

# Twist-related protein 1-mediated regulation of mesenchymal change contributes to the migration and invasion of cervical cancer cells

DANQING WANG, QINGLI LI, KEMIN LI, PING XIAO and RUTIE YIN

Department of Obstetrics and Gynecology, West China Second University Hospital,  
Sichuan University, Chengdu, Sichuan 610041, P.R. China

Received October 2, 2014; Accepted July 7, 2015

DOI: 10.3892/ol.2015.3650

**Abstract.** Twist-related protein 1 (Twist1), is a class II basic helix-loop-helix transcription factor, which has been demonstrated to be a major regulator of epithelial-mesenchymal transition (EMT), and therefore is involved in promoting carcinoma metastasis. Previous studies have demonstrated that Twist1 expression is upregulated in cervical cancer cases with poor clinical outcomes. However, the mechanisms that mediate the role of Twist1 in cervical cancer metastasis are poorly understood. To the best of our knowledge, the present study provides the first evidence that the downregulation of Twist1 by short hairpin RNA lentivirus (LV-shRNA) resulted in the inhibition of invasion and migration of cervical cancer cells. Furthermore, the present study presents evidence that reducing Twist1 expression prevents cervical cancer cells from undergoing EMT. The expression of the epithelial cell marker, E-cadherin, was elevated; and the expression levels of mesenchymal cell markers [fibronectin, vimentin, matrix metalloproteinase-9 (MMP-9) and MMP-2] were reduced in the LV-sh-Twist1 group in cervical cells. Collectively, these findings indicate that Twist1-mediated modulation of EMT is important in the invasion and migration of cervical cells, and also indicates the potential therapeutic importance of strategies involving the inactivation of Twist1-mediated mesenchymal changes in cervical cancer.

## Introduction

Cervical cancer is the second most common cause of cancer-associated mortality in women worldwide (1), and

its global incidence increased at an annual rate of 0.6% between 1980 and 2010 (2). Invasion and metastasis are the primary causes of treatment failure and subsequent mortality in patients with cervical cancer (3). Recurrence and metastasis of cervical carcinoma to other sites, including the lymph nodes (4), bones (5), lungs (6) and liver (7) may also occur. Therefore, the inhibition of metastasis is an auxiliary strategy for curing patients of cancer. However, the molecular alterations that drive invasion and metastasis in cervical cancer are not well established. Identifying these molecular mechanisms may provide insights into potential targets for diagnosis and therapy.

Twist-related protein 1 (Twist1) is a class II member of the highly conserved family of basic helix-loop-helix transcription factors. Twist1 is overexpressed in a number of types of cancer, and correlates with low E-cadherin expression, high cancer aggressiveness and poor patient survival rates (8,9). The role of Twist1 in tumor invasion and metastasis has been attracting increasing interest. Previous studies have demonstrated that carcinoma invasion and metastasis are driven by a process termed epithelial-mesenchymal transition (EMT) (10), which is a process whereby epithelial cells acquire mesenchymal properties and override senescence (11). Twist1 overexpression promotes metastasis *in vivo* by inducing EMT (8). Suppression of Twist1 by small interfering RNA in prostate cancer cells induced the expression of epithelial components and specifically inhibited their capacity for invasion and metastasis (12,13). Furthermore, Twist1 expression also enhances cell migration and invasion in gastric cancer *in vitro* and *in vivo* (14). Therefore, targeting Twist1 may be a novel therapeutic approach for the treatment of cervical cancer.

The present study targeted Twist1 in human cervical cancer HeLa cells and reduced its expression levels using a short hairpin (sh)RNA lentivirus (LV-sh-Twist1) and assessed the resulting effects on migration and invasion of the cells.

## Materials and methods

**Cell culture.** The human cervical cancer cell line HeLa was maintained in RPMI-1640 medium (Gibco, Gaithersburg, MD, USA), supplemented with 10% fetal bovine serum (FBS) (MinHai Bio-Engineering, Lanzhou, China), 1%

---

**Correspondence to:** Professor Rutie Yin, Department of Obstetrics and Gynecology, West China Second University Hospital, Sichuan University, Section 3, Renmin South Road, Chengdu, Sichuan 610041, P.R. China  
E-mail: yrtt2013@163.com; rutieyin@163.com

**Key words:** Twist-related protein 1, cervical cancer, epithelial-mesenchymal transition, invasion, migration

penicillin-streptomycin (Invitrogen Life Technologies, Carlsbad, CA, USA) in a humidified incubator at 37°C, 5% CO<sub>2</sub> atmosphere and 95% air.

**Lentiviral shRNA production and stable knockdown of Twist1.** The GIPZ lentiviral shRNAmir-GFP system (Open Biosystems, Lafayette, CO, USA) was used to knockdown human Twist1 in HeLa cells. Lentiviruses (LVs) that co-express green fluorescent protein (GFP) and shRNAs targeting Twist1, and with expression of GFP and empty vector control were used to infect HeLa cells. The detailed method for making an shRNA-based stable knockdown of Twist1 cell lines is described in a previous study (15). The LVs produced were titrated and stored according to the manufacturer's instructions.

**MTT assay.** HeLa cells were cultured in 96-well plates at a density of 1x10<sup>5</sup> cells per well overnight and infected with LV-sh-Twist1. After 0, 24, 48 and 72 h, 50 µl MTT (1 mg/ml) from Sigma-Aldrich (St Louis, MO, USA) was added to the cell media. After 4 h, the MTT was discarded and 150 µl dimethyl sulfoxide was loaded into each well. The spectrophotometric absorbance of the samples was measured using a microplate reader (Model 680; Bio-Rad Laboratories, Inc., Richmond, CA, USA) at 570 nm with a reference wavelength of 655 nm. The percentage of cell survival was calculated using the following formula: Cell viability = (absorbance value of infected cells / absorbance value of uninfected control cells) x 100. Six duplicate wells were measured at each concentration, and each experiment was performed at least three times.

**Apoptosis assay.** At 48 h after transfection, the HeLa cells were collected and washed twice with cold phosphate-buffered saline, resuspended in 400 µl Annexin V-fluorescein isothiocyanate (FITC) binding buffer at a density of 1x10<sup>6</sup> cells/ml. The cells were stained with 5 µl Annexin V-FITC and 10 µl propidium iodide from an Apoptosis Detection kit (Jingmei Biotech, Shanghai, China) following the manufacturer's instructions. The cells were then subjected to flow cytometry (BD Biosciences, San Jose, CA, USA) to detect cell apoptosis. This experiment was conducted 3 times.

**Cell migration and invasion Transwell assays.** *In vitro* cell invasion assays were carried out in Matrigel-based Transwell plates with slight modifications. HeLa cells (500 µl of 1x10<sup>5</sup> cells/ml in 0.1% FBS + RPMI-1640) were seeded into the Matrigel™-coated upper chambers of an 8 µm pore-sized polycarbonate membrane (Corning Costar, Cambridge, MA, USA). The lower compartments were filled with medium supplemented with 20% FBS. After 24 h, the cells that were present on the other side were stained with crystal violet dye and counted under a light microscope (DP70; Olympus, Melville, NY, USA). The number of cells were determined in eight random fields. The experiment was repeated 3 times for each group. Cell migration assays were carried out in a similar way but without Matrigel™. Migration or invasion of the cells through the chamber to the underside of the filter was assessed as described previously (16).

**Reverse transcription quantitative polymerase chain reaction (RT-qPCR) assay.** Total RNAs were prepared from the treated

cells using TRIzol® reagent (Invitrogen Life Technologies). qPCR was carried out using the ABI 7300 real-time PCR system (Applied Biosystems, Foster City, CA, USA) and performed by SYBR® Green dye according to the manufacturer's instructions. Oligonucleotide primers were synthesized by Sangon Biotech Co., Ltd (Shanghai, China). Sequences of primers used in the qPCR analysis are presented in Table I. The qPCR results were calculated using the 2<sup>-ΔΔCT</sup> method as described previously (17).

**Western blot analysis.** Whole cell proteins were separated on 10% sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) at 6–8 V/cm and transferred to polyvinylidene difluoride membranes using an electrotransfer system (Bio-Rad Laboratories, Inc.). The membranes were then blocked in 5% non-fat milk diluted in Tris-buffered saline. The filters were hybridized with polyclonal rabbit anti-Twist1 (cat no. sc-15393; Santa Cruz Biotechnology, Santa Cruz, CA, USA), mouse anti-E-cadherin (cat no. 14472s), rabbit anti-matrix metalloproteinase-9 (MMP-9; cat no. 3852s), anti-MMP-2 (cat no. 4022s), rabbit anti-vimentin (cat no. 12826; Cell Signaling Technology, Beverly, MA, USA) and rabbit anti-fibronectin (cat no. ab2413; Abcam, Cambridge, UK) antibodies diluted to 1:1,000 at 4°C overnight, followed by incubation with horseradish peroxidase-conjugated goat anti-mouse IgG or goat anti-rabbit IgG secondary antibodies (Santa Cruz Biotechnology; 1:4,000 dilution) for 1 h at room temperature. Mouse anti-GAPDH (cat no. sc-365062; 1:1,000 dilution; Santa Cruz Biotechnology) was used as a loading control. Antibody-antigen complexes were detected with electrochemiluminescence reagents (GE Healthcare, Freiburg, Germany) and the protein bands were quantified by densitometry for subsequent analysis (ImageJ software; National Institutes of Health, Bethesda, MD, USA).

**Statistical analysis.** Statistical analysis was conducted using SPSS software (version 16.0; SPSS, Inc., Chicago, IL, USA). Data from at least three separate experiments are presented as the mean ± standard error of the mean. Paired Student's t-tests were used to determine any significant differences. P<0.05 was considered to indicate a statistically significant difference.

## Results

**LV-sh-Twist1 inhibits cervical cancer cell viability and induces cell apoptosis.** To determine the function of Twist1 in cervical cancer cells, Twist1 was knocked down in HeLa cells using LV-sh-Twist1, which was selected from three candidates by qPCR (data not shown). The effects of LV-sh-Twist1 on Twist1 expression levels were examined by western blotting in cervical cancer HeLa cells. The results demonstrated that transfection of LV-sh-Twist1 resulted in the downregulation of Twist1 (Fig. 1A and B). The expression of Twist1 was reduced in HeLa cells at 24, 48 and 72 h after LV-sh-Twist1 transfection and that the level of inhibition increased in a time-dependent manner (Fig. 1A). The expression level of Twist1 was decreased at 48 h after LV-sh-Twist1 transfection compared with LV-GFP (Fig. 1B).

MTT assay was used to determine the effect of LV-sh-Twist1 on HeLa cell proliferation. The present results revealed that the knockdown of Twist1 evoked a marked inhibition effect

Table I. List of reverse transcription-polymerase chain reaction primers used in the present study.

Gene name	Sequence	Product length (bp)
$\beta$ -actin	F: 5'TGACGTGGACATCCGCAAAG3' R: 5'CTGGAAGGTGGACAGCGAGG3'	205
E-cadherin	F: 5'TGCCGCCATCGCTTACAC3' R: 5'TGCTTAACCCCTCACCTTGA3'	179
Vimentin	F: 5'AAATGGCTCGTCACCTTCG3' R: 5'GGGTATCAACCAGAGGGAGTG3'	186
Fibronectin	F: 5'TGCCAACCTTTACAGACCTATCC3' R: 5'GAAATGTGAGATGGCTGTGGTG3'	122

F, forward; R, reverse.

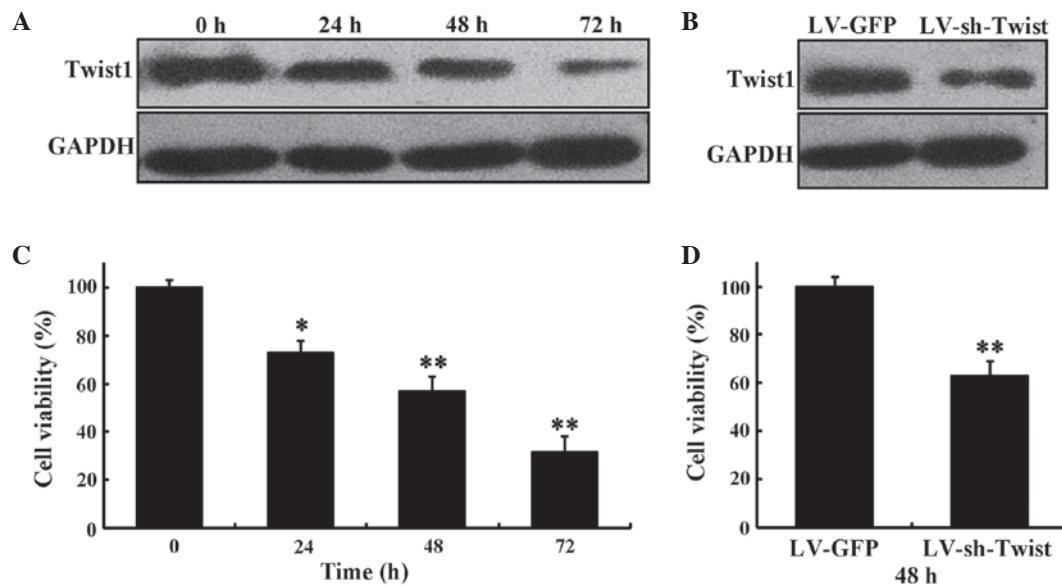


Figure 1. Inhibitory effect of LV-sh-Twist1 on the survival rate of HeLa cells. (A) The expression levels of Twist1 by LV-sh-Twist1 in HeLa cells at 0, 24, 48 and 72 h, respectively. (B) The expression levels of Twist1 at 48 h after transfection with LV-sh-Twist1 or LV-GFP. (C) HeLa cells were treated with LV-sh-Twist1. MTT assay was performed to determine cell viability rates at 0, 24, 48 and 72 h, respectively. (D) At 48 h after transfection with LV-sh-Twist1 or LV-GFP, the viability of HeLa cells was assessed using MTT assay. Data are presented as the mean  $\pm$  standard deviation from three independent experiments. \* $P$ <0.05 and \*\* $P$ <0.01 compared with control. Twist1, Twist-related protein 1; sh, short hairpin; LV, lentivirus; GFP, green fluorescent protein.

on cell proliferation after 24, 48 and 72 h of LV-sh-Twist1 transfection in HeLa cells ( $73.2 \pm 5.3\%$ ,  $P$ <0.05;  $57.4 \pm 6.1\%$ ,  $P$ <0.01; and  $32 \pm 6.7\%$ ,  $P$ <0.01, respectively; Fig. 1C), whereas the cell viability in the LV-sh-Twist1 transfection group was reduced significantly compared with the LV-GFP group at 48 h ( $63.5 \pm 6.6\%$ ,  $P$ <0.01; Fig. 1D).

As it has been demonstrated that cell apoptosis serves a considerable role in the progression and development of tumors (18), the present study further explored whether the cell proliferation inhibition observed was due to the induction of apoptosis. Flow cytometry was used to determine the level of cell apoptosis at 48 h after control, LV-GFP or LV-sh-Twist1 transfection. The results demonstrated that the total cell apoptosis rate of the LV-sh-Twist1 transfection group was significantly increased compared with the control group ( $19.4 \pm 1.5$  vs.  $6.2 \pm 0.6\%$ ,  $P$ <0.01; Fig. 2). The proportions of early and late cell apoptosis rates were consistent with the total cell apoptosis rates.

*Altered expression of Twist1 influences migration and invasion in cervical cancer cells.* The present study further examined whether the migration and invasion of cervical cancer cells is attenuated by the reduction of Twist1 expression via LV-mediated shRNA. Transwell® assays were employed to investigate whether the migration and invasion of cervical cells were affected by LV-sh-Twist1. Notably, when Twist1 was downregulated by LV-sh-Twist1 transfection, the migration of HeLa cells was reduced by  $\sim 53\%$  compared with the control group (Fig. 3A;  $P$ <0.05). Similar results were obtained from invasion assays, which showed a reduction of  $\sim 5\%$  compared with the control group (Fig. 3B;  $P$ <0.05).

*LV-sh-Twist1 inhibits EMT of cervical cells.* As numerous studies have revealed that EMT is closely associated with the migration and invasion of cancer cells (19,20), the present study investigated the effect of LV-sh-Twist1 transfection on EMT processes in cervical cells by examining the changes in

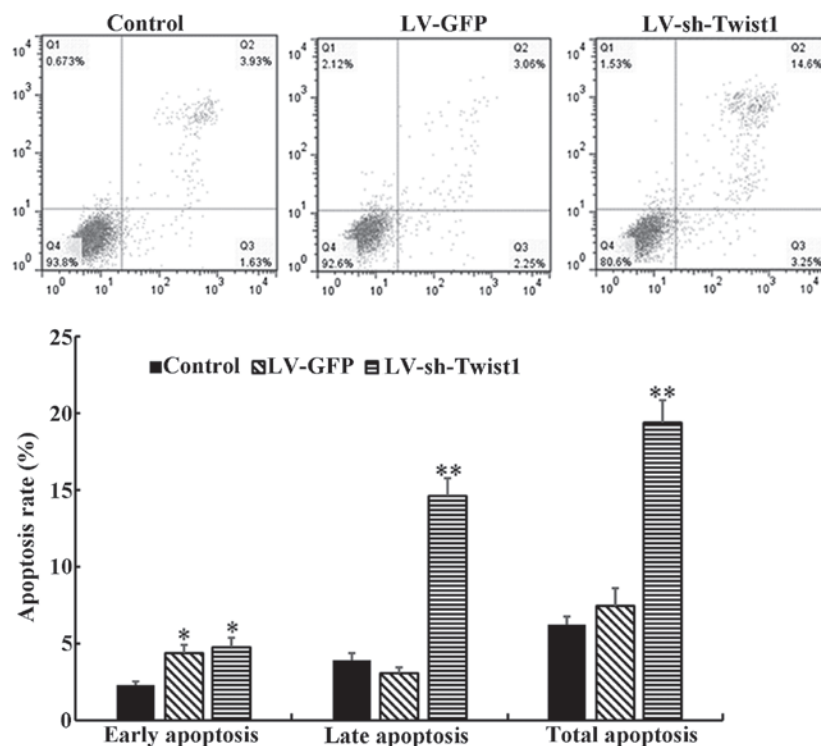


Figure 2. The impact of Twist1 expression on cell apoptosis. Downregulation of Twist1 induced cell apoptosis in HeLa cells. Cells were harvested at 48 h after transfection, followed by an apoptosis assay using the Annexin V-fluorescein isothiocyanate apoptosis detection kit. Cells in the right lower and upper quadrants are considered to indicate early and late apoptosis, respectively, and those in the left upper quadrants are considered to indicate dead cells. The results were analyzed by FlowJo software. These data are expressed as the mean  $\pm$  standard deviation of three independent experiments. \* $P<0.05$  and \*\* $P<0.01$  compared with control. Twist1, Twist-related protein 1; LV, lentivirus; GFP, green fluorescent protein; sh, short hairpin.

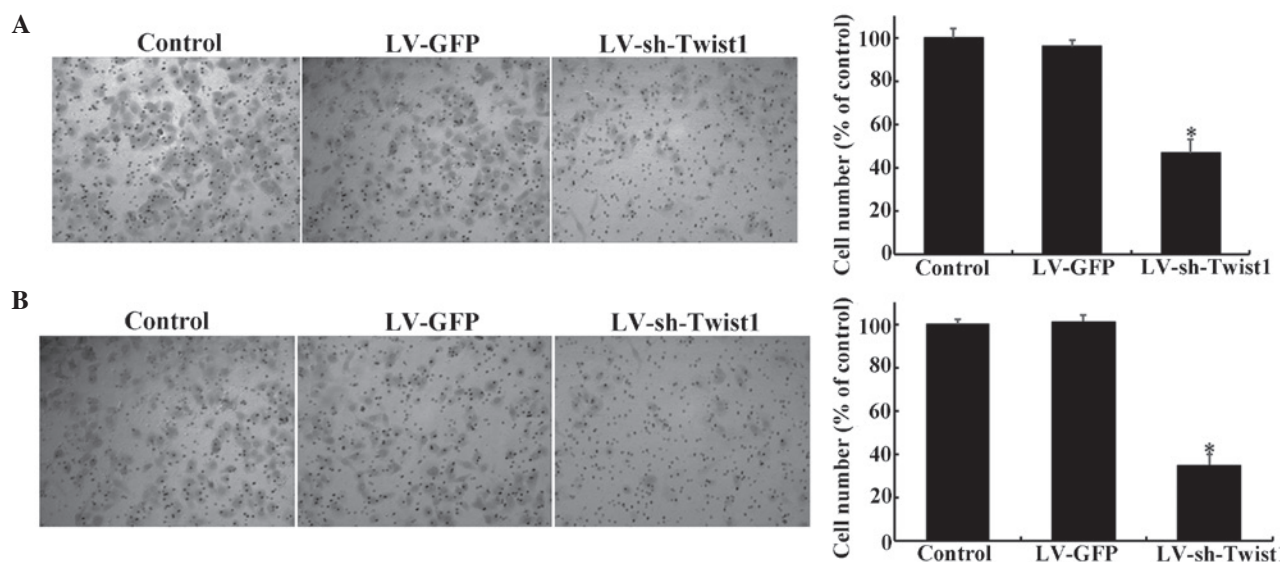


Figure 3. Knockdown of Twist1 suppressed the migration and invasion of HeLa cells. HeLa cells were infected with lentiviral vectors encoding shRNA against Twist1. The results of the Transwell assay showed that the lentiviral delivery of shRNA targeting Twist1 resulted in reduced cell (A) migration and (B) invasion in HeLa cells. Three independent experiments were performed. \* $P<0.05$  compared with control. Twist1, Twist-related protein 1; shRNA, short hairpin RNA; LV, lentivirus; GFP, green fluorescent protein.

E-cadherin, fibronectin, MMP-9, MMP-2 and vimentin expression. RT-qPCR results demonstrated that the expression of the epithelial cell marker, E-cadherin, was significantly elevated in HeLa cells 48 h after LV-sh-Twist1 transfection ( $P<0.05$ ). As hypothesized, the expression levels of mesenchymal cell markers (fibronectin and vimentin) were significantly reduced

in the LV-sh-Twist1 transfection group ( $P<0.05$ ; Fig. 4). In addition, similar results were observed from western blot analysis; the expression levels of fibronectin, vimentin, MMP-9 and MMP-2 were downregulated, whereas E-cadherin was upregulated in the LV-sh-Twist1 transfection group (Fig. 4). These results provide evidence for a potential role of EMT



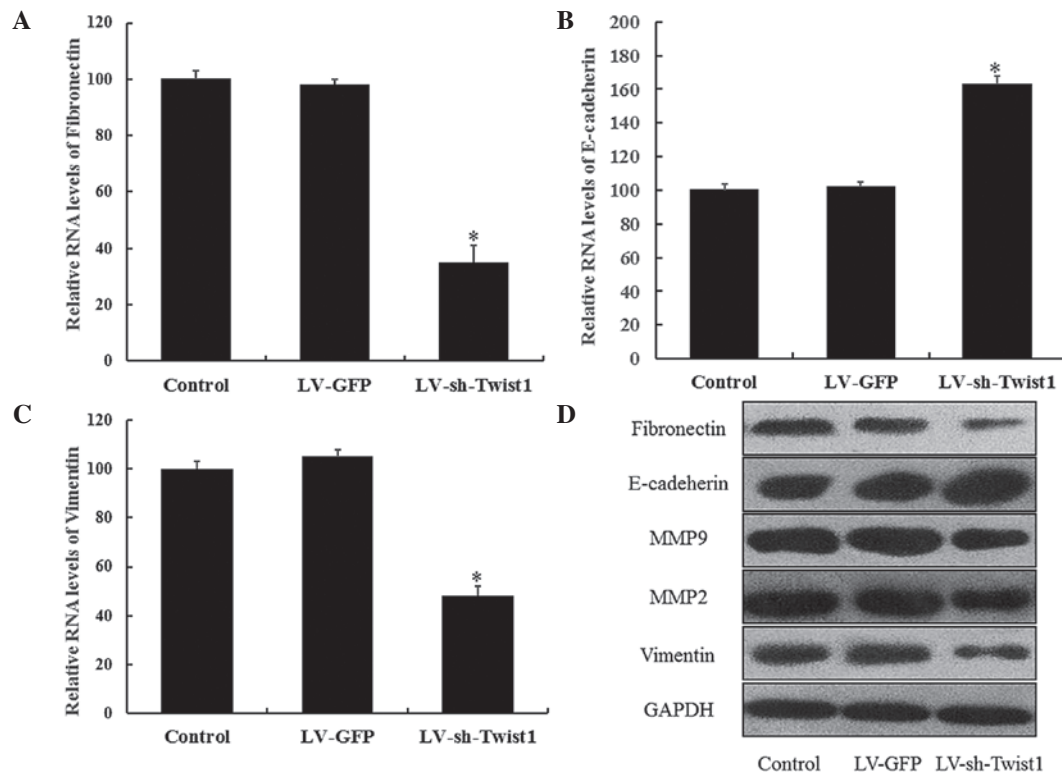


Figure 4. Inhibition of Twist1 expression regulates the epithelial and mesenchymal markers in HeLa cells. HeLa cells were transfected with control, LV-GFP or LV-sh-Twist1 and incubated for 48 h. mRNA expression of (A) E-cadherin, (B) vimentin and (C) fibronectin were quantified by reverse transcription quantitative polymerase chain reaction. Each expression was normalized to that of  $\beta$ -actin, and the relative expression levels compared with the sample of each control solvent are shown. Data are presented as the mean  $\pm$  standard error of the mean of three different experiments. \* $P < 0.05$  compared with control. (D) Whole-cell extracts were analyzed by SDS-PAGE and western blot analysis with specified antibodies. Fibronectin, E-cadherin, MMP-9, MMP-2 and vimentin proteins were determined and GAPDH was selected as the endogenous control. Densitometry was used to quantify and analyze the data. Twist1, Twist-related protein 1; MMP, matrix metalloproteinase; sh, short hairpin; LV, lentivirus; GFP, green fluorescent protein.

during the effects of Twist1 downregulation, which reduces the migration and invasion of cells in cervical cancer.

## Discussion

Cervical cancer remains the only major gynecological malignancy that is clinically staged. At present, no accurate, efficient techniques for indicating prognosis and diagnosing parametrium invasion and lymph node metastasis are available for the selection of the most suitable treatment (21). The identification and functional characterization of molecules critically involved in prognosis, parametrium invasion and lymph node metastasis may reveal targets for diagnostic and therapeutic applications.

The majority of cancer-related mortality events occur as a result of metastasis rather than the original tumor; therefore, inhibiting cancer cell metastasis is a crucial aspect of cancer prevention. Previous studies observed that Twist1 expression promoted the migration and invasion capabilities of human breast cancer and hepatocellular carcinoma cells (22,23), which are essential for tumor metastasis (8). Furthermore, Twist1 expression in cervical cancer is associated with poor disease outcome (24). These results indicate that Twist1 is closely correlated with the invasion of cervical cancer cells. The objective of the present study was to investigate whether the migration and invasion of cervical cancer cells was regulated by Twist1, and if this was the case, which molecular mechanisms and signaling

pathways were involved. To investigate the therapeutic relevance of inhibiting Twist1 in cervical cancer, Twist1 expression was knocked down using shRNA and the effects on cell invasion and migration were assessed. The results of the present study indicated that specific inhibition of Twist1 expression resulted in marked reductions in cervical cancer cell invasion *in vitro*. These findings are consistent with the pro-invasive functions of Twist1 in cervical cancer and support the therapeutic potential of inhibiting Twist1 or Twist1-mediated EMT to inhibit cervical cancer cell invasion and migration. The present data demonstrated that the inhibition of Twist1 expression resulted in a notable reduction in cervical cancer cell growth and an increased cell apoptosis rate. These results indicate that the inhibition of Twist1 may have therapeutic potential, resulting in the targeting of cervical cancer cell invasiveness that contributes to tumor growth, progression and treatment resistance. To further address this potential, ongoing and future studies should address the effects of Twist1 inhibition in cervical cancer cells on tumor growth, invasion and response to therapy *in vivo*. The present study revealed that the downregulation of Twist1 by LV-sh-Twist1 transfection attenuates the cell migration and invasion abilities of cervical cancer cells through the reversal of EMT or suppression of MMP expression.

EMT is characterized by increased migratory features, reduced epithelial cell adhesion, loss of cytoskeleton components and acquisition of mesenchymal components (25), which is also critical for cancer metastasis. Induction of EMT may

result in cancer cells invading the surrounding stroma, and to intravasation, dissemination and colonization of distant sites. Thus, reversal of EMT is considered to be an effective strategy against cancer metastasis (26). In the present study, downregulation of Twist1 by LV-sh-Twist1 was demonstrated to be capable of reversing the process of EMT by reducing the expression of mesenchymal markers vimentin and fibronectin, and increasing the expression of the epithelial marker E-cadherin. These findings indicate that the inhibition of invasion by LV-sh-Twist1 in HeLa cells may be partly attributed to the reversal of EMT.

MMPs serve a critical role in cancer invasion, migration, metastasis and tumorigenesis. Blocking tumor cell expression of MMPs significantly reduces tumor invasion and metastasis (27). MMP-2 and -9 are major components of the extracellular matrix and basement membrane. A number of human tumors have been reported to be associated with increased expression of MMP-2 and -9 (28), and tumor aggressiveness has been found to significantly correlate with increased levels of MMP-2 and -9 in prostate (29) and breast (30) cancer. Cytokines and inhibitors regulate MMP-2 and -9 expression in cervical and ovarian cancer cells (31). In the present study, knockdown of Twist1 reduced expression of MMP-2 and -9 in the cervical cancer cell line.

In conclusion, the present study provides experimental evidence that knockdown of Twist1 by LV-sh-Twist1 suppresses cell migration and invasion in cervical cancer, which in turn drives EMT. Therefore, the results demonstrate an effect of Twist1 on cervical cancer cell invasion and metastasis, which may lead to the identification of novel diagnostic markers and therapeutic targets, and thus aid the understanding of the mechanisms behind cervical cancer metastasis.

## Acknowledgements

The present study was supported by grants from the Project of the Science and Technology Bureau Foundation of Chengdu City (no. 0GGYB452SF-023) and the Health and Family Planning Commission Foundation of Sichuan Province (no. 100368).

## References

- Jemal A, Bray F, Center MM, Ferlay J, Ward E and Forman D: Global cancer statistics. *CA Cancer J Clin* 61: 69-90, 2011.
- Ferlay J, Forman D, Mathers CD and Bray F: Breast and cervical cancer in 187 countries between 1980 and 2010. *Lancet* 379: 1390-1391, 2012.
- Waggoner SE: Cervical cancer. *Lancet* 361: 2217-2225, 2003.
- Takeuchi H, Kitajima M and Kitagawa Y: Sentinel lymph node as a target of molecular diagnosis of lymphatic micrometastasis and local immunoresponse to malignant cells. *Cancer Sci* 99: 441-450, 2008.
- Thanappapras D, Nartthanarung A, Likittanasombut P, Na Ayudhya NI, Charakorn C, Udomsubpayakul U, Subhadarbandhu T and Wilailak S: Bone metastasis in cervical cancer patients over a 10-year period. *Int J Gynecol Cancer* 20: 373-378, 2010.
- Yamamoto K, Yoshikawa H, Shiromizu K, Saito T, Kuzuya K, Tsunematsu R and Kamura T: Pulmonary metastasectomy for uterine cervical cancer: A multivariate analysis. *Ann Thorac Surg* 77: 1179-1182, 2004.
- Park JY, Lim MC, Lim SY, Bae JM, Yoo CW, Seo SS, Kang S and Park SY: Port-site and liver metastases after laparoscopic pelvic and para-aortic lymph node dissection for surgical staging of locally advanced cervical cancer. *Int J Gynecol Cancer* 18: 176-180, 2008.
- Yang J, Mani SA, Donaher JL, Ramaswamy S, Itzykson RA, Come C, Savagner P, Gitelman I, Richardson A and Weinberg RA: Twist, a master regulator of morphogenesis, plays an essential role in tumor metastasis. *Cell* 117: 927-939, 2004.
- Qin Q, Xu Y, He T, Qin C and Xu J: Normal and disease-related biological functions of Twist1 and underlying molecular mechanisms. *Cell Res* 22: 90-106, 2011.
- Kalluri R and Weinberg RA: The basics of epithelial-mesenchymal transition. *J Clin Invest* 119: 1420-1428, 2009.
- Campisi J: Senescent cells, tumor suppression and organismal aging: Good citizens, bad neighbors. *Cell* 120: 513-522, 2005.
- Alexander NR, Tran NL, Rekapally H, Summers CE, Glackin C and Heimark RL: N-cadherin gene expression in prostate carcinoma is modulated by integrin-dependent nuclear translocation of Twist1. *Cancer Res* 66: 3365-3369, 2006.
- Kwok WK, Ling MT, Lee TW, Lau TC, Zhou C, Zhang X, Chua CW, Chan KW, Chan FL, Glackin C, *et al*: Up-regulation of TWIST in prostate cancer and its implication as a therapeutic target. *Cancer Res* 65: 5153-5162, 2005.
- Luo GQ, Li JH, Wen JF, Zhou YH, Hu YB and Zhou JH: Effect and mechanism of the Twist gene on invasion and metastasis of gastric carcinoma cells. *World J Gastroenterol* 14: 2487-2493, 2008.
- Fu J, Qin L, He T, Qin J, Hong J, Wong J, Liao L and Xu J: The twist/mi2/nurd protein complex and its essential role in cancer metastasis. *Cell Res* 21: 275-289, 2010.
- Komiya E, Ohnuma K, Yamazaki H, Hatano R, Iwata S, Okamoto T, Dang NH, Yamada T and Morimoto C: CD26-mediated regulation of periostin expression contributes to migration and invasion of malignant pleural mesothelioma cells. *Biochem Biophys Res Commun* 447: 609-615, 2014.
- Bu Q, Hu Z, Chen F, Zhu R, Deng Y, Shao X, Li Y, Zhao J, Li H, Zhang B, *et al*: Transcriptome analysis of long non-coding RNAs of the nucleus accumbens in cocaine-conditioned mice. *J Neurochem* 123: 790-799, 2012.
- Evan GI and Vousden KH: Proliferation, cell cycle and apoptosis in cancer. *Nature* 411: 342-348, 2001.
- De Craene B and Berx G: Regulatory networks defining EMT during cancer initiation and progression. *Nat Rev Cancer* 13: 97-110, 2013.
- Condeelis JS and Segall JE: Intravital imaging of cell movement in tumours. *Nat Rev Cancer* 3: 921-930, 2003.
- Rogers L, Siu SS, Luesley D, Bryant A and Dickinson HO: Radiotherapy and chemoradiation after surgery for early cervical cancer. *Cochrane Database Syst Rev* 5: CD007583, 2012.
- Cheng GZ, Chan J, Wang Q, Zhang W, Sun CD and Wang LH: Twist transcriptionally up-regulates AKT2 in breast cancer cells leading to increased migration, invasion and resistance to paclitaxel. *Cancer Res* 67: 1979-1987, 2007.
- Matsuo N, Shiraha H, Fujikawa T, Takaoka N, Ueda N, Tanaka S, Nishina S, Nakanishi Y, Uemura M, Takaki A, *et al*: Twist expression promotes migration and invasion in hepatocellular carcinoma. *BMC Cancer* 9: 240, 2009.
- Shibata K, Kajiyama H, Ino K, Terauchi M, Yamamoto E, Nawa A, Nomura S and Kikkawa F: Twist expression in patients with cervical cancer is associated with poor disease outcome. *Ann Oncol* 19: 81-85, 2008.
- Kang Y and Massagué J: Epithelial-mesenchymal transitions: Twist in development and metastasis. *Cell* 118: 277-279, 2004.
- Tsai JH and Yang J: Epithelial-mesenchymal plasticity in carcinoma metastasis. *Genes Dev* 27: 2192-2206, 2013.
- Liotta LA, Tryggvason K, Garbisa S, Hart I, Foltz CM and Shafie S: Metastatic potential correlates with enzymatic degradation of basement membrane collagen. *Nature* 284: 67-68, 1980.
- Bérubé M, Deschambeault A, Boucher M, Germain L, Petitclerc E and Guérin SL: MMP-2 expression in uveal melanoma: Differential activation status dictated by the cellular environment. *Mol Vis* 11: 1101-1111, 2005.
- Nemeth JA, Yousif R, Herzog M, Che M, Upadhyay J, Shekarri B, Bhagat S, Mullins C, Fridman R and Cher ML: Matrix metalloproteinase activity, bone matrix turnover and tumor cell proliferation in prostate cancer bone metastasis. *J Natl Cancer Inst* 94: 17-25, 2002.
- Jones JL, Glynn P and Walker RA: Expression of MMP-2 and MMP-9, their inhibitors and the activator MT1-MMP in primary breast carcinomas. *J Pathol* 189: 161-168, 1999.
- Roomi MW, Monterrey JC, Kalinovsky T, Rath M and Niedzwiecki A: In vitro modulation of MMP-2 and MMP-9 in human cervical and ovarian cancer cell lines by cytokines, inducers and inhibitors. *Oncol Rep* 23: 605-614, 2010.