Transcription Repressor Slug Promotes Carcinoma Invasion and Predicts Outcome of Patients with Lung Adenocarcinoma

Jin-Yuan Shih,¹ Meng-Feng Tsai,¹ Tzu-Hua Chang,¹ Yih-Leong Chang,² Ang Yuan,³ Chong-Jen Yu,¹ Shin-Bey Lin,¹ Geou-Yarh Liou,¹ Meng-Larn Lee,⁵ Jeremy J.W. Chen,⁶,⁸ Tse-Ming Hong,⁵ Shuenn-Chen Yang,⁵ Jen-Liang Su,⁷ Yung-Chie Lee,⁴ and Pan-Chyr Yang¹,⁵,⁶,⁹

Abstract

Purpose: In a previous genome-wide gene expression profiling analysis using an invasion cancer cell lines model, we have identified Slug as selectively overexpressed in the highly invasive cancer cells. Here, we investigated the clinical significance of Slug in lung adenocarcinoma and the role of Slug in the process of cancer cell invasion and metastasis.

Experimental Design: Real-time quantitative reverse transcription-PCR was used to investigate Slug mRNA in surgically resected lung adenocarcinoma of 54 patients and its correlation with survival. We overexpressed Slug in a lung adenocarcinoma cell line with very low Slug levels and investigated the in vitro and in vivo effects of Slug expression.

Results: High expression of Slug mRNA in lung cancer tissue was significantly associated with postoperative relapse (P = 0.03) and shorter patient survival (P < 0.001). The overexpression of Slug enhanced xenograft tumor growth and increased microvessel counts in angiogenesis assay. Both inducible and constitutive overexpression of Slug suppressed the expression of E-cadherin and increased the in vitro invasive ability. Zymography revealed increased matrix metalloproteinase-2 activity in Slug overexpressed cells. ELISA, reverse transcription-PCR, and immunohistochemistry confirmed the increase of matrix metalloproteinase-2 proteins and mRNA in Slug overexpressed cells and xenograft tumors.

Conclusions: Slug expression can predict the clinical outcome of lung adenocarcinoma patients. Slug is a novel invasion-promoting gene in lung adenocarcinoma.

Lung cancer is the leading cause of cancer death worldwide. Metastasis is the most common cause of death in lung cancer patients and is a major obstacle to the successful treatment. The spread of tumor cells from a primary tumor to the secondary sites within the body is a complicated process involving cell proliferation and migration, degradation of basement membrane, invasion, adhesion, and angiogenesis (1). A variety of positive and negative factors are involved in this highly sophisticated process of metastasis (2). Current clinical means cannot accurately identify those patients who will develop metastasis. To develop effective new strategies for the prediction, diagnosis, and treatment of metastasis of lung cancer, molecular mechanisms controlling metastasis must be identified (3).

Cancers are a mass of heterogeneous neoplastic cells with different properties, including metastatic potential (4). During cancer development, some tumor cells acquire metastatic phenotypes, overexpression of metastasis-promoting genes or loss of expression of metastasis-suppressing genes. Recently, several groups have successfully used gene expression profiling techniques and model systems with different invasive or metastatic ability to identify genes that correlate with invasiveness or metastatic potential (5–9).

Multiple rounds of in vitro and in vivo selection of subclones of cancer cells originating from the same primary lung adenocarcinoma may result in the establishment of several phenotypically stable cell lines that differ strongly in their invasive and metastatic potential both in vitro and in vivo (10, 11). We have established previously a panel of lung cancer cell line with different invasion capability (CL1-0, CL1-1, CL1-5, and CL1-5-F4) in order of increasing invasion activity; refs. 7, 10). CL1-5 and CL1-5-F4 cells have a high potential of invading through natural or artificial basement membranes and form distant metastases when injected into severe combined immunodeficient (SCID) mice. Conversely, CL1-0 cells have a low capability of invading through basement membranes and do not form metastases in SCID mice. By using cDNA
microarray, we were able to identify invasion- and metastasis-associated genes on a genome-wide scale in model lung cancer cell lines (7, 8). Among these metastasis-associated genes, we identified one candidate gene, Slug, whose mRNA expression showed a positive correlation with invasive potential in this panel of cell lines.

Slug is a member of the Snail family of zinc finger transcription factors. They recognize the CAGGTG-binding site identified first in Drosophila and then in mammals and humans (12, 13). The Snail family has been shown to participate in mesoderm formation, neural crest cell formation and migration, cell differentiation, cell adhesion, cell invasion, cell cycle regulation, and antiapoptosis (14–18). Although the Snail family has been supposed to play a role in epithelial-mesenchymal transitions (EMT) concomitantly with downregulation of E-cadherin expression, most of the studies are about the functions of Snail (19), and the effect of Slug expression in cancer cells has not been clarified. The aim of this study was to evaluate the clinical significance of Slug mRNA expression in lung adenocarcinoma patients and the role of Slug in cancer cell invasion and metastasis.

**Patients and Methods**

**Patients and specimens.** Fifty-four patients who underwent resection for adenocarcinoma lung cancer at the National Taiwan University Hospital between September 1994 and December 1996 were studied. This study was approved by the institutional review board of National Taiwan University Hospital. Written informed consent was obtained from all patients. Specimens of lung cancer tissue obtained at surgery were immediately snap frozen in liquid nitrogen and stored until use.

The histologic classification of these tumors was based on the WHO criteria (20). Pathologic staging was done according to the tumor-node-metastasis system for lung cancer staging (21). The patients consisted of 24 men and 30 women (mean age, 60.2 ± 10.8 years). The surgicopathologic stage of disease was I in 19 patients, II in 7 patients, III in 20 patients, and stage IV in 8 patients. Tumor status was T1 in 12 patients, T2 in 26 patients, T3 in 13 patients, and T4 in 3 patients.

**Real-time quantitative reverse transcription-PCR.** Total mRNA was extracted from resected cancer tissue using a RNA extraction kit (RNeasy Mini kit; Qiagen, Valencia, CA). The quality of the RNA samples was confirmed by DNA sequencing. The reaction conditions were according to a standard kit (7000 sequence detection system; Applied Biosystems, Foster City, CA). The Transwell filters were coated with appropriate matrix (Matrigel). Hygromycin-resistant cells were isolated. The expression of Slug in resistant clones was analyzed by real-time quantitative RT-PCR in each clone. Clone Slug33 was selected because it had very low Slug expression when cultured in doxycycline and had high expression of Slug when doxycycline was removed. The Slug expression was measured using SuperScript II reverse transcriptase (Invitrogen). Northern hybridization analysis and reverse transcription-PCR. DNA from cell lines was extracted using Trizol reagent (Invitrogen). Northern hybridization was done as described previously (8). Briefly, each lane on formaldehyde gels was loaded with 20 µg total RNA. After electrophoresis, the gels were blotted onto nylon membranes. After cross-linking and prehybridization, they were hybridized with 32P-labeled DNA probes. The membranes were washed and then exposed to X-ray film overnight at −70°C. The amount of RNA in each lane was measured by comparing with the signal intensity of G3-like probe (a housekeeping gene used as an internal control for RNA quantity; ref. 24).

To analyze the expression of Slug, Snail, E-cadherin, and matrix metalloproteinase-2 (MMP-2) in cell lines, RT-PCR was done. Polyadenylated RNA was isolated from the different tumor cell lines or stable transfectant clones and treated with DNase I before cDNA synthesis. The mRNA was reverse transcribed using SuperScript II reverse transcriptase (Invitrogen). PCR for Slug, Snail, E-cadherin, and MMP-2 were done at an annealing temperature of 60°C. G3-like was amplified after 28 cycles at an annealing temperature of 56°C. Primer sequences were as follows: Slug forward 5′-AGACTTACACCCGAAAAAG-3′ and reverse 5′-TTTCTACATTGCGAGTGCA-3′; Snail forward 5′-GGGTCGCCCTTACTATAT-3′ and reverse 5′-TCTTGGCAGGAGTTTCT-3′; E-cadherin forward 5′-TGGCTCAGTCTCAG-3′ and reverse 5′-TCTTGGCAGGAGTTTCT-3′; and MMP-2 forward 5′-ATGGCTGATACCCCTTT-3′ and reverse 5′-GGCTTGTATCCCTTCTG-3′.

**In vitro cell invasion and migration assay.** In vitro Matrigel invasion assays were done using 6.5-mm Costar transwell chambers (8-µm pore size; Corning, NY). The Transwell filters were coated with appropriate Matrigel (Becton Dickinson, Franklin Lakes, NJ). After the Matrigel solidified at 37°C, 1 × 106 cells were seeded onto the Matrigel. After 24-hour incubation, the filter was gently removed from the chamber and the noninvasive cells on the upper surface were removed by wiping
with a cotton swab. The cells that invaded the Matrigel and attached to the lower surface of the filter were fixed with methanol and stained with Giemsa solution. The number of cells attached to the lower surface of the polycarbonate filter was counted at 400 magnification under a light microscope. Each type of cell was assayed in triplicate.

Cell motility was assessed using a scratch wound assay. The cells were seeded into six-well tissue culture dishes at a concentration of 1 × 10⁵ and cultured in medium containing 10% FBS to nearly confluent cell monolayers, which were then carefully wounded using a cell scraper. Any cellular debris was removed by washing with PBS. After making wounds, the cultures were incubated at 37°C and photographed immediately (t = 0) and 24 hours later. Migration was evaluated by the number of cell migration into the cell-free zone. The experiments were repeated in quadruplicate wells thrice.

**Cell proliferation assay.** The cells were seeded onto 96-well plates at 4,000 per well in culture medium (100 μL). After culturing for various durations, cell numbers were measured by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay as described previously (8). Briefly, at each time point, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (10 μL; 5 mg/mL) was added to each well and incubated for 4 hours at 37°C. The reaction was stopped by adding 100 μL of 0.04 N HCl in isopropanol to each well, with vigorous mixing to solubilize colored crystals produced by the reaction. The absorbance was measured at 570 nm to absorbance at 630 nm as reference wave was measured by a multwell scanning spectrophotometer. Each data point is the average of six determinations and each experiment was repeated thrice.

**Cloning of E-cadherin and transient transfection.** The full-length human E-cadherin cDNA was cloned into the constitutive mammalian expression vector pCDNA3 (Invitrogen). The resultant plasmid was named pCDNA3-Ecad. Subsequently, the CL1-5 cells were transfected with pCDNA3-Ecad and pCDNA3 empty vector using LipofectAmine method. Twenty-four hours after transfection, the cells were collected for *in vitro* invasion assay. For Western blotting, these cells were lysed 48 hours after transfection and subjected to SDS-PAGE. Antibodies used for Western blot analyses were anti-E-cadherin monoclonal antibody (sc-8426, Santa Cruz Biotechnology, Inc., Santa Cruz, CA) and anti-a-tubulin monoclonal antibody (CP06, Calbiochem, San Diego, CA) and an enhanced chemiluminescence system (Amersham Pharmacia Biotech, Piscataway, NJ) as substrate.

**Zymography for gelatinase.** Zymographic analysis of gelatinase activity in secreted medium was done in 10% polyacrylamide gels containing 0.1% gelatin (25). Cells were cultured in RPMI 1640 containing 10% FBS. After 2 hours, cells were washed extensively and changed to serum-free RPMI 1640. After an overnight incubation, media were collected and mixed with sample buffer for electrophoresis. After electrophoresis, the SDS was removed from the gel by incubating in 2.5% (v/v) Triton X-100 for 30 minutes. The gels were then incubated at 37°C overnight in development buffer [50 mmol/L Tris-HCl (pH 7.6), containing 0.2 mol/L NaCl, 5 mmol/L CaCl₂] and stained with 40% methanol/10% glacial acetic acid containing 0.5% (w/v) Coomassie brilliant blue G-250 for 20 minutes.

**ELISA assay for matrix metalloproteinase-2.** Commercial ELISA kit (Calbiochem) was used to analyze the cellular level of MMP-2. Briefly, anti-MMP-2 monoclonal antibody was precoated on the 96-well microtiter plate. The second anti-MMP-2 antibody was added to each well. The standard or unknown sample (100 μL) was then added to each well. The plate was then incubated at room temperature for 2 hours and washed. A substrate solution was then added to all wells and incubated for 30 minutes. At this point, a stop solution was added to all wells. Color development and intensity of the color were measured using an ELISA plate reader. A standard curve was prepared, plotting the absorbance versus the concentration of the cytokine expressed as picogram per milliliter in the original samples.

**In vivo murine angiogenesis assays.** All animal works were done under protocols approved by the Institutional Animal Care and Use Committee of the College of Medicine, National Taiwan University. The effect of Slug on the *in vivo* angiogenesis was evaluated by the murine angiogenesis model using Matrigel plug assay as described by Passaniti et al. with modification (26). Briefly, the 1 × 10⁶ cells were mixed with Matrigel (8.0 mg/mL; 0.4 mL), and the Matrigel plug was injected s.c. into each SCID mouse (supplied by the animal center in the College of Medicine, National Taiwan University). In total, three mice were injected with Matrigel plug containing mock cells and three mice were injected with Matrigel plug containing Slug⁺ cells. After 10 days, mice were sacrificed, and the Matrigel plug was removed to assess the angiogenesis activity. For histologic analysis, the Matrigel plug, in combination with surrounding skin and soft tissue, was embedded in onithine carbamyl transferase and frozen in −80°C. Sections (5 μm) were then stained with rat anti-mouse monoclonal antibody CD31 (BD Pharmingen, Bedford, MA) for mouse endothelial cell staining. The microvessels surrounding the tumor nest were calculated at ×200 field, and three fields of area with most intense neovascularization surrounding the tumor nest were counted.

**Tumorigenicity in severe combined immunodeficient mice.** Six-week-old SCID mice were housed in an isolator and *ad libitum* fed with autoclaved food. For tumor growth in animals, cancer cells were trypsinized, washed, centrifuged, and resuspended in HBSS (Invitrogen). A total volume of 0.2 mL containing 5 × 10⁶ cells was s.c. injected on the dorsal region of each animal. Control cells (mock) were injected on the left side and Slug transfectant (Slug⁺) was injected on the right side. A total of six mice were studied. Injected mice were examined every 7 days for tumor appearance and tumor volumes were estimated from the length (a) and width (b) of the tumors using the formula: V = ab²/2 (27). After 49 days, animals were sacrificed, and tumors were confirmed by histologic examination. For histologic examination, tissues were fixed in PBS/10% formalin and embedded in paraffin. From each paraffin block, three consecutive sections were cut, which were stained with H&E, anti-MMP-2 antibody (Daichi Fine Chemical Co. Ltd., Tokyo, Japan), and anti-E-cadherin antibody (Takara Shuzo Co. Ltd., Kyoto, Japan). Immunohistochemical staining was carried out using a modified avidin-biotin peroxidase complex method. Intensity of immunohistochemical staining was scored from 0 to 2+: 0, no staining of cancer cells; 1+, heterogeneous staining of cancer cells; and 2+, homogeneous staining of cancer cells.

**Statistical analysis.** Where appropriate, the data are presented as the mean ± SD. All statistical analyses were done with SPSS version 11.0 (SPSS, Inc., Chicago, IL). Continuous data were compared using Student’s *t* test. The Fisher’s exact test was used to compare the clinicopathologic characteristics of patients with high or low Slug mRNA expression. Survival curves were plotted by the Kaplan-Meier method and compared by log-rank test. For multivariate analysis of survival, Cox regression model procedure was done. *p* < 0.05 were considered statistically significant.

**Results**

**Slug mRNA expression in lung cancer tissue correlates with postoperative relapse and survival of lung cancer patients.** Real-time quantitative RT-PCR was used for quantifying transcript copy number of Slug. The threshold cycle (CT) was defined as the fractional cycle number at which the fluorescence generated by cleavage of the probe exceeds a fixed threshold above baseline. For a chosen threshold, a smaller starting copy number results in a higher CT value. In this study, we used *TPB* mRNA as an internal control. The relative amounts of tissue *Slug* mRNA, standardized against the amount of *TPB* mRNA, were expressed as −ΔCT = −[CT*_{Slug} − CT_{TPB}], where *K* is a constant (8). Of the 54 tumor samples, the −ΔCT value ranged from −4.69 to 4.96 with a median of −0.09. The median value was used to classify patients as *Slug* high-expression group or *Slug* low-expression group. There were no differences in age, CT value, Karnofsky score, gender, smoking, and tumor stage. The Slug high-expression group had significantly shorter postoperative relapse and survival than the Slug low-expression group. These results agreed with our prediction.
gender, disease stage, tumor status, and lymph node metastasis between the two groups (Table 1). Counter to expectations, Slug expression was not associated with presence of lymph node metastasis or stage. The median duration to postoperative recurrence was shorter in the Slug high-expression group (11.0 months; 95% confidence interval, 8.7-13.4 months) than in the Slug low-expression group (27.0 months; 95% confidence interval, 0.54-8 months; \( P = 0.03 \), log-rank test; Fig. 1A). The Slug high-expression group (median survival, 14.9 months; 95% confidence interval, 4.9-24.9 months) had a significantly shorter survival than the Slug low-expression group (median survival, 41.8 months; \( P < 0.001 \), log-rank test; Fig. 1B).

Univariate analysis showed that Slug mRNA expression, disease stage, tumor status, nodal status, adjuvant chemotherapy and/or radiotherapy, and age were prognostic factors for relapse and survival. Multivariate analysis using the Cox regression model, Slug mRNA expression (\( P = 0.02 \)), stage of disease (\( P = 0.01 \)), and age (\( P = 0.002 \)) were the significant prognostic factors for survival, whereas Slug mRNA expression (\( P = 0.002 \)) and stage of disease (\( P < 0.001 \)) were significant factors for predicting recurrence.

Identification of differentially expressed Slug mRNA by cDNA microarray. Previously, we used cDNA microarray with colorimetric detection to identify differentially expressed genes among lung cancer cell lines (CL1-0, CL1-1, CL1-5, and CL1-5-F4) with varying degrees of invasive properties (7, 8). We found that the mRNA expression of Slug correlated positively with cell line invasiveness (Fig. 2A). Northern hybridization confirmed that the level of Slug expression was drastically increased in CL1-5 and CL1-5-F4 relative to CL1-0 and CL1-1 (Fig. 2B). Real-time quantitative RT-PCR of Slug in cell lines also confirmed the result of cDNA microarray (Fig. 2C). Then, we checked the Snail expression in this panel of cell lines by RT-PCR and found the amount of Snail mRNA was equal in the series of cell lines (data not shown). Therefore, we focused our study on the function of Slug in cancer invasion.

Overexpression of Slug promotes in vitro carcinoma cells invasion and suppresses E-cadherin expression. Slug-transfected CL1-0 clones (Slug4 and Slug6) expressed higher levels of Slug mRNA (Fig. 3A) than the control clone (mock) and CL1-0. We used an in vitro–reconstituted basement membrane invasion assay to investigate whether Slug expression affected the invasive activity of cancer cells. After a 24-hour incubation, we noted a statistically significant increase in the invasive activity of Slug4 (\( P = 0.01 \)) and Slug6 (\( P = 0.002 \)) than the control clone (Fig. 3B). Slug-transfected cells (Slug4 and Slug6) and CL1-5 have similar range of Slug/TBP mRNA ratio (Figs. 2 and 3) and similar in vitro invasion abilities (7, 10).

To investigate whether a causal relationship exists between the invasion phenotype and Slug expression, Tet-Off Slug cDNA-transfected clone (Slug33) and Tet-Off mock transfectant T2 were established. Slug33 displayed elevated levels of Slug mRNA compared with doxycycline-treated Slug33 and T2 (doxycycline-treated or untreated; Fig. 3C). We used a Matrigel

| Table 1. Clinicopathologic characteristics of tumors with high and low Slug mRNA expression |
|---------------------------------|---------------------------------|---------------------|
| Characteristics                | Slug mRNA                       | \( P \)              |
|                                 | \(- \Delta CT <-0.09, no. patients\) | \(- \Delta CT >-0.09, no. patients\) |
| Mean age (y)                   | 60 ± 11                         | 60 ± 11             | 0.897* |
| Sex                             |                                 |                     |       |
| Male                            | 11                              | 13                  | 0.786 |
| Female                          | 16                              | 14                  |       |
| Stage                           |                                 |                     |       |
| I-II                            | 13                              | 13                  | 1.0   |
| III-IV                          | 14                              | 14                  |       |
| Tumor status                    |                                 |                     |       |
| T1-2                            | 17                              | 21                  | 0.372 |
| T3-4                            | 10                              | 6                   |       |
| Nodal status                    |                                 |                     |       |
| N0                              | 15                              | 9                   | 0.170 |
| N1-2                            | 12                              | 18                  |       |
| Adjuvant chemotherapy and/or radiotherapy |                                |                     |       |
| Positive                        | 8                               | 12                  | 0.260 |
| Negative                        | 19                              | 15                  |       |

*Derived using Student’s \( t \) test; other \( Ps \) were derived using Fisher’s exact.

RT-PCR and found the amount of Snail mRNA was equal in the series of cell lines (data not shown). Therefore, we focused our study on the function of Slug in cancer invasion.

 Slug in Lung Carcinoma Invasion and Survival

Fig. 1. Kaplan-Meier survival plots of disease-free survival (A) and overall survival (B) for non–small cell lung cancer patients grouped according to Slug mRNA expression. There was a significant difference in disease-free survival (\( P = 0.03 \)) and overall survival (\( P < 0.001 \)) between patients with high and low expression of Slug mRNA.

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invasion assay to determine whether Slug expression affects cancer cell invasion. After a 24-hour incubation, a significant increase in invasive potential was noted in Slug33 compared with doxycycline-treated Slug33 and T2 (doxycycline-treated or untreated; \( P < 0.01; \) Fig. 3D).

Loss of E-cadherin expression is associated with cancer cell invasion. Snail has been firmly established as a repressor of E-cadherin in different types of cancer cells (19). The role of Slug, as a potential E-cadherin repressor, has remained uncertain. We used these constitutive and inducible Slug expression clones to study the relationship of Slug and E-cadherin. \( \text{E-cadherin} \) expression was lost in the overexpressed clones (Slug4 and Slug6; Fig. 3E). In the Tet-Off system, after the addition of doxycycline, the expression of Slug in Slug33 clone was suppressed and the expression of \( \text{E-cadherin} \) was desuppressed (Fig. 3F).

To show that suppression of \( E\text{-cadherin} \) expression is the cause of Slug-induced invasion, we examined whether ectopic expression of \( E\text{-cadherin} \) could suppress the invasion ability of Slug-expressed cells. The pCDNA3-Ecad plasmid was transiently transfected into CL1-5 cells. As shown in Fig. 3G and H, the \( E\text{-cadherin} \) protein expressed in CL1-5 after transfection and the invasion activity of \( E\text{-cadherin}-\)transfected CL1-5 was significantly reduced compared with mock control cells (\( P < 0.01 \)). These data show that \( E\text{-cadherin} \) reexpressed in Slug expression cells could inhibit the invasion ability.

**Expression of Slug does not affect cancer cell migration and proliferation in vitro.** To examine whether the Slug invasion-promoting potential is associated with its promoting on the cell motility, the effects of Slug on the migration capability of cells was analyzed. In the standard scratch wound assay, confluent monolayers of mock, Slug4 and Slug6 cells were scratch wounded using a cell scraper. We noted that there was no significant difference in the migration capability of these cells (data not shown). There was no significant difference in the cell proliferation rates between mock, Slug4, and Slug6 cells as shown by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay (data not shown).

**Slug increases the expression and activity of matrix metalloproteinase-2 and in vivo murine angiogenesis.** Zymographic analysis was used to assess whether the invasive nature of the Slug overexpression clones correlated with their gelatinase activity. A 66-kDa gelatinase activity could be observed with the Slug4 and Slug6, but low activity was observed for mock control and CL1-0 (Fig. 4A). The ELISA assay of supernatant medium confirmed that the MMP-2 protein amount is higher in Slug4 (\( P < 0.001 \)) and Slug6 (\( P = 0.012 \)) than mock and CL1-0 (Fig. 4B). RT-PCR also showed that Slug expression clones (Slug4 and Slug6) had higher expression of MMP-2 mRNA (Fig. 4C).

Because MMP-2 can regulate angiogenesis, to understand whether Slug expression cells can induce angiogenesis, we did \( \text{in vivo} \) angiogenesis assay. The microvessel count of the tumor of Slug4 (86.7 \( \pm \) 16.9; \( \times200 \) field) was significantly higher than that of the tumor of mock (15.7 \( \pm \) 6.4; \( P < 0.01 \), Student’s \( t \) test). The angiogenesis activity of Slug4 increased \( \sim5.5\)-fold compared with the mock by \( \text{in vivo} \) murine angiogenesis assay (Fig. 4D and E).

**Slug promotes in vivo tumor growth.** We next investigated the effect of Slug expression on tumorigenicity \( \text{in vivo} \). Over-expression of Slug resulted in a marked increase of the growth of tumors formed by lung cancer cell in SCID mice (Fig. 5A). Our results showed that mock transfectant failed to develop tumors in mice (six of six) 4 weeks after inoculation, whereas Slug4 developed tumors (six of six) larger than 1 cm\(^3\) within 3 weeks. After 7 weeks, the tumor sizes from the mock transfectants were \(<1\) cm\(^3\), whereas the tumor sizes from the Slug4 reached 3.5 cm\(^3\). It is evident that Slug expression promotes the tumorigenicity \( \text{in vivo} \). However, no lung or liver metastasis by microscopic examinations was noted while SCID mice were sacrificed on week 7. The xenograft tumors were studied with immunohistochemical study and graded by 0 to 2+ as described in Patients and Methods showed increased expression of MMP-2 in the Slug4 clones compared with the mock (\( P = 0.038 \), Mann-Whitney test). A representative figure was shown in Fig. 5B and C. The expression of E-cadherin in xenograft was scanty in both Slug4 and mock transfectants. We also got the three xenograft tumors of CL1-5 in SCID mice; all three were diffusely stained by anti-MMP-2 antibody (graded as 2+), but all three had no staining by anti-E-cadherin (graded as 0). Representative pictures of expression of MMP-2 and E-cadherin in CL1-5 were shown in Fig. 5D and E.

**Discussion**

In this study, we showed that Slug, a novel invasion-associated gene identified by a genome-wide cDNA microarray
screening, is indeed an invasion-promoting gene. High Slug mRNA expression in lung adenocarcinoma patients can predict postoperative recurrence and shortened survival. Overexpression of Slug in lung cancer cells can promote cancer cell invasiveness in vitro and angiogenesis and tumor growth in vivo. Increase of cancer cell invasion by Slug is mediated through the suppression of E-cadherin expression and up-regulation of MMP-2 expression and enzyme activity.

Slug is a member of the Snail superfamily of zinc finger transcription factors (13). The Snail superfamily has been found in Drosophila and then in many species, including nonvertebrates, vertebrates, and humans (13). The Snail superfamily in human includes Slug, Snail, Snail-like, Scratch1, and Scratch2 (13). These proteins share an evolutionarily conserved function and are implicated in the generation and migration of mesoderm and neural crest cells in several species (28, 29). EMT is a process that allows epithelial cells to separate from their neighbors and migrate to populate distal regions during embryonic development (30, 31). The EMT confers migratory and invasive properties to epithelial cells and is an essential event during gastrulation movements and neural crest formation but has also been suggested to play a fundamental role during invasion and metastasis of carcinoma cells (31). Snail superfamily members have been implicated in the...
occupying a central position in triggering EMT in physiologic and pathologic situations (32).

In recent years, there were studies about how Snail superfamily regulates EMT (33–36). Loss of E-cadherin is found in many cancers and a major phenomenon of EMT. Snail has been firmly established as a repressor of E-cadherin in melanoma cell lines and several epithelial cell lines, such as oral squamous cell carcinoma, hepatocellular carcinoma, breast cancer, and diffuse-type gastric cancer tissue (37, 38). The role of Slug as a potential E-cadherin repressor was uncertain. Overexpression of Slug in rat bladder carcinoma cells (NBT-II) was not able to suppress E-cadherin but instead induced desmosome dissociation (29). In addition, a collection of mouse epidermal keratinocyte cell lines did not show any correlation between E-cadherin and Slug expression profiles (19). However, Hajra et al. reported that Slug but not Snail is the repressor of E-cadherin in breast carcinoma cell lines (39). Stable transfection of Slug in Madin-Darby canine kidney cells leads to a full EMT associated with the complete repression of E-cadherin expression (40). In our experiment, we showed overexpression of Slug suppressed E-cadherin expression in lung cancer cell lines. These apparent discrepancies in relation to E-cadherin regulation can reflect the specific contribution of different cellular contexts.

Invasion is the early process of metastasis for cancer cells to go through the basement membrane and into the stroma. Invasion is one of the markers of the cellular malignancy and poor prognosis of cancer (4). Previous reports showed Snail-transfected Madin-Darby canine kidney cells have increased Matrigel invasion abilities than control Madin-Darby canine kidney mock clones (18, 40). However, previous reports of Slug transfection studies did not report the invasion analysis. Increase of cancer cell invasion ability in experiment could be due to increase of motility. Our investigation found that the motility of Slug-transfected cells were the same as those of mock-transfected control. This is consistent with the findings that Slug-transfected NBT-II did not increase migration ability compared with parental NBT-II cells (29). However, Bolos et al. reported that the migratory ability of Madin-Darby canine kidney Slug cells in the wound assays was much increased compared with the Madin-Darby canine kidney mock clone (40).

MMPs play an important role in degradation of extracellular matrix, which is an essential step in the cascade of metastasis (41). In the present study, the zymography analysis, ELISA test, and RT-PCR all showed that Slug-transfected cells had increased MMP-2 RNA and protein production and activities. MMP-2 degrades type IV collagen, which is a major component of basement membrane. MMP-2 is a prominent predictor of poor prognosis for patients with various cancers (42). MMP-2 has also been reported to be up-regulated by Snail (43, 44). Snail-transfected A431 (vulval squamous cell carcinoma) showed increased expression of MMP-2 and the up-regulation of MMP-2 promoter activity (43). Similarly, expression of MMP-2 was up-regulated in Snail-transfected HepG2 (hepatocellular carcinoma cell line; ref. 44). We propose that regulating the extracellular matrix in addition to the loss of cell-cell adhesion is another fundamental role of Slug in promoting cancer invasion.

There were several reports about the expression of Snail in human cancer tissue. Cheng et al. did RT-PCR in invasive ductal carcinoma patients and found that the expression of Snail increased in those with low E-cadherin (37). Blanco et al. showed that the expression of Snail in infiltrative ductal carcinoma patients inversely correlates with the differentiation and positively correlated with lymph node metastasis (38). Sugimachi et al. showed that the Snail mRNA correlated with capsular invasion but Slug mRNA did not correlate with tumor invasion of hepatocellular carcinoma (45). Martin et al. also reported that neither Slug nor Snail showed a correlation with tumor-node-metastasis status of breast cancer by quantitative RT-PCR (46). In contrast, Uchikado et al.
reported that Slug was related to depth of tumor invasion, lymph node metastasis, stage, and venous invasion of esophageal cancer by immunohistochemistry study (47). Our study showed that Slug mRNA expression promoted cancer cell invasion through suppression of E-cadherin and increase of MMP-2 expression, promoted tumor growth, and was associated with patient survival but was not associated with tumor status, nodal metastasis, or stage. This is quite similar to MMP-2, which promoted cancer cell invasion, promoted tumor growth, and was associated with patient survival but was not associated with lymph node metastasis or cancer stage in lung cancer (48, 49).

Results of Slug mRNA expression can predict postoperative recurrence and overall survival of patients with lung adenocarcinoma in this study are consistent with reports of Slug protein expression was associated with adverse survival in patients with esophageal squamous cell carcinoma (47). High Snail expression was associated with shorter recurrence-free survival in hepatocellular carcinoma patients (50). There are two points we need to mention. First, cells expressing Slug were resistant to chemotherapy and radiotherapy (16–18). Although there was no statistical difference in the distribution of patients receiving adjuvant therapy between Slug mRNA high-expression and low-expression groups, the survival benefit of low-expression group could be partially due to better effect of adjuvant therapy. Second, the cut point of Slug mRNA obtained in this study may not be extrapolated to other population samples. The cut point value of Slug mRNA should be assessed in sufficiently large prospective study.

The application of large-scale gene expression analysis to cancer studies has made identification of the differentially expressed genes responsible for invasion a practical approach. Slug is a metastasis-promoting gene, which has significant value to predict postoperative recurrence and overall survival of patients with lung adenocarcinoma. Disclosing the genes regulated by Slug will provide further clues to its biological roles and more generally will contribute to the understanding of the mechanisms underlying the invasion of lung cancer.

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**References**


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