Nonsteroidal Anti-inflammatory Drug-Activated Gene-1 Expression Inhibits Urethane-Induced Pulmonary Tumorigenesis in Transgenic Mice

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Abstract

The expression of nonsteroidal anti-inflammatory drug-activated gene-1 (NAG-1) inhibits gastrointestinal tumorigenesis in NAG-1 transgenic mice (C57/BL6 background). In the present study, we investigated whether the NAG-1 protein would alter urethane-induced pulmonary lesions in NAG-1 transgenic mice on an FVB background (NAG-1\textsuperscript{Tg+/FVB}). NAG-1\textsuperscript{Tg+/FVB} mice had both decreased number and size of urethane-induced tumors, compared with control littermates (NAG-1\textsuperscript{Tg+/FVB} = 16 ± 4 per mouse versus control = 20 ± 7 per mouse, \(P < 0.05\)). Urethane-induced pulmonary adenomas and adenocarcinomas were observed in control mice; however, only pulmonary adenomas were observed in NAG-1\textsuperscript{Tg+/FVB} mice. Urethane-induced tumors from control littermates and NAG-1\textsuperscript{Tg+/FVB} mice highly expressed proteins in the arachidonic acid pathway (cyclooxygenases 1/2, prostaglandin E synthase, and prostaglandin E\(_2\) receptor) and highly activated several kinases (phospho-Raf-1 and phospho-ERK2, extracellular signal-regulated kinase 1/2). However, only urethane-induced p38 mitogen-activated protein kinase (MAPK) phosphorylation was decreased in NAG-1\textsuperscript{Tg+/FVB} mice. Furthermore, significantly increased apoptosis in tumors of NAG-1\textsuperscript{Tg+/FVB} mice compared with control mice was observed as assessed by caspase-3/7 activity. In addition, fewer inflammatory cells were observed in the lung tissue isolated from urethane-treated NAG-1\textsuperscript{Tg+/FVB} mice compared with control mice. These results paralleled in vitro assays using human A549 pulmonary carcinoma cells. Less phosphorylated p38 MAPK was observed in cells overexpressing NAG-1 compared with control cells. Overall, our study revealed for the first time that the NAG-1 protein inhibits urethane-induced tumor formation, probably mediated by the p38 MAPK pathway, and is a possible new target for lung cancer chemoprevention.

Lung cancer is the leading cause of cancer-related death in men and women in the United States, and pulmonary adenocarcinoma is the most common type of lung cancer, according to the American Cancer Society. Rodents develop chemically induced lung tumors with molecular and histologic features similar to pulmonary adenocarcinoma in humans (1–4). In animal models of lung adenocarcinoma, including rodents, urethane has been used as a carcinogen that specifically induces the development of lung tumors from alveolar type II pneumocytes and Clara cells (2, 4–6).

Nonsteroidal anti-inflammatory drug–activated gene-1 (NAG-1) is highly induced by many drugs and chemicals that influence development of tumorigenesis. Also known as a macrophage inhibitory cytokine-1, growth and differentiation factor-15, placental transforming growth factor \(\beta\), prostate-derived factor, and placental bone morphogenetic protein (7), the NAG-1 protein shows broad activities in various tissues. However, its molecular mechanisms, the receptor, or molecules interacting with NAG-1 are incompletely characterized. As previously published by our group and others, NAG-1 has anti-inflammatory, antiproliferative, and proapoptotic effects in several types of cancer in vitro (8–10) and is induced by certain drugs and chemicals. These include nonsteroidal anti-inflammatory drugs (8), chemopreventive dietary compounds (11–14), and peroxisome proliferator activated receptor \(\gamma\) ligands (15–17). Furthermore, NAG-1 is an important downstream target of the tumor suppressor gene \(p53\) (11), EGR-1 (18), and the PI3K/AKT/GSK-3\(\beta\) pathways (19). Thus, NAG-1 plays a pivotal role in antitumorigenesis induced by chemopreventive compounds.
Transgenic mice (NAG-1Tg+/BL6) expressing human NAG-1 have been developed by our group (9) and we have found that NAG-1Tg+/BL6 mice are resistant to chemically and genetically induced intestinal polyp formation. An approximately 50% reduction in polyps was observed after azoxymethane treatment of NAG-1Tg+/BL6 and 40% inhibition of polyp formation in the intestine by crossing NAG-1Tg+/BL6 mice with ApcMin+ mice, compared with control littersmates. These results indicate that NAG-1 is a potential tumor suppressor gene in colorectal cancers (9). Because a BL6 background model is not susceptible to chemically induced lung cancer, we have back-crossed NAG-1Tg+/BL6 mice with the FVB background to generate the NAG-1 transgenic mice with the FVB background (NAG-1Tg+/FVB) and investigated whether the expression of human NAG-1 would suppress urethane-induced pulmonary adenocarcinoma formation in a mice model. There are a few studies examining a potential role of NAG-1 in lung tumorigenesis (20, 21), based on data showing the down-regulation of NAG-1 expression in lung tumors compared with normal tissue.

In this report, we describe the role of NAG-1 as an antitumorigenic protein in tumors in a urethane-induced mice model. The overexpressed human NAG-1 protein in NAG-1Tg+/FVB mice inhibited the formation of lung tumors through down-regulation of the p38 mitogen-activated protein kinase (MAPK) signaling pathway and induced apoptosis through the activation of caspase-3/7. In addition, we have confirmed our findings in vitro using human A549 pulmonary carcinoma cells. A decreased phosphorylation of p38 MAPK was observed in cells overexpressing NAG-1 compared with the control cells after various treatments. Data from this study strongly suggest that the NAG-1 protein and its signaling pathway could be potential new targets for prevention and/or treatment of lung cancer.

Materials and Methods

Reagents, antibodies, and cells

Urethane was purchased from Sigma-Aldrich; cigarette smoke condensate was obtained from Murty Pharmaceuticals, Inc.; epidermal growth factor (EGF) and insulin-like growth factor-1 (IGF-1) were purchased from BD Biosciences; and prostaglandin E2 (PGE2) was purchased from Cayman Chemical Co. NAG-1 antibody was previously described (8). Microsomal PGE2 synthase antibody was purchased from Oxford Biomedical Research, and lysozyme antibody was purchased from Dako North America, Inc. Antibodies for cyclooxygenase (COX)-2, cyclin D1, p27, p53, and actin were purchased from Santa Cruz Biotechnology. COX-1 and EP2 antibodies were obtained from Cayman Chemical Co. Phospho-Raf-1 (Ser259), phospho-p38 MAPK (Thr180/Tyr182), p21, and cleaved caspase-3 (Asp175) antibodies were purchased from Cell Signaling Technology. Human A549 lung carcinoma cell line was obtained from American Type Culture Collection. The cells were maintained in Ham’s F12K medium supplemented with 10% fetal bovine serum and antibiotics (100 IU penicillin and 100 μg/mL streptomycin) and grown in an atmosphere of 5% CO2 at 37°C.

Animals and experimental design

All animal research procedures were approved by the University of Tennessee Institutional Animal Care and Use Committee and were in accordance with NIH guidelines. NAG-1 transgenic mice were originally developed on a C57BL/6 genetic background (9). NAG-1Tg+/BL6 mice were backcrossed to FVB strain mice for eight generations. Mice were maintained at 22 ± 2°C on a 12 h light/dark cycle with free access to standard rodent chow and tap water. Eleven-week-old control littermates (NAG-1Tg-/FVB, n = 11) and NAG-1 transgenic mice (NAG-1Tg+/FVB, n = 10) received i.p. injections of urethane (1 mg of urethane dissolved in 0.9% NaCl/g body weight) or 0.9% NaCl alone once per week for 6 wk (Fig. 1A). At age 30 wk, mice were sacrificed and lung tissues were collected and kept in RNase later solution for protein and RNA analysis and in 10% neutral-buffered formalin for paraffin embedding.

Fig. 1. Characterization of NAG-1Tg+/FVB mice. A, schematic diagram of the experimental design. B, body weight for control and NAG-1Tg+/FVB mice (**, P < 0.01; ***, P < 0.001). C, human NAG-1 expression in lung tissue of NAG-1Tg+/FVB mice was confirmed by reverse transcription-PCR and Western blotting. Human HCT-116 colorectal cancer cell lysate was used as the standard (STD) for human NAG-1 expression.
Lung tumor enumeration
Surface (gross) lung lesions were counted by three blinded readers after removing the lung from sacrificed mice. The microscopic evaluation of lung lesions was done using H&E-stained lung tissue slides.

Histology and immunohistochemistry
Lung tissues were formalin fixed, embedded in paraffin, and sectioned at 5 μm. Immunohistochemical staining was done as described previously (3). The images were captured by an Olympus DP70 camera (Olympus Optical Col) attached to an Olympus microscope. For scoring of lysozyme staining in inflammatory cells (22), slides were reviewed by three blinded readers. For each lung specimen (n = 3 per treatment group), six normal cross-sectional lung areas, four edge areas of neoplasia, and one central area of neoplasia were evaluated and scored for intensity (1 = weak, 2 = moderate, 3 = intense staining). Scores for number and intensity of staining of inflammatory cells were then multiplied and normalized to the control group.

Measuring the diameter of neoplasia in lungs
To measure the diameter of neoplasia, photographic images (magnification 2×) of the lung lobes were taken. The diameters of the neoplasia were measured by the Olympus software package. For each treatment group, ∼30 neoplastic foci were measured and divided into four groups according to size. For evaluation of percentage of cross-sectional area occupied by neoplasia, H&E lung images of each mouse were taken at a magnification of 2× and measured using Scion Image software to compare the area of normal and neoplastic pulmonary tissue. Measured areas of all neoplasia from the same lung were combined, divided by the area of the whole lung, and multiplied by 100 to get a result as a percentage. The results were presented as a mean ± SD for each treatment group, and statistical analyses were done.

Reverse transcription-PCR
Total RNA was isolated from mice lung tissue using an RNeasy mini kit (Qagen), and then cDNA was synthesized from 1 μg of total RNA using an iScript cDNA Synthesis kit (Bio-Rad) according to the protocol.

Fig. 2. Suppression of urethane-induced pulmonary neoplasia in NAG-1Tg+/FVB mice. A, top, images of dissected lungs from control (left) and NAG-1Tg+/FVB (right) mice. The bottom graph shows that NAG-1Tg+/FVB mice had a significantly lower gross incidence of urethane-induced pulmonary neoplasia compared with control littermates. Columns, mean of surface tumors from each treatment group; bars, SD. The Student’s t test was used to analyze the data (*, P < 0.05). B, top, a representative lung section stained by H&E with pulmonary tumors from control (left) and NAG-1Tg+/FVB (right) mice. Magnification, 20×; scale bar, 1.0 mm. Columns, mean tumor numbers per lung; bars, SD. The Student’s t test was used to analyze the data (*, P < 0.05). C, representative images of foci of hyperplasia (HP, asterisk, top left), atypical adenomatous hyperplasia (AAH, asterisk, top right), multiple adenomas (AD, asterisk, bottom left), and adenocarcinomas (AC, asterisk, bottom right) characterized as well differentiated and compressing the surrounding tissues (arrows in AD), and adenocarcinomas (AC, asterisk, bottom right) with localized fingering invasion into surrounding parenchyma or airways (arrows in AC). Magnification, 400× and 200×; scale bars, 50 and 100 μm, respectively. Graph at right shows evaluation of each type of lesion per lung section of each treatment group. Columns, mean; bars, SD. The Student’s t test was used to analyze the data. D, the distribution of tumor numbers as a percentage of total numbers of control (n = 33) and n = 29 of NAG-1Tg+/FVB mice as related to size (diameter, mm). The tumor diameters were divided into four groups according to size (<0.5, 0.5-1.0, 1.1-1.5, and >1.5 mm).
NAG-1 and Lung Tumorigenesis

Characterization of NAG-1Tg+/FVB mice

To explore the role of NAG-1 in lung tumorigenesis, NAG-1Tg+/FVB mice were bred with wild FVB strain mice to generate NAG-1Tg+/FVB mice, which are a more susceptible model for lung carcinogenesis (22). To evaluate the effects of NAG-1 on lung tumorigenesis, urethane was used to induce pulmonary adenomas and adenocarcinomas in mice (6). Eleven-week-old NAG-1Tg+/FVB (n = 10) and control littermate mice (n = 11) received i.p. injections of urethane or 0.9% NaCl alone once per week for 6 wk. Fourteen weeks after the last urethane treatment, mice were sacrificed and lung tissues were examined and collected for further analysis (Fig. 1A).

NAG-1Tg+/Bl6 mice have been reported viable and fertile with no distinguishable behavioral, clinical, or histopathologic phenotype except that the mice had reduced body weight compared with the control littermates (9). A similar decrease in body weight was observed in the NAG-1Tg+/FVB compared with control mice (Fig. 1B; NAG-1Tg+/FVB = 24.8 ± 1.1 g per mouse versus control = 32.3 ± 5.2 g per mouse at 30 wk, P < 0.001). However, the weight of dissected lungs from NAG-1Tg+/FVB mice was not significantly reduced compared with lungs from control mice (NAG-1Tg+/FVB = 0.219 ± 0.03 g per mouse versus control = 0.245 ± 0.01 g per mouse, P = 0.14).

NAG-1 expression in lungs of NAG-1Tg+/FVB mice was confirmed by reverse transcription-PCR and Western blotting analysis (Fig. 1C). RNA transcripts of the human NAG-1 gene were amplified from lung samples of NAG-1Tg+/FVB mice, whereas no amplified products were detectable in control mice (Fig. 1C, top). Cell lysates from urethane-treated lung tissue were subjected to Western blotting analysis, and the NAG-1 protein was detected only in tissues obtained from the NAG-1Tg+/FVB mice (Fig. 1C, bottom). NAG-1 expression in NAG-1Tg+/FVB mice was also seen in other tissues, including skin, colon, brain, and kidney (data not shown).

NAG-1Tg+/FVB mice had reduced urethane-induced lung lesions

To characterize the urethane-induced lesions, lungs were dissected from mice and evaluated by gross examination and light microscopy. There was a 100% incidence of lung lesions in both the control and NAG-1Tg+/FVB mice treated with urethane; however, no lung lesions were observed in saline-treated groups (data not shown). To determine whether NAG-1 expression alters urethane-induced lung tumorigenesis, surface lung tumors were counted (Fig. 2A). The NAG-1Tg+/FVB mice had a modest but significantly lower number of urethane-induced pulmonary tumors, compared with the control littermates (NAG-1Tg+/FVB = 16 ± 4 per mouse versus control = 20 ± 7 per mouse, P < 0.05). The light microscopic examination of multiple lung sections H&E stained with roughly equivalent cross-sectional areas revealed the location of most neoplasia at the periphery of the lungs (Fig. 2B). Lungs from urethane-treated control mice had significantly more lesions compared with urethane-treated NAG-1Tg+/FVB mice (NAG-1Tg+/FVB = 7.4 ± 2.4 per lung versus control = 10.7 ± 3.8 per lung, P < 0.05). No significant pulmonary pathology was observed in the lungs from the saline-treated control mice (data not shown). In the lung sections from the urethane-treated control ([n = 11] and NAG-1Tg+/FVB mice ([n = 9]), foci of hyperplasia (Fig. 2C), atypical adenomatous hyperplasia (Fig. 2C), and multiple pulmonary epithelial neoplasia were present. The majority of the neoplastic foci were considered adenomas (Fig. 2C), characterized by being well-differentiated, compressing the surrounding tissues (Fig. 2C), with no to minimal mitotic activities, and solid to mixed (solid and papillary) architectural pattern. Approximately 20% of the neoplasias in the urethane-induced control mice were considered adenocarcinomas (Fig. 2C) with localized fingering invasion into surrounding parenchyma or airways, and with an average mitotic index of 3.2 mitotic figures per 40× objective


Western blot

Lung tissues were homogenized and then sonicated in ice-cold radioimmunoprecipitation assay buffer (1× PBS, 1% NP40, 0.5% sodium deoxycholate, 0.1% SDS) supplemented with protease and phosphatase inhibitors (1 μg/mL aprotinin, 1 μg/mL leupeptin, 1 mmol/L phenylmethylsulfonyl fluoride, 1 mmol/L Na3VO4, and 25 mmol/L NaF). Proteins from A549 cells were used for immunoblotting as described previously (24).

Caspase-3/7 activity

The Caspase-Glo 3/7 Assay kit was used to measure apoptosis in mouse lung tissue following the manufacturer’s protocol. Briefly, the tissue lysates were prepared using radioimmunoprecipitation assay buffer, and a total of 30 μg of proteins were added into 96-well tissue culture plates with white walls and a clear bottom, and an equal amount of luminescence substrate for caspase-3/7 was added to each sample. After 1-h incubation in the dark at room temperature, the luminescence was measured in a plate-reading luminometer (FLx800) as directed by the manufacturer (BioTek Instruments).

Terminal deoxynucleotidyl transferase–mediated nick-end labeling assay

TACS2 TdT-DAB In Situ Apoptosis detection kit was purchased from Trevigen and used to detect apoptotic cells. Briefly, the lung sections were deparaffinized, rehydrated, and washed in 1× PBS. Tissue sections were counterstained with methyl green staining. As a positive control, we used a lung tissue pretreated with TACS-Nuclease to generate DNA breaks in cells. The results were analyzed under a microscope.

Transient transfection

All transfection experiments were done using Lipofectamine 2000 reagent (Invitrogen Corporation) according to the manufacturer’s instructions, as described previously (8). After transfection and serum starvation, the cells were treated with the indicated compounds for 0.5 and 2 h.

Statistical analysis

We used the Student’s t test and ANOVA test to analyze the data. Results were considered statistically significant at *P < 0.05, **P < 0.01, and ***P < 0.001.

Results

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field; however, no metastasis was observed. Interestingly, no adenocarcinomas were identified in lung sections from the urethane-treated NAG-1Tg+/FVB mice (n = 10). The results are based on analysis of the sections from lung lobes of each mouse; thus, obtained data are from only a limited area of the lung. Approximately the same areas were analyzed from each treatment group. The diameters of tumors from the NAG-1Tg+/FVB mice (n = 29) were compared with the diameters of neoplasia from the control littermates (n = 33). Most of the tumors of the control mice were >0.5 mm in size, whereas 58% of NAG-1Tg+/FVB mice had lung tumors with diameters more than 0.5 mm in size (Fig. 2D). In general, the tumors in the NAG-1Tg+/FVB mice were smaller than the tumors in the control mice. Overall, NAG-1Tg+/FVB mice had reduced tumor amount and size, with no adenocarcinomas compared with control littermates, indicating the possible role of NAG-1 in inhibition of lung tumor progression.

**Phospho-38 MAPK is affected by NAG-1 in urethane-induced lung tumorigenesis**

To further characterize the effects of the NAG-1 protein on lung tumorigenesis and to identify possible mechanisms involved in pulmonary tumor growth and progression, we examined protein expression in lung tissue from urethane-treated NAG-1Tg+/FVB and control mice. Proteins of the arachidonic acid pathway play important roles in lung tumorigenesis (25) and several proteins involved in this pathway were examined. The expression of COX-2, COX-1, and PGE2 synthase was up-regulated in lung tumor tissues from both treated control and NAG-1Tg+/FVB mice (Fig. 3A). The expression of EP2 and EP4, two members of the prostaglandin E receptor family, were also examined; however, we were not able to detect EP4 receptor expression in mice lung tissue (data not shown). In contrast, the EP2 receptor was highly expressed in lung tumor tissues from both NAG-1Tg+/FVB and control mice. The expression of several other signaling proteins involved in lung tumorigenesis was examined. The active Raf-1 and extracellular signal-regulated kinase 1/2 play an important role in lung tumorigenesis (24, 26, 27), and an increased activation of Raf-1 and extracellular signal-regulated kinase 1/2 was observed in tumor tissue from both NAG-1Tg+/FVB and control mice (Fig. 3B). We also examined cell cycle–related proteins, including cyclin D1, p53, p27, and p21. However, as shown in Fig. 3C, the expression of these proteins was not affected by NAG-1 overexpression.

Urethane-induced phosphorylation of p38 MAPK at Thr^{180}/Tyr^{182} was increased in tumor tissue compared with normal...
tissue from control mice. In contrast, the phosphorylation of p38 MAPK was significantly lower in tumor and normal tissue isolated from NAG-1^TG+/FVB mice, suggesting that the expression of NAG-1 inhibits phosphorylation of p38 MAPK (Fig. 3B). There were no significant differences in NAG-1^TG+/FVB and control mice in the expression of either phospho-AKT or phosphorylated stress-activated protein kinase/c-Jun-NH2-kinase (data not shown). Our data suggest that NAG-1 expression may cause alteration of p38 MAPK in urethane-induced lung tumorigenesis.

Immunohistochemical analysis was also done to confirm and localize protein expression in the pulmonary tissues. Using an antibody specific for the phosphorylated form of p38 MAPK at Thr^180/Tyr^182, there was a substantial decrease in staining intensity for the active p38 MAPK in nuclei and cytoplasm in the lung tumors of NAG-1^TG+/FVB mice (data not shown). Our data suggest that NAG-1 expression may cause alteration of p38 MAPK in urethane-induced lung tumorigenesis.

**NAG-1 protein activates apoptosis in urethane-induced pulmonary adenomas**

It has been reported that NAG-1 induces caspase activity (28). To evaluate the possible involvement of NAG-1 in regulating lung tumorigenesis through apoptosis, caspase-3/7 activities in normal and tumor tissues of the lungs were measured. The caspase-3/7 activities in lung tumors were highly significantly increased in NAG-1^TG+/FVB mice, compared with control mice and with the normal lung of NAG-1^TG+/FVB mice (Fig. 4A). There was no significant difference in caspase-3/7 activities between the normal lungs from control and NAG-1^TG+/FVB mice.

To further show that the NAG-1 protein modulates apoptotic pathways in lung tumorigenesis, the lung tissues were treated with an antibody specifically recognizing only the cleaved form of caspase-3. Immunohistochemical staining was positive for active caspase-3, localized to the cytoplasm in the tumors of NAG-1^TG+/FVB mice, but not in the tumors of control mice (data not shown). The appearance of apoptosis was confirmed by terminal deoxyribonucleotide transferase-mediated nick-end labeling (TUNEL) assay as shown in Fig. 4B.

**NAG-1 protein inhibits urethane-induced inflammation**

In addition to the role of NAG-1 in antitumorigenesis, it has been shown that NAG-1 affects anti-inflammatory activity by reducing tumor necrosis factor-α secretion in macrophages (29). Urethane- or cigarette smoke–induced lung tumour formation may be potentiated by inflammation (22, 30). To check the role of NAG-1 in inflammation, we performed immunohistochemical staining of lysozyme to detect the presence of inflammatory cells in lung tissue. Lysozyme is an enzyme highly expressed in cytoplasmic granules of the granulocytic series of inflammatory cells, such as macrophages and polymorphonuclear neutrophils (Fig. 5A). As shown in Fig. 5B, NAG-1^TG+/FVB mice had a significant 50% reduced number of lysozyme-positive cells in the lung over control mice (P < 0.05). Thus, this suggests that NAG-1 suppresses urethane-induced inflammation in lung tissue.

**Inhibition of p38 MAPK phosphorylation in human A549 lung carcinoma cells by NAG-1 overexpression**

To verify the role of the NAG-1 protein in inhibition of lung tumors in NAG-1^TG+/FVB mice through the p38 MAPK, human
A549 lung carcinoma cells were transiently transfected with a plasmid construct containing the human NAG-1 gene. After transfection, A549 cells were treated with 12-O-tetradecanoylphorbol-13-acetate (20 nmol/L), cigarette smoke condensate (40 μg/mL), EGF (100 nmol/L), IGF-I (100 nmol/L), and PGE₂ (50 nmol/L) for 0.5 and 2 h. As shown in Fig. 6A, treatment with cigarette smoke condensate had the ability to induce phosphorylation of p38 MAPK at 2 h and its expression was diminished in the presence of the NAG-1 protein. Similar results were observed when A549 cells were treated with both growth factors EGF and IGF-I, as well with inflammatory cytokine PGE₂ (Fig. 6B and C). Interestingly, the NAG-1 protein had no effect on the phosphorylation of p38 MAPK after treatment with 12-O-tetradecanoylphorbol-13-acetate (Fig. 6A). In addition, the NAG-1 protein had no effect on the phosphorylation of p42/p44 MAPK after activation by all tested agents in transiently transfected A549 cells (data not shown).

Discussion

NAG-1 has antiproliferative and proapoptotic effects in several types of cancer in vitro and is highly induced by many chemopreventive compounds (7). NAG-1 is highly expressed in normal tissue of the small intestine and it is significantly reduced in human colorectal carcinomas and neoplastic intestinal polyps of ApcMin mice (31). In the human lung, NAG-1 was reported to be highly expressed in normal tracheobronchial epithelium, but absent in several tumor tissues from adenoma, small cell, large cell, and squamous cell carcinomas (20). Those findings are in agreement with observations in this study, in which the expression of the human NAG-1 protein plays an important role in lung tumorigenesis.

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NAG-1 transgenic mice on a C57BL/6J background were generated using the Cre/LoxP system (9). NAG-1Tg+/FVB mice were viable and fertile with no apparent phenotype other than a reduction in body weight compared with nontransgenic littermate controls. In this study, we generated NAG-1Tg+/FVB mice because the FVB strain is a more susceptible model for urethane-induced lung tumorigenesis. With more than eight generations of backcross with wild-type mice with FVB background, we found that body weight was still less in NAG-1Tg+/FVB mice compared with the control mice (Fig. 1B), indicating that NAG-1–induced body weight reduction is seen not only in C57BL/6J mice but also in other strains of mice.

It has been known that urethane-induced lung tumors in rodents provide an excellent model to determine the efficacy of tumor suppressor genes as a preventative method, as well to evaluate mechanisms responsible for antitumorigenesis. This experimental system can be vigorously examined throughout lung carcinogenesis, from the appearance of early preneoplastic proliferative lesions and small adenomas to malignancy. Urethane-induced pulmonary adenomas predominantly occur in the periphery of the lung (2, 4, 6). Primary mouse lung tumors share morphologic, histologic, and molecular characteristics with human lung tumors. Our data suggest that NAG-1Tg+/FVB mice had a significantly lower incidence of urethane-induced pulmonary lesions compared with the control littermates, with the localization of most neoplasia at the periphery of the lungs. Histology of the lung sections from urethane-treated control and NAG-1Tg+/FVB mice revealed the formation of hyperplasia and pulmonary epithelial neoplasia (Fig. 2C). Nearly all neoplasia were considered adenomas, but only in the control mice, urethane also induced
adenocarcinomas with typical invasion into surrounding tissue. However, no adenocarcinomas were observed in the lung tissue sections from NAG-1Tg/FVB mice. Based on these data, NAG-1 may play a role in inhibition of malignancy in lung tumorigenesis. Similarly, another study suggests that NAG-1 expression induces the differentiation of normal tracheobronchial epithelium (20), although the defined biological role of the NAG-1 protein in the epithelium is not yet fully understood.

Chronic inflammation is linked to carcinogenesis in several organ systems, including the colon and lung, and inflammatory cells increase expression of factors that may support the growth, angiogenesis, and metastasis of cancer cells. The p38 MAPK activation is well associated with extracellular matrix remodeling, inflammation, and contractile dysfunction of the heart (32). However, the role of p38 MAPK in tumorigenesis depends on cell type and stimuli (33). In contrast to a number of publications discussing the role of the p38 MAPK pathway as antitumorigenic, many publications have provided evidence for its role in the progression of tumorigenesis via increasing production of proinflammatory cytokines. For example, recently published results by Stathopoulos et al. (22) showed that urethane-induced lung tumor formation is initiated by inflammation through the activation of nuclear factor-κB. Another study shows that mice, after exposure to cigarette smoke, show increased lung inflammatory cell influx, activation of nuclear factor-κB and p38 MAPK, and increased levels of matrix metalloproteinase-9 and proinflammatory cytokines, such as tumor necrosis factor-α and interleukin-6 (30). Because NAG-1 appears to have anti-inflammatory activity by reducing tumor necrosis factor-α secretion in macrophages (29) and p38 MAPK was inactivated in the NAG-1Tg/FVB mice after urethane exposure, our data indicated that p38 MAPK could be a novel downstream target of the NAG-1 signaling pathway, resulting in the reduction of inflammatory cells (Fig. 5) and potentially leading to inhibition of the lung tumorigenesis. The importance of NAG-1 in lung tumorigenesis was confirmed by in vitro experiments. Our data revealed that cigarette smoke condensate-, IGF-I-, EGF-, or PGE2-induced phosphorylation of p38 MAPK was down-regulated in the presence of overexpressed NAG-1 in human A549 lung carcinoma cells (Fig. 6A-C).

Western blot for NAG-1 in A549 cells (Fig. 6) and in mice lung tissue (Fig. 1C) revealed two bands that migrate as a doublet (35 kDa) on SDS-PAGE gels. This phenomenon was observed in other cell lines, such as human LNCaP prostate carcinoma cells (34). We speculated that the NAG-1 gene has

Fig. 6. NAG-1 inhibits phosphorylation of p38 MAPK in A549 cells. A549 cells were grown and transiently transfected with empty or pcDNA3.1/NAG-1 expression vector. After transfection, A549 cells were treated with 20 nmol/L 12-O-tetradecanoylphorbol-13-acetate (TPA) and 40 μg/mL cigarette smoke condensate (CSC; A), 100 ng/mL EGF and 100 ng/mL IGF-I (B), or 50 nmol/L PGE2 (C) for 30 and 120 min. The phosphorylation of p38 MAPK, NAG-1, and actin expression was evaluated by Western blotting analysis. The numbers below represent densitometry analysis of phospho-p38 normalized to actin, and then compared with the controls (0 min set as 1.0 in each transfection). D, schematic diagram of the role of NAG-1 in lung tumorigenesis.
two translational initiation codons, which produce two different peptides with 13-amino-acid differences. Given that both bands are induced by several anticancer compounds including vitamin D (35), and Western blot with NAG-1 peptide showed disappearance of both bands, we strongly believe that these are from different usage of the translation initiation start site. However, the biological function of the short form is still unknown and needs to be addressed in future studies.

Prevention by eliminating tumor promoters, early diagnosis, and new target treatment are keys to reduce the numbers of deaths caused by lung cancer. In the present study, we propose antitumorigenic activities of NAG-1 in lung cancer. Overexpressed human NAG-1 reduced tumor number and size and protected the progression of urethane-induced pulmonary neoplasia in mouse models. The newly identified NAG-1 downstream molecular target was p38 MAPK. NAG-1 had proapoptotic activity by increasing caspase-3/7 activities. To our knowledge, we have shown for the first time that NAG-1 has anti-inflammatory activity in lungs through the inhibition of inflammatory cells. Our in vivo data were also confirmed by in vitro data using human A549 lung carcinoma cells overexpressing human NAG-1. We conclude that NAG-1 plays a role as a tumor suppressor gene in lung tumorigenesis, and the elucidation of NAG-1 downstream signaling can help us to better understand the regulation of lung cancer prevention (Fig. 6D).

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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References


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