis. Data are shown as mean \pm SD from three experiments and β -actin was used as loading control, * $P < 0.05$, ** $P < 0.01$ vs. control group.

major obstacles for successful chemotherapy (23). Accordingly, the effects of SB-T-121205 on the migration and invasion of MCF-7/PTX and MDA-MB-453 cells were evaluated by wound healing scratch and Transwell invasion methods, respectively. MCF-7/PTX cells treated with SB-T-121205 displayed decreased migratory abilities at 24 and 48 h (Fig. 4A). The percent wound closure of four groups at 48 h were $70.59 \pm 5.80\%$ (control), $63.43 \pm 5.13\%$ (paclitaxel, 600 nM), $43.75 \pm 4.52\%$ (SB-T-121205, 10 nM) and $39.39 \pm 1.80\%$ (SB-T-121205, 20 nM), respectively. Also, SB-T-121205 (10 and 20 nM) reduced the number of invasive cells in a dose-dependent manner (Fig. 4B), wherein 10 nM of SB-T-121205 showed an equivalent effect to 600 nM of paclitaxel.

Similarly, treating MDA-MB-453 cells with paclitaxel (55 nM, a concentration close to the IC_{50} value) or SB-T-121205 (19.5 nM, a concentration close to the $1/2IC_{50}$ value) or SB-T-121205 (39 nM, a concentration close to the IC_{50} value) inhibited the migration and invasion of MDA-MB-453 cells (Fig. 5A and B). SB-T-121205 exhibited its effects on migration and invasion

of MDA-MB-435 cells in a dose-dependent manner, and was clearly more effective than paclitaxel. Thus, we have found that SB-T-121205 not only suppresses the EMT process, but also inhibits migratory and invasive abilities of MCF-7/PTX and MDA-MB-435 human breast cancer cells much more effectively than paclitaxel.

SB-T-121205 represses transgelin 2 expression and activation of the PI3K/Akt pathway in MCF-7/PTX cells. To understand molecular mechanism by which SB-T-121205 receded cell proliferation and migratory/invasive abilities of MCF-7/PTX cells, the protein levels of transgelin 2 and the PI3K/Akt pathway were analyzed. After the treatment of MCF-7/PTX cells with SB-T-121205, the expression of transgelin 2, p-Akt and p-GSK-3 β was downregulated with a concomitant augment expression of PTEN, whereas the levels of Akt and GSK-3 β were unaffected (Fig. 6A).

Furthermore, the deactivation of Akt signaling pathway augmented the expression of pro-apoptotic factor Bax and

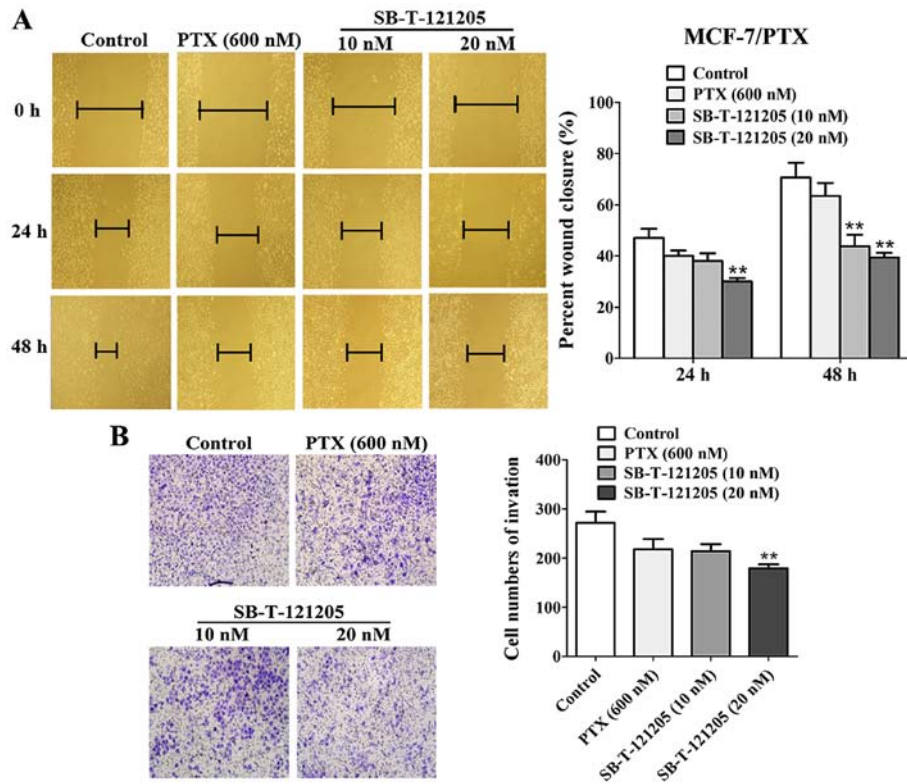


Figure 4. SB-T-121205 inhibits the migration and invasion abilities of MCF-7/PTX cells. (A) Migration of MCF-7/PTX cells treated with paclitaxel or SB-T-121205 was determined by wound healing assay (original magnification, x100). (B) Invasiveness of MCF-7/PTX cells treated with paclitaxel or SB-T-121205 was detected by Transwell invasion assay (original magnification, x100). Data are shown as mean \pm SD from three experiments, ** P <0.01 vs. control group.

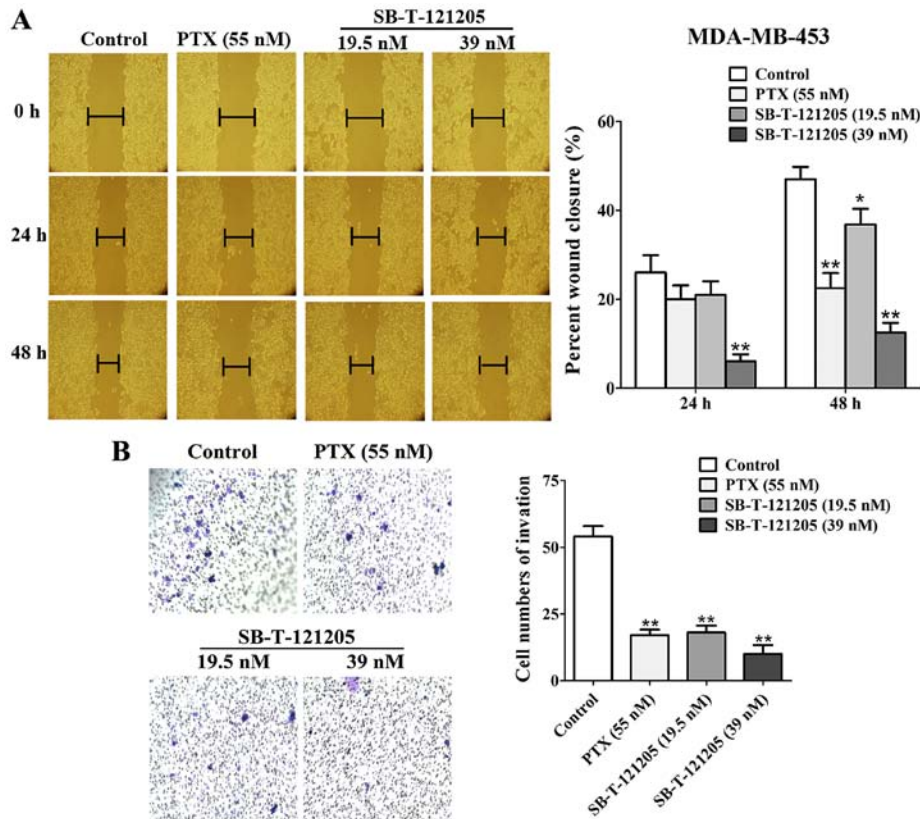


Figure 5. SB-T-121205 inhibits the migration and invasion abilities of MDA-MB-453 cells. (A) Migration of MDA-MB-453 cells treated with paclitaxel alone (55 nM) or SB-T-121205 alone (19.5 and 39 nM) was determined by wound healing assay (original magnification, x100). (B) Invasiveness of MDA-MB-453 cells treated with paclitaxel or SB-T-121205 was detected by Transwell invasion assay (original magnification, x100). Data are shown as mean \pm SD from three experiments, * P <0.05, ** P <0.01 vs. control group.

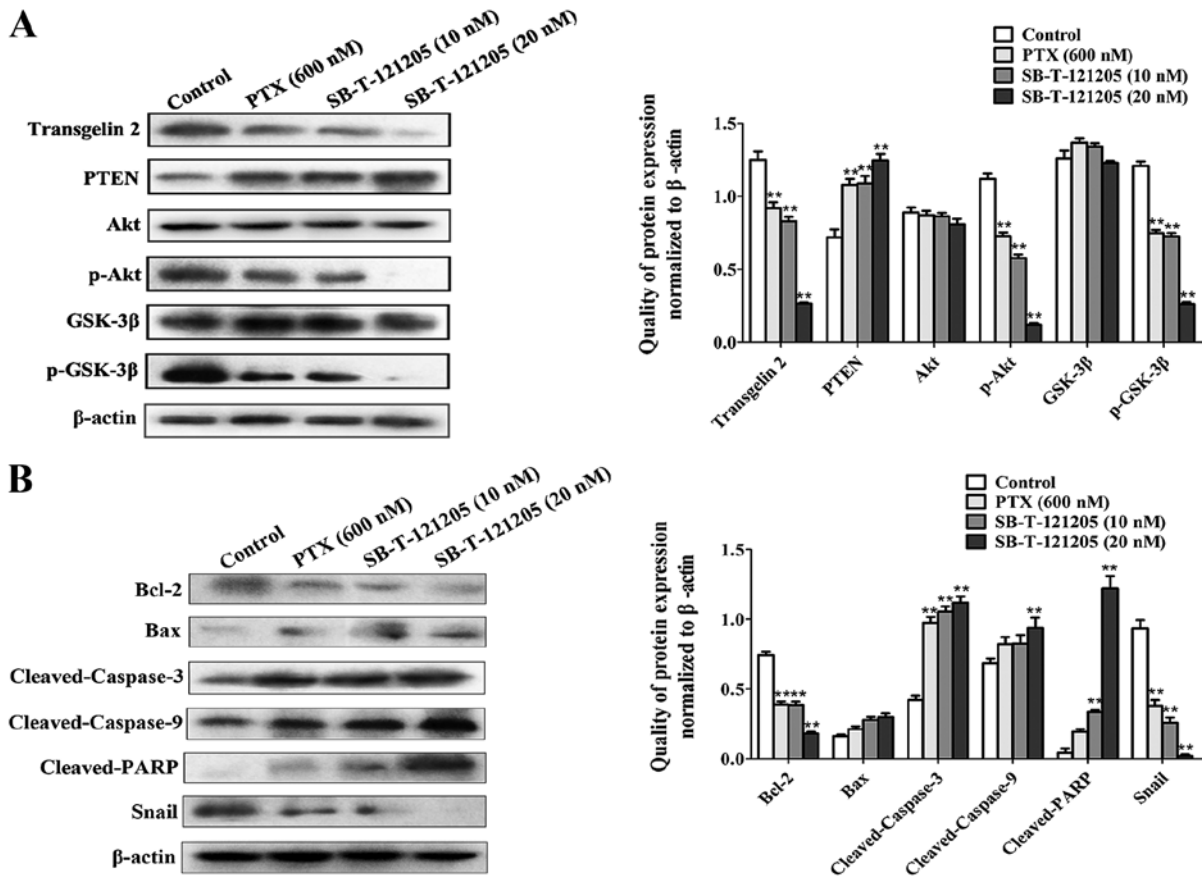


Figure 6. SB-T-121205 suppresses the PI3K/Akt pathway in MCF-7/PTX cells. (A) The levels of transgelin 2, PTEN, Akt, p-Akt, GSK-3β, and p-GSK-3β were tested in MCF-7/PTX cells treated with paclitaxel alone or SB-T-121205 alone for 48 h. (B) Expression of Bcl-2, Bax, cleaved-caspase-3, cleaved-caspase-9, cleaved-PARP, and Snail was examined in MCF-7/PTX cells treated with paclitaxel or SB-T-121205. Data are presented as mean ± SD from three experiments, and β-actin was used as loading control, **P<0.01 vs. control group.

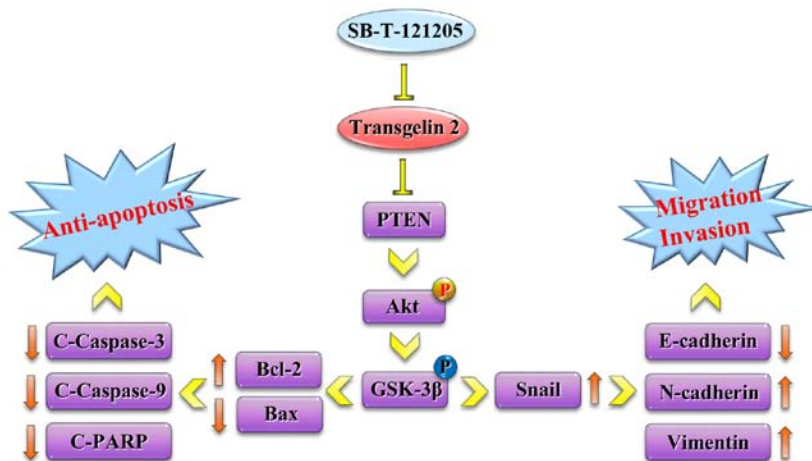


Figure 7. Proposed mechanism of action of SB-T-121205 for inhibition of the growth, migration, and invasion of MCF-7/PTX cells. SB-T-121205 suppresses transgelin 2, then inhibits the PI3K/Akt pathway.

the cleavage of caspase-3, caspase-9, PARP significantly, while suppressed pro-survival factor Bcl-2, ultimately leading to apoptosis. On the other hand, the downstream molecule Snail was strongly downregulated (Fig. 6B). In short, these observations suggest that SB-T-121205 is an antitumor agent that affects cell behavior by modulating transgelin 2 and the PI3K/Akt pathway.

Discussion

Paclitaxel was first approved in April 1992 for the treatment of platinum-resistant breast cancer by the Food and Drug Administration, USA. It exerts vital anticancer effect through its distinct antimetabolic mechanism of action (24). However, a number of studies since then have revealed that treatment

with paclitaxel brought about undesirable adverse effects, including drug-resistance, hence seriously restricting its therapeutic effects and clinical applications (25). For this reason, it is essential to deal with the problem of paclitaxel resistance to enhance the survival of patients with breast cancer.

There are two main ways to solve the problem of drug resistance. The first is to develop resistance reversal agents. Scientists in the past few decades have screened many compounds to identify compounds with multidrug resistance reversal activities against various drug-resistant cell lines. Compounds such as verapamil (26) and metformin (27) were discovered through these efforts and developed. These compounds sensitize tumor cells to chemotherapeutic drugs, and this line of research is continuing. The second is to discover novel compounds with antitumor activities that may have high efficacy against drug-resistant targets and then directly kill cancer cells, which would also provide new insights into prevention and treatment of breast cancer.

Considerable efforts have been made to develop new-generation taxoids with outstanding antitumor activity, much better than paclitaxel. For example, Nikolakakis *et al* (28) reported that 7 β -*O*-glycosylated taxanes (9 and 15) were more potent (IC₅₀ 12-15 nM) than docetaxel (IC₅₀ 40 nM) and much more potent than paclitaxel (IC₅₀ >5 μ M) against adriamycin-resistant human breast cancer cells (MCF-7/ADR). It was also documented that 2'-(*N*-methylpyridinium acetate) derivative of paclitaxel showed excellent potency in lung cancer cells and breast cancer cells (29). Based on structure-activity relationships (SAR) study, a series of new-generation taxanes have been developed by Ojima *et al* (10,30), which exhibited 2-3 orders of magnitude higher potency than paclitaxel or docetaxel against multidrug-resistant breast, ovarian, colon, pancreatic and prostate cancer cell lines (31). These new-generation taxanes have modifications at C10, C3', C3'/N and/or C2. A newly developed next-generation taxane, SB-T-121205 possesses a 3-trifluoromethylbenzoyl group at C2 on the top of modifications in the new-generation taxanes mentioned above. The present study disclosed, for the first time, the excellent activities of SB-T-121205 in inhibiting the growth of MCF-7/S, MCF-7/PTX and MDA-MB-453 human breast cancer cells. An interesting observation in this study was that BEAS-2B normal human cells were relatively insensitive to SB-T-121205, which means that SB-T-121205 has a good therapeutic index. It was observed that the apoptosis induced at 20 nM SB-T-121205 in MCF-7/PTX cells was more powerful than 600 nM paclitaxel, suggesting SB-T-121205 possesses an extremely strong anti-proliferative activity. SB-T-121205 induced G2/M phase arrest in MCF-7/PTX cells in a manner similar to paclitaxel. In addition, SB-T-121205 changed cell morphology, modulated EMT marker expression and weakened the mammosphere forming ability, then mitigated the EMT process in MCF-7/PTX cells. Importantly, SB-T-121205 exhibited its ability to restrain the migration and invasion capacities of MCF-7/PTX cells and MDA-MB-453 cells. Consequently, as a novel next-generation taxane, SB-T-121205 appears to be a very promising lead compound for drug development.

Transgelin 2, located at chromosome 1q21-q25, is an important actin-binding protein responsible for the actin

cytoskeleton dynamics (12). Abundant evidence has indicated that transgelin 2 exerts oncogenic activity. Transgelin 2 has been shown to be involved in lymph node metastasis, distant metastasis as well as tumor-lymph node-metastasis (TNM) staging system in colorectal cancer (CRC). Transgelin 2 may serve as a new biomarker for predicting progression and prognosis of CRC (14). Nohata *et al* (32) revealed that transgelin 2, directly regulated by miR-1, was downregulated by a siRNA and then decreased cell proliferation and invasion in human neck squamous cell carcinoma cells. In our models of paclitaxel-resistant breast cancer, we found that SB-T-121205 suppressed the transgelin 2 protein expression, which can explain the observed altered biological behavior of MCF-7/PTX cells. It has been generally accepted that the PI3K/Akt pathway participates in drug resistance, tumor migration, differentiation and apoptosis. Suppression of the PI3K/Akt pathway has been proven to be an efficient way to attenuate cell growth and migration (33,34). Wang *et al* (35) verified that the PI3K/Akt pathway was activated in cisplatin-resistant lung cancer cells (A549/CDDP), and deactivation of Akt signaling pathway significantly suppressed Snail expression and subsequently induced a substantial decrease in migratory ability and invasiveness of A549/CDDP cells. Snail, a zinc-finger transcription factor, is known as a crucial regulator in the aggressive phenotype of EMT (36). It was supported that PI3K/Akt signal played an essential function during miR-519a-induced hepatocellular carcinoma cell proliferation and cell cycle progression (37). We found that the downregulation of transgelin 2 by SB-T-121205 caused repression of the PI3K/Akt pathway. Deactivation of Akt signal led to revitalization of the mitochondria apoptosis pathway and downregulation of Snail in MCF-7/PTX cells (Fig. 7), which appears to be an important contributor to the unique mechanism of action of SB-T-121205.

In conclusion, we found that SB-T-121205 enhances cell apoptosis, as well as inhibits the migration and invasion abilities of MCF-7/PTX cells, partly by targeting transgelin 2 and the PI3K/Akt pathway. We also found that SB-T-121205 downregulates the transgelin 2 expression. Deactivation of transgelin 2 can be further explored as a basis for new strategies for breast cancer treatment. These findings strongly indicate that SB-T-121205 is a highly promising lead compound for the development of next-generation chemotherapeutic agents in breast cancer treatment.

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