

# RETRACTED ARTICLE: Mannose Suppresses the Proliferation and Metastasis of Lung Cancer by Targeting the ERK/GSK-3 $\beta$ / $\beta$ -Catenin/SNAIL Axis

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**Introduction:** It has been found that mannose exerts antitumoural properties in vitro and in animal models. Whether mannose has potential anti-proliferative and anti-metastatic properties against non-small-cell lung cancer (NSCLC) is unclear.

**Methods:** Here, we performed ex vivo experiments and established a nude mouse model to evaluate the anticancer effects of mannose on NSCLC cells and its effects on the ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL axis. A CCK-8 assay was conducted to evaluate the effects of mannose on lung cancer cells (A549 and HCC827) and normal lung cells (HPAEPiC). Transwells were used to examine the motility of cancer cells. qRT-PCR was used to evaluate the effects of mannose on the mRNA expression of  $\beta$ -catenin. Western blotting was conducted to explore the effects of mannose on the ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL axis and nuclear accumulation of  $\beta$ -catenin. An animal model was established to evaluate the antitumoural effect of mannose on hepatic metastasis in vivo.

**Results:** In this study, we found that mannose inhibited the proliferation of A549 and HCC827 cells in vitro, both time- and dose-dependently. However, it exerted only a slight influence on the viability of normal lung cells in vitro. Moreover, mannose also inhibited the migration and invading capacity of NSCLC cells in vitro. Using Western blotting, we observed that mannose reduced SNAIL and  $\beta$ -catenin expression and ERK activation and promoted phospho-GSK-3 $\beta$  expression. The ERK agonist LM22B-10 promoted the metastatic ability of NSCLC cells and increased SNAIL and  $\beta$ -catenin expression in cancer cells, which could be reversed by mannose. Furthermore, ERK-mediated phosphorylation of the  $\beta$ -catenin-Tyr654 residue might participate in the nuclear accumulation of  $\beta$ -catenin and its transcriptional function. The results from animal experiments showed that mannose effectively reduced hepatic metastasis of A549 cells in vivo. Furthermore, mannose inhibited ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL in tumour tissues obtained from nude mice.

**Discussion:** Collectively, these findings suggest that mannose exerts anti-metastatic activity against NSCLC by inhibiting the activation of the ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL axis, which indicates the potential anticancer effects of mannose.

**Keywords:** non-small-cell lung cancer, mannose, metastasis,  $\beta$ -catenin

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## Introduction

Lung cancer has become a global problem and is also the leading cause of cancer-associated death in China.<sup>1</sup> Non-small-cell lung cancer accounts for 85% to 90% of all lung cancers. Although many therapies for advanced NSCLC have been developed over the past decades, the inhibition of metastasis is still crucial to reduce the mortality associated with lung cancer.<sup>2</sup>

Gonzalez et al reported that mannose, a kind of monosaccharide, exerts anti-proliferative effects on several kinds of cancer cells in vitro and sensitizes cancer cells to chemotherapy, including osteogenic sarcoma, ovarian cancer and pancreatic cancer.<sup>3</sup> Whether mannose exerts anti-metastatic effects on NSCLC cells remains unknown.

$\beta$ -Catenin is overexpressed in many cancer tissues and is considered to be a protumoural molecule. In NSCLC,  $\beta$ -catenin has been reported to participate in the acquisition of stemness,<sup>4</sup> chemoresistance,<sup>5</sup> epithelial-to-mesenchymal transition, and metastasis in cancer patients.<sup>6-8</sup> Whether  $\beta$ -catenin is a potential target of mannose against NSCLC needs to be explored.

In this work, we aimed to identify the effects of mannose on the metastasis of NSCLC cells, A549 and HCC827, and the potential mechanisms behind its anticancer effects.

## Materials and Methods

### Cancer Cell Lines

A549 and HCC827 cells were obtained from ATCC (USA) and cultured in DMEM (Thermo Fisher Scientific, Inc., Waltham, MA, USA) with 10% FBS. Human pulmonary alveolar epithelial cells (HPAEPiC) were purchased from ATCC and cultured in DMEM/F12 (Thermo Fisher Scientific) with 10% FBS.

### Cell Counting Kit-8 (CCK-8) Assay

Cellular viability was evaluated by the CCK-8 reagent (Dojindo, Japan) according to the manufacturer's instructions. Mannose at different concentrations (0, 15, 30, 60 mM) was used to treat cells for 24 h. In addition, 30 mM mannose was used to treat cancer cells for 12, 24 or 48 h. To evaluate the effect of the ERK agonist LM22B-10 (#10) on NSCLC cells in vitro, #10 at different concentrations (0, 250, 500, 1000 nM) was used to treat cells for 24 h. According to the CCK-8 results, 1000 nM #10 was selected for subsequent experiments.

### Transwell Migration and Invasion Assays

For the Transwell invasion assay, 50  $\mu$ L Matrigel (1:6 dilution; BD) was placed in the upper chamber. After being treated with or without 30 mM mannose, cancer cells were digested and resuspended at a density of  $1 \times 10^5$  cells/mL with DMEM without FBS. Then, we added 0.5 mL of the cell suspension to each upper chamber of the 24-well plate, while 0.5 mL DMEM containing

20% FBS was added to the lower chambers. After 24 h, the upper chambers were washed, fixed with 4% paraformaldehyde for 20 min, stained with 0.25% crystal violet for 30 min, and imaged by a microscope (Nikon, Japan). Four fields (10 $\times$ ) were selected randomly, and the number of NSCLC cells was counted. For detection of the migrating ability of cancer cells in vitro, the protocol was the same as that for invasion but without Matrigel.

### RNA Extraction and Real-Time PCR Analysis

RNA was isolated by TRIzol reagent (Invitrogen, Carlsbad, CA). qRT-PCR-related reagents were purchased from QIAGEN (USA). Primer sequences were as follows:  $\beta$ -catenin: forward primer, 5'-ATCATCCTGGGCAATGGAG-3', reverse primer, 5'-GCACCAACAAGCAACTG AAC-3'; SNAIL: forward primer, 5'-ACCCCAATCGGA AGCCTAACT-3', reverse primer, 5'-GGTCGTAGGGCT GCTGG-3'; and  $\beta$ -actin: forward primer, 5'-CGACA GGTTCGAGAAGGAG-3', reverse primer, 5'-ACATCTG CTGGAAGGTG-3'.  $\beta$ -Actin expression was used as a reference.

### Western Blotting Assay

For Western blotting, total protein lysate was extracted by RIPA buffer, and the nuclear/cytoplasmic protein fractions were extracted by NE-PER™ nuclear and cytoplasmic extraction reagents (Thermo Fisher Scientific, Inc., USA) according to the manufacturer's instructions. Protein samples were separated by SDS-PAGE, transferred to polyvinylidene difluoride membranes, blocked with 5% non-fat milk, and incubated with primary antibodies against the following antigens at 4°C overnight:  $\beta$ -catenin (1:1000, CST, USA), SNAIL (1:1000, CST), phospho- $\beta$ -catenin-Tyr654 (1:1000, Abcam, USA), phospho-ERK1/2 (1:1000; Abcam), total-ERK (1:1000; Abcam), histone H3 (1:1000; Abcam), phospho-GSK-3 $\beta$  (1:1000, Abcam),  $\beta$ -Actin (1:1000, Abcam), and GAPDH (1:2500, Abcam). The next day, the membranes were washed with TBST and incubated with horseradish peroxidase-conjugated secondary antibodies (1:2500; Abcam). Electrochemiluminescence was assessed to visualize the protein bands (Abcam). GAPDH expression was used as an internal standard for total protein lysate. Histone H3 and  $\beta$ -Actin expression levels were used as internal standards for nuclear proteins and cytoplasmic proteins, respectively.

## Tumorigenesis Assays

Four-week-old female BALB/c nude mice were purchased from the Laboratory Animal Department of Sichuan Academy Medical Sciences and raised under specific pathogen-free conditions. The animal handling and protocols were approved by the ethics committee of Sichuan Academy Medical Sciences and Sichuan Provincial People's Hospital. To establish a tumour-bearing mouse model, single-tumour cell suspensions ( $2 \times 10^6$ ) of A549 cells were injected into nude mice intraperitoneally. Then, mice were randomly classified into the control group and mannose group (5 mice/group). Mannose (20%) was added to the drinking water. The body weight of nude mice was measured every week. After 28 days, the mice were sacrificed, the metastatic lesions on the liver were calculated, and serum samples were collected. The concentrations of hepatic transaminases (GPT and GOT) were evaluated by microhaematocrit kits (Beijing Solarbio Science & Technology Co., Ltd, Beijing, China).

## Immunohistochemistry (IHC) Staining

Tumour tissues were deparaffinized, dehydrated, incubated with 3%  $H_2O_2$ , and treated with heated ethylene diamine tetraacetic acid for antigen retrieval. Then, a horse radish peroxidase/diaminobenzidine detection IHC kit was used according to the manufacturer's instructions (Pierce). The antibodies used in this study were against the following antigens:  $\beta$ -catenin (1:200; Abcam), phospho-ERK1/2 (1:100; CST), phospho-GSK-3 $\beta$  (1:100; Abcam), and SNAIL (1:100; Abcam).

## Statistical Analysis

The results are shown as the mean  $\pm$  standard error. Student's *t*-test or one-way ANOVA was performed to examine the statistical significance by GraphPad Prism (GraphPad Software, USA).

## Results

### Mannose Inhibits the Proliferative Ability of NSCLC Cells in vitro

Mannose is a carbohydrate that plays an important role in human metabolism (Figure 1A). To evaluate the anti-proliferative effects of mannose on NSCLC cells in vitro, we used A549 and HCC827 cell lines. A CCK-8-based cell viability assay was conducted to test whether mannose exerts anticancer effects on NSCLC cells. The results showed that mannose significantly inhibited the viability of A549 and

HCC827 cells dose-dependently at 24 h in vitro (Figure 1B and C). Furthermore, we used human pulmonary alveolar epithelial cells (HPAEPiC) to evaluate the safety of mannose in normal lung cells in vitro. The results showed that a low concentration of mannose exerted only a slight effect on the viability of HPAEPiC cells in vitro (Figure 1D). The IC50 of mannose in A549 and HCC827 cells at 24 h was approximately 30 mM, which was selected as the experimental concentration in the subsequent assays. In addition, mannose significantly reduced the viability of A549 and HCC827 cells time-dependently in vitro (Figure 1E and F). However, 30 mM mannose did not show an anti-proliferative effect against HPAEPiC cells at 48 h (Figure 1G).

### Mannose Reduces the Migration and Invasion of NSCLC Cells in vitro

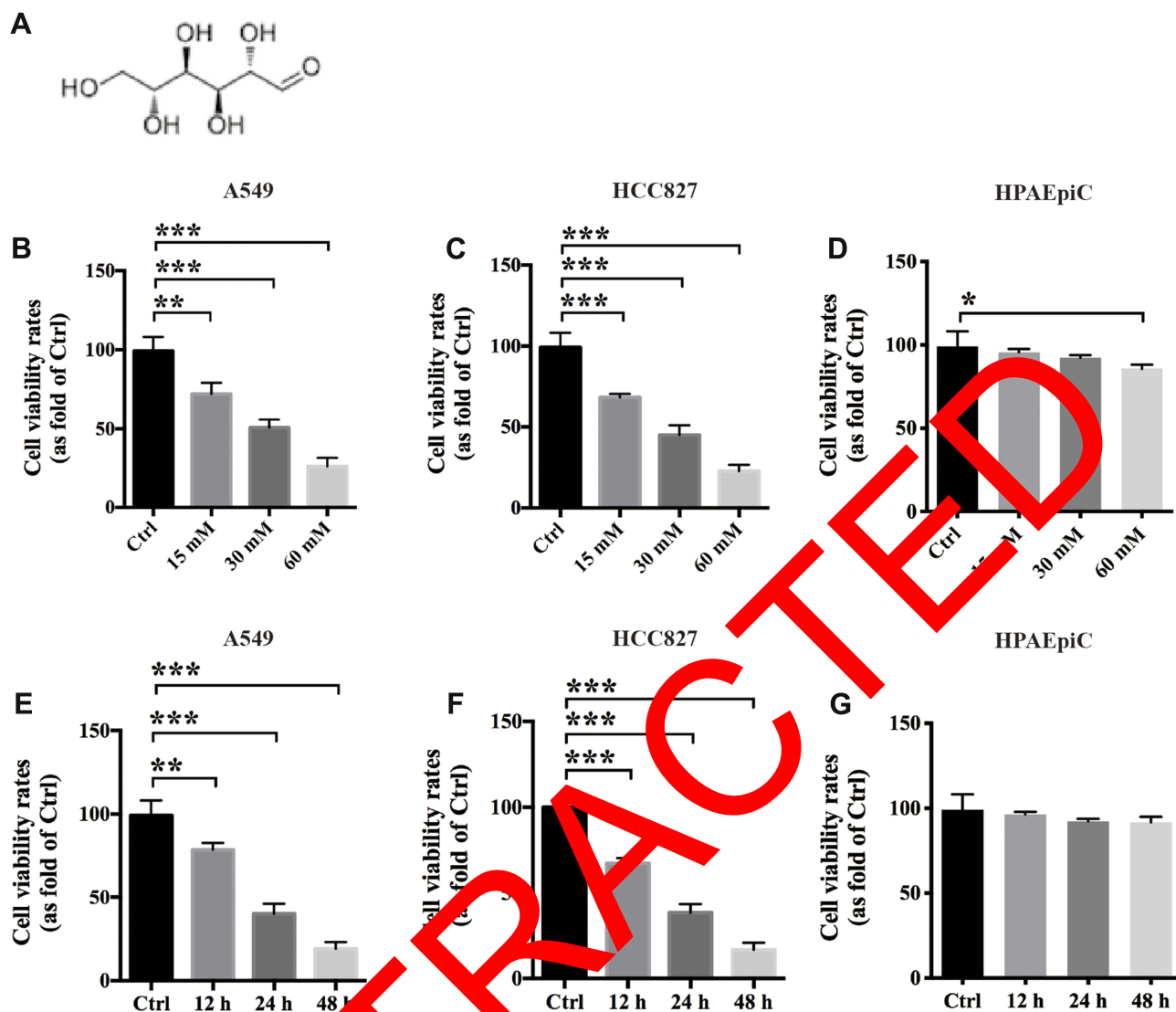
Here, Transwell chambers were used to evaluate whether mannose can affect the migration and invasion of NSCLC cells in vitro. The results revealed that 30 mM mannose could significantly reduce the migration and invasion of both A549 and HCC827 cells at 24 h in vitro (Figure 2).

### Mannose Inhibits $\beta$ -Catenin and SNAIL Expression in NSCLC Cells

$\beta$ -Catenin and SNAIL have been reported to play important roles in cancer metastasis.<sup>9</sup> Next, we used real-time PCR to explore the influence of mannose on the mRNA expression of both  $\beta$ -catenin and SNAIL. We found that mannose exerted a slight influence on  $\beta$ -catenin expression in NSCLC cells in vitro (Figure 3A). However, mannose significantly reduced SNAIL expression in NSCLC cells (Figure 3B). Furthermore, we conducted Western blotting to examine the protein expression of  $\beta$ -catenin and SNAIL in NSCLC cells after treatment with 30 mM mannose for 24 h. The results revealed that mannose significantly inhibited the expression of both  $\beta$ -catenin and SNAIL in NSCLC cells in vitro (Figure 3C and D).

### Mannose Reduces the Phosphorylation Level of Both $\beta$ -Catenin and ERK and Promotes the Phosphorylation Level of GSK-3 $\beta$

$\beta$ -Catenin has been found to regulate the transcription of several epithelial-mesenchymal transition factors, including SNAIL.<sup>10</sup> The phosphorylation of tyrosine 654 in  $\beta$ -catenin facilitates the nuclear translocation of



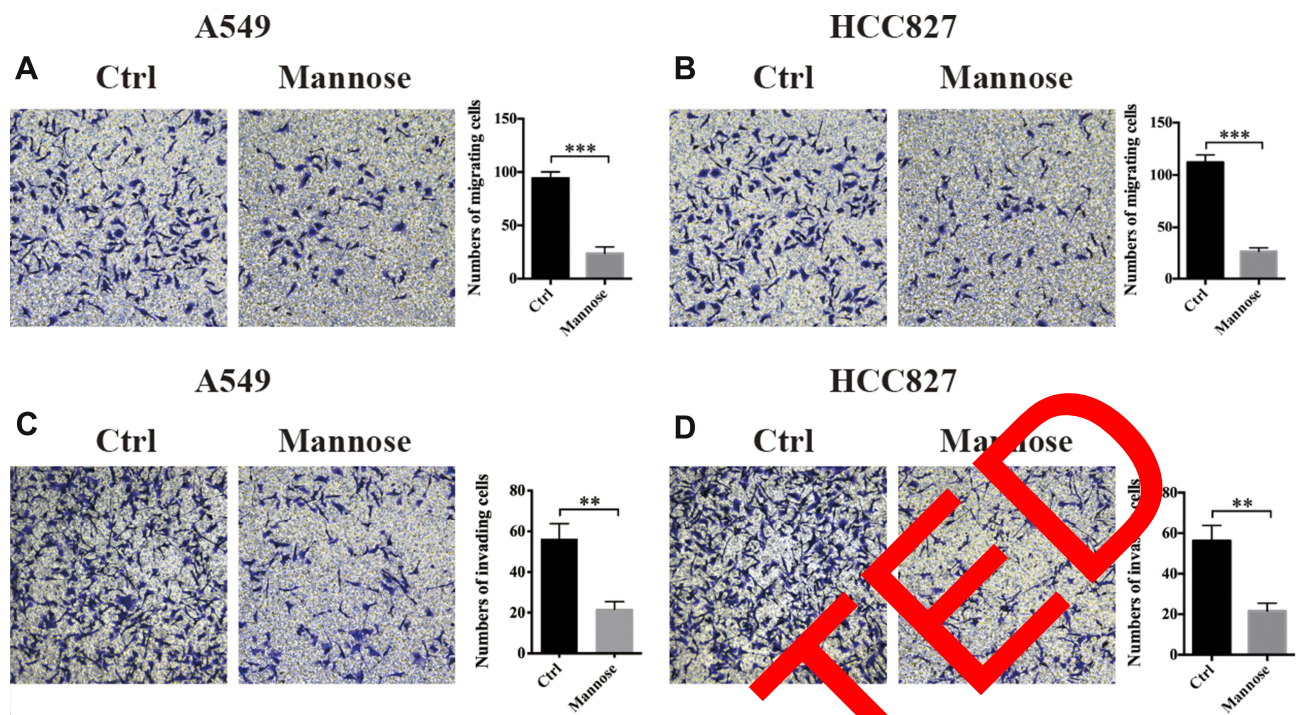
**Figure 1** Mannose inhibits the proliferative ability of non-small-cell lung cancer cells in vitro. The chemical structure of mannose (A). The results from the CCK-8 assay showed that mannose exerts anticancer effects on A549 and HCC827 cells in vitro both dose-dependently (B, C) and time-dependently (E, F). However, mannose did not exert an anti-proliferative effect on HPAEpiC cells in vitro (D). Data are represented as the means  $\pm$  SD. \*, p-value<0.05; \*\*, p-value<0.01; \*\*\*, p-value<0.001. One-way ANOVA was used in Figure 1.

$\beta$ -catenin, which regulated its function as a transcription factor.<sup>11</sup> The Western blotting results revealed that mannose significantly decreased the phosphorylation level of tyrosine 654 in  $\beta$ -catenin in both A549 and HCC827 cells in vitro. Furthermore, we found that mannose could also decrease the phosphorylation level of ERK in NSCLC cells in vitro (Figure 4). It has been reported that phosphorylation of GSK-3 $\beta$  inhibits its function and promotes degradation of  $\beta$ -catenin.<sup>12</sup> In this study, we found that mannose promotes the expression of phospho-GSK-3 $\beta$  in A549 and HCC827 cells. These results indicate that ERK/GSK-3 $\beta$ / $\beta$ -catenin is one of the targets of mannose in lung cancer cells.

## The ERK Agonist LM22B-10 Facilitates the Migration and Invasion of NSCLC Cells and Promotes the Nuclear Accumulation of $\beta$ -Catenin, Which Is Reversed by Mannose

To explore whether the ERK signalling pathway is crucial for the migration and invasion of NSCLC cells and the nuclear accumulation of  $\beta$ -catenin, we used the ERK agonist LM22B-10 (#10) to activate the ERK signalling pathway. The results of CCK-8 assays showed that #10 significantly increased the viability of A549 and HCC827 cells in a dose-dependent manner (Figure 5A and B). Next,





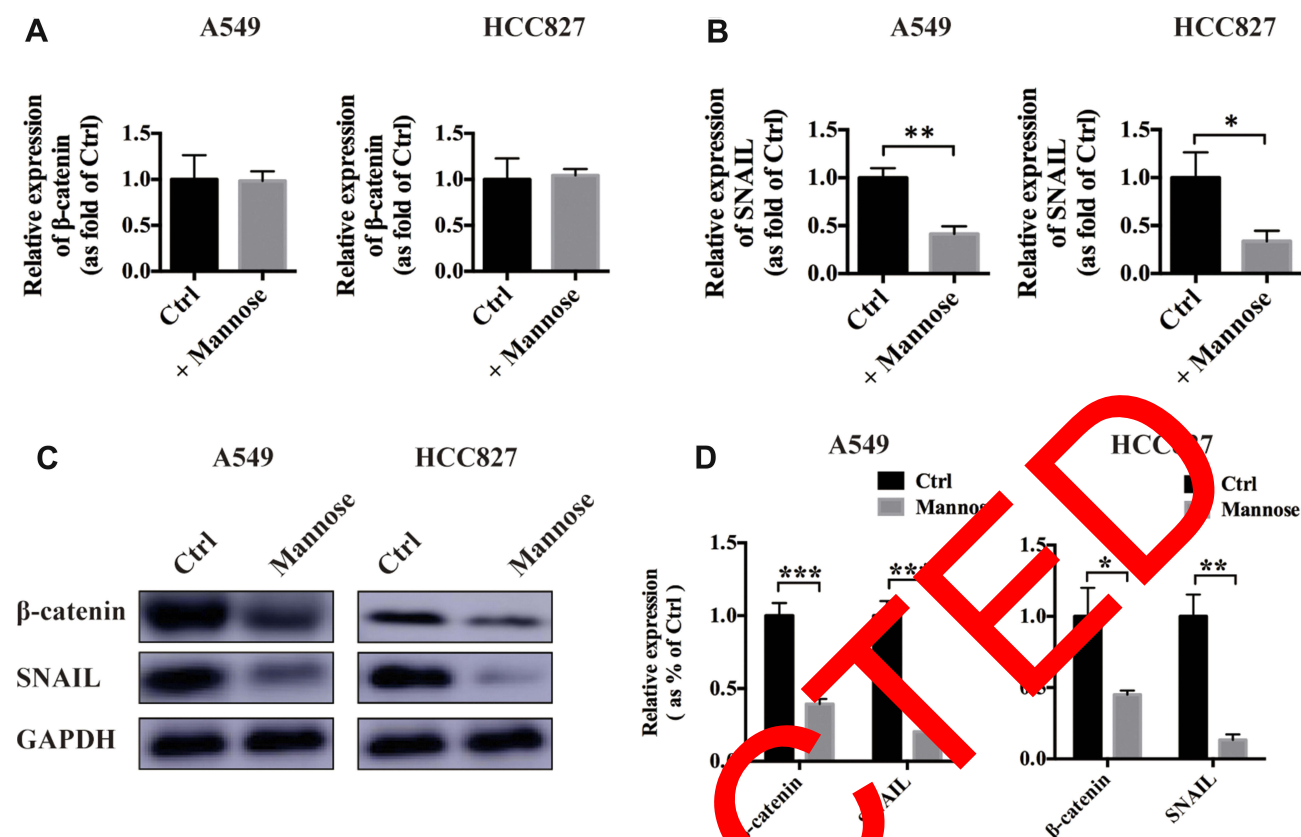
**Figure 2** Mannose reduces the migration and invasion ability of NSCLC cells in vitro. The results from Transwell assay showed that 30 mM mannose significantly inhibited the migration (A, B) and invasion (C, D) of NSCLC cells in vitro. Data are represented as the means  $\pm$  SD. \*\*, p-value<0.01; \*\*\*, p-value<0.001.

we observed that #10 increased the phosphorylation level of Tyr654 in a dose-dependent manner (Figure 5C and D). Based on the results from CCK-8 and Western blotting assays, we chose 1000 nM as the working concentration of #10 and used it in subsequent experiments. Next, the results from the Transwell assay showed that 1 mM #10 increased the migration and invasion abilities of NSCLC cells in vitro, which were significantly reversed by mannose (Figure 5E, F, G and H). To examine the effects of ERK activation on the nuclear accumulation of  $\beta$ -catenin, we extracted the nuclear and cytoplasmic protein fractions from NSCLC cells after treatment with 1 mM #10 or 1 mM #10 + 30 mM mannose for 24 h. By using Western blotting, we found that #10 promoted  $\beta$ -catenin expression in the nucleus in NSCLC cells and that mannose reduced the #10-mediated nuclear accumulation of  $\beta$ -catenin (Figure 5I and J).

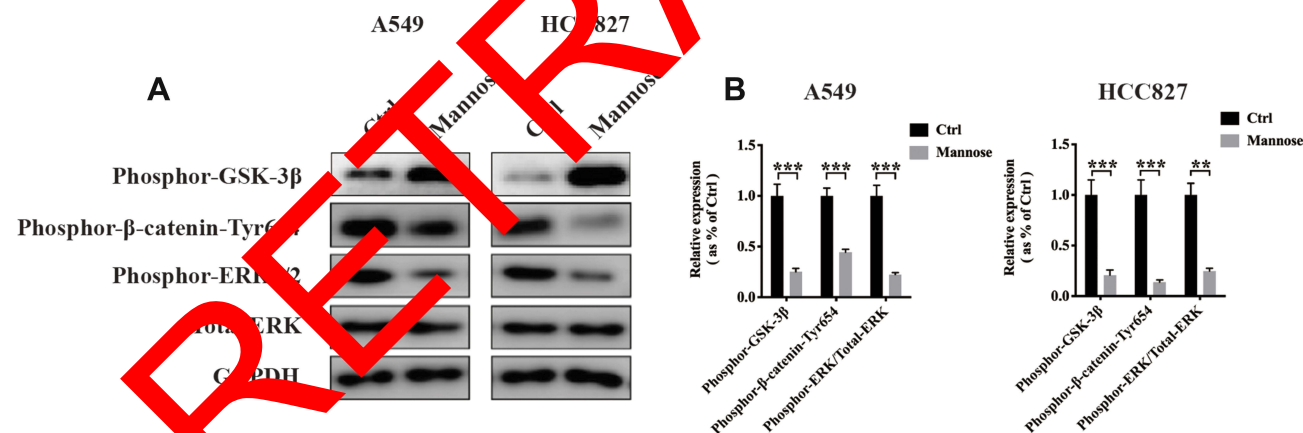
### Mannose Inhibits Hepatic Metastasis of A549 Cells in vivo by Decreasing the ERK/GSK-3 $\beta$ / $\beta$ -Catenin/SNAIL Axis

To evaluate the anti-metastasis effects of mannose on NSCLC cells, a nude mouse model was established by intraperitoneal injection of A549 cells. After injecting A549 cells, mice in the control group were fed normal

drinking water, and mice in the mannose group were fed water containing 20% mannose.<sup>3</sup> We found that mannose increased the body weight of tumour-bearing nude mice (Figure 6A). Furthermore, we measured hepatic transaminases (glutamic-pyruvic transaminase/GPT and glutamic-oxaloacetic transaminase/GOT) in serum samples to evaluate the influence of mannose on the liver function of mice. The results showed that mannose exerted slight effects on GPT and GOT in tumour-bearing nude mice (Figure 6B). Twenty-eight days after injection into nude mice, we observed that mannose significantly inhibited the number of hepatic lesions in nude mice (Figure 6C; n=5). We conducted immunohistochemistry to examine  $\beta$ -catenin, phospho-ERK1/2, phospho-GSK-3 $\beta$ , and SNAIL expression in tumour tissues. We found that mannose decreased  $\beta$ -catenin, phospho-ERK1/2, and SNAIL levels in tumour tissues compared with control tissues. However, mannose increased the expression level of phospho-GSK-3 $\beta$  in tumour tissues (Figure 6D). Moreover, we conducted Western blotting and observed that the expression of  $\beta$ -catenin, phospho-ERK1/2, and SNAIL were all downregulated and the expression of phospho-GSK-3 $\beta$  was upregulated in tumour tissues obtained from mice treated with mannose (Figure 6E; n=3).



**Figure 3** Mannose inhibits  $\beta$ -catenin and SNAIL expression in NSCLC cells. Real-time PCR was used to evaluate the effects of mannose on the mRNA expression of  $\beta$ -catenin and SNAIL in A549 and HCC827 cells (**A**, **B**). Western blotting was conducted to evaluate the effects of mannose on the protein expression of  $\beta$ -catenin and SNAIL in A549 and HCC827 cells (**C**, **D**). Data are represented as the means  $\pm$  SD. \*, p-value<0.05; \*\*, p-value<0.01; \*\*\*, p-value<0.001.

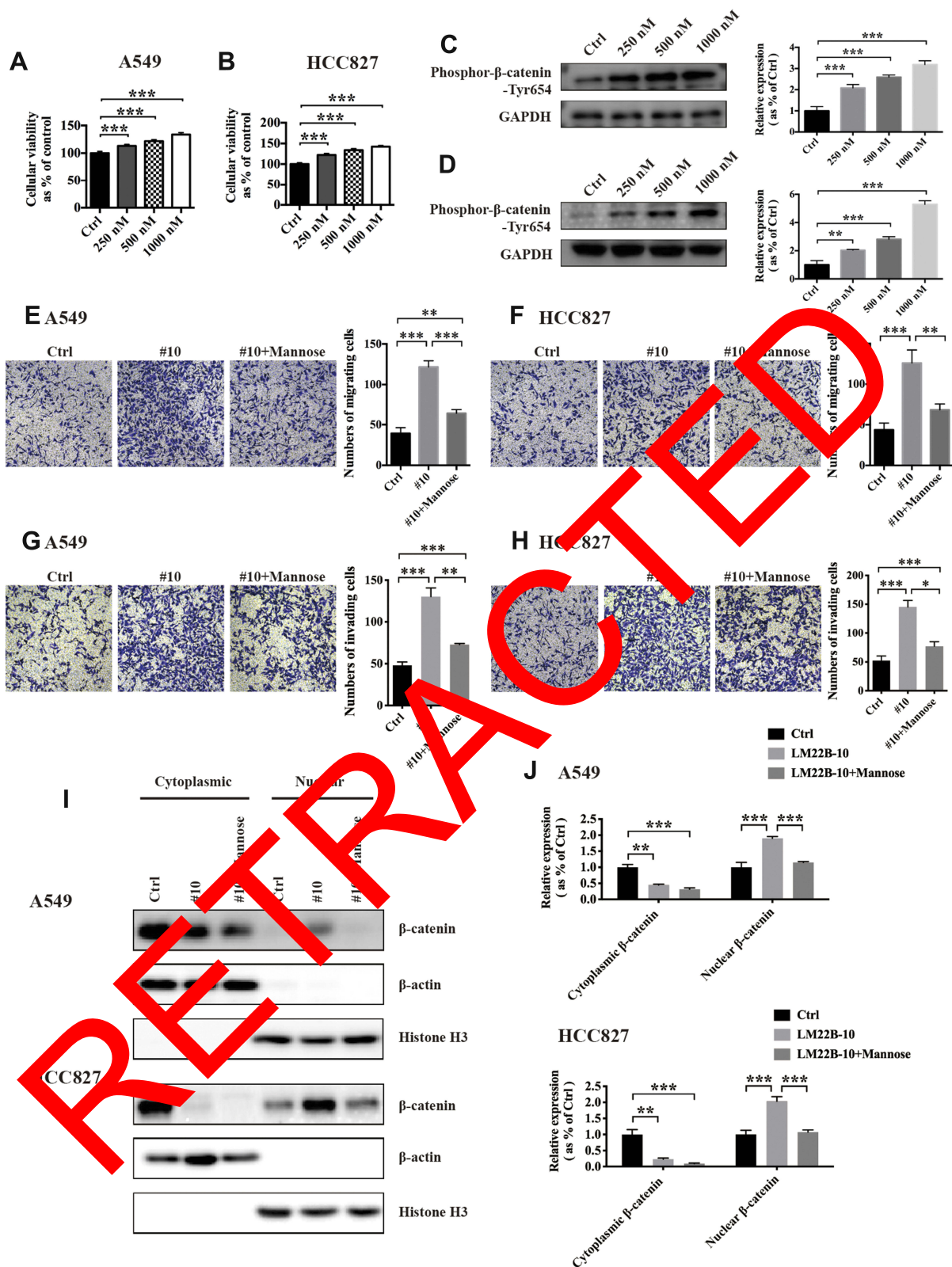


**Figure 4** Mannose regulates the phosphorylation levels of  $\beta$ -catenin, ERK and GSK-3 $\beta$ . Western blotting was conducted to evaluate the effects of mannose on the phosphorylation levels of  $\beta$ -catenin (Tyr654), ERK, and phospho-GSK-3 $\beta$  in NSCLC cells (**A**). The statistical analysis of Western blotting data is shown in (**B**). Data are represented as the means  $\pm$  SD. \*\*, p-value<0.01; \*\*\*, p-value<0.001.

## Discussion

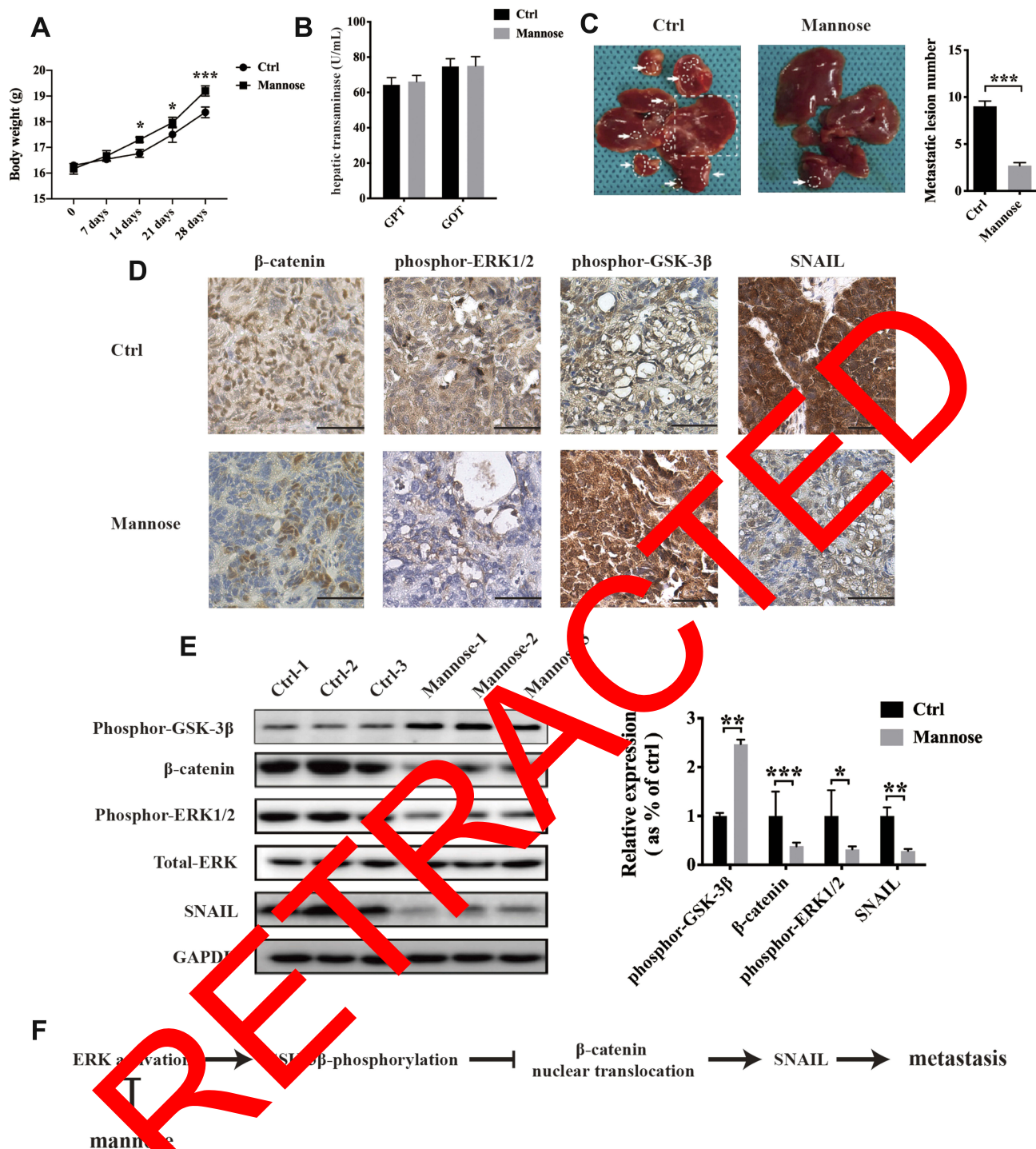
In this work, we found that mannose exerted anticancer effects against NSCLC cells in vivo and in vitro and that the ERK/ $\beta$ -catenin/SNAIL axis was one of the potential targets of mannose in NSCLC treatment. Gonzalez et al

revealed that monosaccharide mannose suppresses proliferation in several types of cancer, including osteosarcoma cells and pancreatic cancer cells. Moreover, mannose can enhance the toxicity of chemotherapy against cancer cells, such as cisplatin and doxorubicin.<sup>3</sup> It was found that



**Figure 5** The ERK agonist LM22B-10 facilitates the migration and invasion of NSCLC cells and promotes the nuclear translocation of β-catenin, which is reversed by mannose. A CCK-8 assay was used to test the effects of LM22B-10 on the viability of NSCLC cells in vitro (**A**, **B**). Western blotting was conducted to test the effects of #10 on the expression of phospho-β-catenin-Tyr654 (**C**, **D**). Transwell assays were used to evaluate whether mannose can reverse the LM22B-10-induced pro-migration (**E**, **F**) and pro-invasion (**G**, **H**) effects on NSCLC cells in vitro. Western blotting was used to examine whether mannose can reverse LM22B-10-mediated nuclear translocation of β-catenin in NSCLC cells (**I**, **J**). Data are represented as the means ± SD. \*, p-value<0.05; \*\*, p-value<0.01; \*\*\*, p-value<0.001.





**Figure 6** Mannose inhibits hepatic metastasis of A549 cells in vivo via downregulation of the ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL axis. Mannose increased the body weight of tumour-bearing nude mice (A). Mannose did not affect the liver function of tumour-bearing nude mice, as demonstrated by evaluating hepatic transaminases (GPT and GOT) in serum samples (B). Mannose significantly reduced hepatic metastasis of A549 cells in a nude mouse model (C). The metastatic lesions in mouse livers are labelled by arrows, circles and squares. Immunohistochemistry was used to explore the effects of mannose on the expression of  $\beta$ -catenin, phospho-ERK1/2, phospho-GSK-3 $\beta$  and SNAIL in tumour tissues obtained from a tumour-bearing nude mouse model (D). Western blotting was conducted to evaluate the expression of  $\beta$ -catenin, phospho-ERK1/2, phospho-GSK-3 $\beta$ , and SNAIL in tumour tissues (E). Schematic diagram of the inhibitory effects of mannose on lung cancer metastasis (F). Data are represented as the means  $\pm$  SD. \*, p-value<0.05; \*\*, p-value<0.01; \*\*\*, p-value<0.001. Scale bar, 200  $\mu$ m.

mannose can be isomerized to fructose-6-P by mannose phosphate isomerase (MPI) after being phosphorylated by hexokinase in animal cells. Hernanz et al found that the

toxicity of mannose against lymphocytes was enhanced by MPI activity in the spleen,<sup>13</sup> which indicates that MPI activity is important for mannose to exert its anticancer

properties. In this work, we found that mannose could decrease the migration and invasion ability of NSCLC cells *in vitro* and in an animal model via the ERK/ $\beta$ -catenin/SNAIL axis. However, the expression pattern of MPI and the relationship between MPI and NSCLC have never been reported before. In addition, whether high MPI activity contributes to resistance to mannose and facilitates the metastasis of NSCLC remains unknown. Cazet et al reported that MPI knockdown significantly decreased glioma survival and increased radiosensitivity, which showed the potential value of the combination of mannose and an MPI-targeted strategy for cancer therapy.<sup>14</sup> In addition, the mannose receptor (MR) is important for macrophage migration and could be used as a prognostic marker in colorectal cancer (CRC).<sup>15</sup> Collectively, these results highlight the potential value of exploring the effects of both mannose and its receptor on cancer metastasis.

Epithelial-mesenchymal transition (EMT) plays a crucial role in embryonic development and in cancer metastasis.<sup>16</sup> The GSK-3 $\beta$ / $\beta$ -catenin signalling pathway has been reported to regulate EMT occurrence in cancer cells. Active and stabilized  $\beta$ -catenin can bind with the T cell factor/lymphoid enhancer factor (TCF/LEF) family and exert transcriptional regulation of EMT-related genes, such as SNAIL.<sup>17</sup> The adhesion protein E-cadherin is important for maintaining epithelial morphogenesis and suppressing tumour metastasis. During the acquisition of metastatic potential, E-cadherin expression is decreased at the late stages of epithelial tumour progression. The  $\beta$ -catenin/LEF complex promotes SNAIL expression, which can bind to the promoter of E-cadherin and inhibit the expression of E-cadherin, promoting EMT.<sup>18</sup> In addition, SNAIL expression also shows prognostic value in NSCLC. Wang et al revealed that high expression of Twist and SNAIL, and low expression of E-cadherin were significantly associated with poor prognosis of patients with NSCLC.<sup>19</sup> In addition to  $\beta$ -catenin/LEF, SNAIL is regulated by many other factors, such as miRNAs, transcriptional co-activator, and long non-coding RNAs. It has been reported that downregulation of miR-22<sup>20</sup> and miR-30<sup>21</sup> increases SNAIL expression and facilitates EMT and invasion of lung cancer. Yang et al found that FOXP3 can activate Wnt/ $\beta$ -catenin signal transduction, induce EMT, upregulate SNAIL expression, and promote tumour metastasis in NSCLC.<sup>22</sup> Decreased NKILA expression was observed in NSCLC tissues and was reported to be regulated by TGF- $\beta$ . Furthermore, NKILA exerts inhibitory effects on the migration and invasion of NSCLC cells by downregulating the

NF- $\kappa$ B/SNAIL pathway.<sup>23</sup> These results indicate the potential mechanisms of mannose-mediated downregulation of EMT-related SNAIL expression.

$\beta$ -catenin is overexpressed in many cancer cells. It plays an important role in cadherin-based adherens junctions<sup>24</sup> and regulating canonical Wnt signalling.<sup>25</sup> Phosphorylation of tyrosine, serine and threonine in  $\beta$ -catenin is crucial for its stabilization, degradation, nuclear translocation and transcriptional regulatory function. Bonvini et al reported that upregulation of phospho- $\beta$ -catenin-Tyr654 decreased the  $\beta$ -catenin/E-cadherin interaction and increased  $\beta$ -catenin-mediated transcription in melanoma cells.<sup>26</sup> Furthermore, they found that geldanamycin destabilized ErbB2, stimulates tyrosine dephosphorylation of  $\beta$ -catenin, decreases nuclear accumulation, inhibits transcriptional regulation and substantially reduces cell motility. Coluccia et al reported that Bcr-Abl could directly interact with  $\beta$ -catenin. Bcr-Abl has tyrosine kinase activity and can phosphorylate  $\beta$ -catenin at the Y86 residue, which enables phospho- $\beta$ -catenin-Tyr86 to bind to the TCF4 transcription factor.<sup>27</sup> The authors also found that imatinib, an antagonist of Bcr-Abl, could disturb  $\beta$ -catenin/TCF4-related transcriptional activity and cause unphosphorylated  $\beta$ -catenin to be retained in the cytoplasm. In addition to the Tyr654 and Tyr86 residues, Ser33/44/41/45/552 and Thr41 have all been reported to participate in the nuclear translocation of  $\beta$ -catenin.<sup>28-30</sup> These findings indicate the important role of  $\beta$ -catenin phosphorylation, and the targeting phosphorylated residues might be potential therapies for lung cancer metastasis. In this work, we found that mannose did not change the mRNA expression of  $\beta$ -catenin but significantly reduced the protein level of  $\beta$ -catenin in lung cancer cells. Furthermore, we found that mannose post-transcriptionally regulated  $\beta$ -catenin by inhibiting the ERK/phospho-GSK-3 $\beta$ /phospho- $\beta$ -catenin-Tyr654 axis and further inhibited  $\beta$ -catenin-mediated transcription of SNAIL and cancer metastasis. Whether mannose exerts inhibitory effects on the nuclear translocation of  $\beta$ -catenin by dephosphorylating other Tyr, Ser, or Thr residues in  $\beta$ -catenin remains unknown, and how mannose affects molecules upstream of ERK needs further study.

Many mechanisms have been reported to regulate the phosphorylation and nuclear translocation of  $\beta$ -catenin, such as the ERK and AKT signalling pathways. Ding et al found that ERK interacts with GSK-3 $\beta$  and can phosphorylate GSK-3 $\beta$  at the Thr43 residue, which promotes GSK-3 $\beta$ -mediated phosphorylation of Ser9 via p90RSK and increases expression of  $\beta$ -catenin.<sup>31</sup> In this study, we observed that the ERK agonist LM22B-10 significantly increased the



phosphorylation of  $\beta$ -catenin-Tyr654, promoted nuclear localization and enhanced the expression of SNAIL, which was consistent with previous findings. Furthermore, we reported here that mannose showed potential anti-metastasis effects by regulating the ERK/phospho-GSK-3 $\beta$ /phospho- $\beta$ -catenin-Tyr654/SNAIL signalling pathway, which has never been reported before. Fang et al observed that AKT signalling can phosphorylate  $\beta$ -catenin and cause  $\beta$ -catenin disassociation from the cell-cell junctions, which results in accumulation in the nucleus, promotes interaction with 14-3-3zeta and facilitates invasion and development of cancer cells.<sup>32</sup> Li et al reported that mannose exerted inhibitory effects on the invasion and metastasis of hepatic cancer cells through the AKT signalling pathway,<sup>33</sup> which indicates the possibility that AKT/ $\beta$ -catenin might be a potential target of mannose-induced anticancer effects.

In summary, our work provides evidence that mannose inhibits metastasis of NSCLC cells in vivo and in vitro, which is associated with inhibition of the ERK/GSK-3 $\beta$ / $\beta$ -catenin/SNAIL pathway (Figure 6F). Although additional experimental and clinical evaluations are needed, the potential antitumour effects of mannose against cancer metastasis may encourage the identification of novel targets for the therapeutic strategies of lung cancer.

## Acknowledgments

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## Author Contributions

QS Luo and B Li were responsible for the design of this research, performed experiments, analysed and interpreted data, and wrote the manuscript. G Li contributed to the design of the study, revised the manuscript and was responsible for the authenticity of the data. All authors contributed to data analysis, drafting or revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work. All authors read and approved the final manuscript to be published.

## Compliance with Ethical Standards

This study was approved by the ethics committee of Sichuan Academy Medical Sciences and Sichuan Provincial People's Hospital. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

## Disclosure

The authors declare that they have no competing interests in this work.

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