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TrkB/BDNF signaling pathway is a potential therapeutic target for pulmonary large cell neuroendocrine carcinoma

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Abstract

Tropomyosin-related kinase B (TrkB) plays an important role in tumor progression in various kinds of cancers; however, little is known about biological significance of TrkB in human lung cancer, especially large cell neuroendocrine carcinoma (LCNEC). We hereby investigated the expressions of TrkB and its ligand brain-derived neurotrophic factor (BDNF) in clinical specimens and their influences on phenotypes of invasiveness and tumorigenicity for LCNEC. The expressions of TrkB and BDNF analyzed by immunohistochemistry for patients samples with lung cancer (n=104) were significantly higher in neuroendocrine tumor (NET) compared with non-NET. In particular, LCNEC, a subtype of NET, exhibited significantly higher TrkB and BDNF expressions than another NET type: small cell lung cancer (SCLC), and a significant correlation between TrkB and BDNF expressions was noted in LCNEC but not in SCLC. *In vitro* assay, exogenous BDNF addition enhanced the invasion into matrigels of LCNEC cells, whereas inhibition of TrkB or BDNF suppressed matrix metalloproteinase-2 and -9 activities and the invasiveness. Exogenous BDNF also increased anchor-independent colony formation on soft agar gels for LCNEC, while inhibition of TrkB or BDNF suppressed the anchorage-independency. *In vivo* experiments, implanted LCNEC cells pretreated with TrkB-siRNA developed no

subcutaneous tumor in all six nude mice, although those with control-siRNA formed tumors in four of six nude mice. In conclusion, BDNF/TrkB signal is involved in malignant progression of invasiveness and tumorigenicity for LCNEC, and may be a potential target for LCNEC without standard therapy.

1. Introduction

Lung cancer is the leading cause of death among the malignant tumors worldwide, and most of these deaths are caused by the metastasis of tumor (1). Among several types of lung cancers, neuroendocrine carcinomas: small cell lung carcinoma (SCLC) and large cell neuroendocrine carcinoma (LCNEC) exhibit especially aggressive phenotypes due to their frequent recurrence and high metastatic potential (2). Based on large-scale clinical trials, the guide line of standard therapies for SCLC has been established, despite the outcome has met with limited success (3). On the other hands, much less is known about LCNEC, and no consensus on therapy has been reached. Therefore, effective target for LCNEC regulation are earnestly desired to be identified.

Tropomyosin-related kinase B (TrkB) is a member of Trk family, functions as a receptor tyrosine kinase for brain-derived neurotrophic factor (BDNF), a member of nerve growth factor family. BDNF and TrkB are necessary for the normal development of the nervous system (4, 5) and lung (6). BDNF and TrkB are up-regulated in a variety of malignant solid tumors, including neuroblastoma (7), bladder (8), pancreatic (9), and ovarian cancers (10). TrkB is also known as a negative prognostic factor for patients with neuroblastoma, Wilms' tumor, pancreatic, hepatocellular, and gastric

cancers(11-13). When stimulated by BDNF ligand, TrkB induces the activation of downstream AKT (14, 15), ERK (16, 17), HIF-1 α (18) signals, which elicits the differential regulation of various cellular activities, such as cell proliferation (19), differentiation (20), apoptosis (21) and invasion (22). Accordingly, TrkB signal contributes to resistance to anoikis, formation of large tumor aggregates and infiltration into lymphatic and blood vessels, resulting in high potential of metastasis (23).

With respect to TrkB in lung cancer, higher expression of TrkB has been shown in non small cell lung cancer and closely correlated with lymph node metastasis (24). It has also reported higher expression of TrkB correlate with overall survival in squamous cell carcinoma (25). Nevertheless, it has not been examined whether TrkB/BDNF pathway is up-regulated and involved in malignant progression for neuroendocrine tumor (SCLC and LCNEC) of lung cancer.

In this study, we investigated the expression and biological significance of TrkB/BDNF signaling for neuroendocrine tumor of lung cancer.

Materials and Methods

2.1. Patients.

Ninety eight patients with lung cancer received curative surgical resection at

Hamanomachi Hospital from August 1995 to August 2009. Six patients with lung cancer underwent curative surgery at Kyushu Kosei Nenkin Hospital from September 2004 to March 2009. All patients have received no chemotherapy or radiation therapy prior to surgery. All patients with LCNEC and SCLC were selected because of the small number of cases while patients with other histological type were quite randomly chosen. The clinicopathological profiles of LCNEC and other histological types are shown in Table 1. Although significant difference is observed only in venous invasion, there were no significant difference in many other clinicopathological factors such as age, gender, tumor size, lymphnode metastasis, lymphnode invasion, and TNM stage among subgroups. The hospital's ethics committee approved the study protocol. All patients were given full explanations and gave written informed consent before treatment.

2.2. Cell lines

We used LCNEC cell lines (NCI-H460, NCI-H810), lung adenocarcinoma cell line (A549), SCLC cell line (SBC-3) and lung large cell carcinoma cell line (LU99). NCI-H460, A549, SBC-3 and LU99 were cultured in RPMI 1640 supplemented with 10% fetal bovine serum (FBS). NCI-H810 was cultured in DMEM:F12 (American Type Culture Collection) supplemented with 5% FBS, 0.005 mg/ml insulin, 0.01 mg/ml

transferrin, 30 nM sodium selenite, 10 nM beta estradiol, 10 nM hydrocortisone, 2 mM L-glutamine.

2.3 Small interfering RNA transfection

Small interfering RNA targeting TrkB (Dharmacon, Lafayette, CO, USA), BDNF, matrix metalloproteinase (MMP)-2, or MMP-9 were transfected into NCI-H460 and NCI-H810 cells (final concentration: 50 nM) by using Lipofectamine RNAiMAX (Invitrogen, Carlsbad, CA, USA) according to the manufacturer's protocol.

Non-targeting siRNA (Dharmacon) was used as the negative control.

2.4. Real-time RT-PCR

Total RNA was isolated with the High Pure Isolation Kit (Roche Diagnostics GmbH, Mannheim, Germany), and reverse-transcribed using the Quantitect Reverse Transcription Kit (Qiagen, Hilden, Germany) according to the manufacturer's protocol. Reactions were performed with SYBR Premix EX Taq II (Takara Bio, Shiga, Japan) on a DNA Engine Opticon 2 system (MJ research, Waltham, MA, USA). The amount of each target gene was normalized to the level of β -actin. The primers used were as follows: *MMP-2*, forward, 5'-TGATCTTGACCAGAATACCATCGA-3' and reverse,

5'-GGCTTGCGAGGGAAGAAGTT-3'; *MMP-9*, forward,

5'-TGGGCTACGTGACCTATGACAT-3' and reverse,

5'-GCCCAGCCCACCTCCACTCCTC-3'; *ACTB*, forward,

5'-TTGTTACAGGAAGTCCCTTGCC-3' and reverse,

5'-ATGCTATCACCTCCCCTGTGTG-3'

2.5. Immunohistochemistry

Paraffin sections of lung cancer were deparaffinized and rehydrated routinely.

The sections were immersed with 3% H₂O₂ and 10% goat serum and incubated with a primary antibody for TrkB (sc-8316, Santa Cruz Biotechnology, Santa Cruz, CA, USA, 1:100) or BDNF (sc-546, Santa Cruz, 1:100) at 4°C overnight. The samples were incubated with HISTOFINE simple stain MAX-PO (R) (Nichirei, Tokyo, Japan) and finally visualized by 3,3'-diaminobenzidine (DAB) with hematoxylin-counterstain.

Both the intensity and percentage of TrkB and BDNF expression were assessed as follows: intensity score 0: absence of staining, 1: weakly stained, 2: moderately stained, 3: strongly stained; percentage score 0: absence of positive cells, 1: 0.1-33% of cells positive, 2: 33.1-66% of cells positive, 3: >66% of cells positive; total score (ranging from 0 to 9) was calculated by multiplying intensity score and percentage score.

2.6. Cell immunofluorescence

NCI-H460 and NCI-H810 cells were fixed with 4% paraformaldehyde and permeabilized with 0.1% Triton X-100. The samples were incubated with a primary rabbit polyclonal antibody for TrkB (sc-8316, 1:100) or BDNF (sc-546, 1:100) at 4°C overnight, following by a secondary Alexa 488-conjugated goat anti-rabbit IgG (Invitrogen, 1:1000). The nuclei were counterstained with 4-6-diamidino-2-phenylindole (DAPI) (Invitrogen), and protein expression level of TrkB and BDNF was evaluated by fluorescence intensity under fluorescence microscopy (Carl Zeiss, Tokyo, Japan), as previously, described (26).

2.7. Western blot analysis

Cultured cells were lysed in SDS-Buffer, proteins were separated on SDS-PAGE and transferred to nitrocellulose membranes. The membranes were incubated with primary antibodies for TrkB (sc-8316, 1:200), BDNF (sc-546, 1:200), MMP-2 (sc-10736, Santa Cruz, 1:200), MMP-9 (sc-6840, Santa Cruz, 1:200), or α -tubulin (Sigma-Aldrich, St. Louis, MO, USA, 1:1000) at 4°C overnight, followed by

peroxidase-labeled secondary antibodies at 37°C. Immunoblots were identified using the ECL Prime Western Blotting Detection System (GE Healthcare Life Sciences, Buckinghamshire, UK) with a Molecular Imager FX (Bio-Rad Laboratories, Hercules, USA).

2.8. Cell invasion assay

The invasiveness of LCNEC cells was assessed by invasion assay described by previously (27). In brief, cells (2×10^5) were added to the upper chamber and incubated for 24 hours. Total number of cells migrated to the lower side of the filter was counted under a light microscope.

2.9. In vivo Xenograft tumor model

Five-week-old female athymic nude mice (BALB/c *nu/nu*) were purchased from Charles River Laboratories Japan (Kanagawa, Japan) and acclimated for two weeks. All animal procedures were approved by the Animal Care and Use Committee at Kyushu University. NCI-H810 cells transfected with TrkB-targeting siRNA or non-targeting control siRNA were subcutaneously implanted into flank regions (5×10^6 cells in PBS per mouse) of the nude mice (n=6 in each). The tumor size was determined

twice a week and the tumor volume was calculated by the following formula: length \times (width)² \times 0.5 (cm³).

2.10. Statistical analysis

All data were represented as mean \pm standard deviations (SD). χ^2 test was applied to analyze the relationship between clinicopathological parameters. Student's *t*-test was used for the comparison of mean values between two groups. Survival curves were plotted by Kaplan-Meier method and analyzed using two-sided log-rank tests. A value of $P < 0.05$ was considered significant.

2. Results

3.1. Clinicopathological characteristics of patients with lung cancer

Total 104 cases of lung cancer were histologically diagnosed as follows. Neuroendocrine tumor (NET) included LCNEC (n=11) and SCLC (n=8), while non-neuroendocrine tumor (non-NET) consisted of large cell carcinoma (n=10), adenocarcinoma (n=20) and squamous cell carcinoma (n=55). Overall survival in NET and non-NET are shown in Fig. 1A. The 5-year survival rates for patients with NET and non-NET were 43.5% and 77.3%, respectively and overall survival in NET was significantly lower than that in non-NET.

3.2. TrkB and BDNF expression in lung cancer tissues of patients

We investigated TrkB and BDNF expression in lung cancer tissues of patients by immunohistochemistry. The expression of TrkB was detected in 91 (88%) out of 104 lung tumors: higher expression (scores of 4, 6, or 9) in 38 cases (37%) and lower expression (scores of 0, 1, 2, or 3) in 66 cases (64%). The expression of BDNF was detected in 88 (85%) out of 104 lung tumors: higher expression (scores of 4, 6, or 9) in 41 cases (39%) and lower expression (scores of 0, 1, 2, or 3) in 63 cases.

We evaluated TrkB and BDNF expression among NET, non-NET and normal bronchial epithelial (NBE) tissues distant from tumor area by immunohistochemistry. The % scores of TrkB and BDNF were significantly higher in NET or non-NET compared with NBE (Fig. 1B). The intensity scores of TrkB and BDNF were significantly higher in NET than NBE or non-NET and there was no difference between non-NET and NBE (Fig. 1C). Accordingly, the total scores of TrkB and BDNF were significantly higher in NET compared with either non-NET or NBE (Fig. 1D). Samples of TrkB and BDNF expression (total score of 0, 3, 6 and 9) in lung cancer are shown in Fig. 1E and 1F, respectively. A high correlation was noted for co-expression of BDNF and TrkB in NET ($P<0.001$) (Fig. 1G).

We further analyzed the expression status of TrkB and BDNF separately for SCLC and LCNEC subtypes of NET lung cancers. Total scores of TrkB and BDNF were significantly higher in LCNEC than SCLC (Fig.2A). The correlation of TrkB and BDNF in SCLC and LCNEC, respectively was also studied. A significant correlation between BDNF and TrkB expression was noted for LCNEC ($P=0.023$), but not for SCLC ($P=0.17$) (Fig. 2B). These data suggested BDNF and TrkB played a more important role in LCNEC than SCLC. Therefore, we used LCNEC cell lines to understand the biologic consequences of BDNF/TrkB signaling *in vitro*.

3.3. BDNF/TrkB signaling enhances invasive phenotype of LCNEC cells

We hypothesized BDNF/TrkB signaling may contribute to some malignant phenotype for LCNEC and examined the role of BDNF/TrkB on invasiveness of LCNEC. TrkB and BDNF expression in lung cancer cell lines was analyzed by Western blotting (Fig. 3A). LCNEC cell lines (NCI-H460 and NCI-H810 showed high TrkB and BDNF expression. TrkB and BDNF expression in NCI-H460 and NCI-H810 was also confirmed immunocytochemistry (Fig. 3B). Addition of recombinant human BDNF (Peprotech, Rocky Hill, NJ, USA) or TrkB tyrosine kinase inhibitor K252a

(Alomone Labs, Jerusalem, Israel) to culture medium did not affect the proliferation of these cells (Fig. 3C). In contrast exogenous BDNF treatment (10, 100 and 1000 ng/ml) significantly enhanced matrigel invasion of these cells (Fig. 3D) in a dose-dependent manner. Reversely, K252a (500, 1000 nM) significantly decreased the invasion in NCI-H460 and NCI-H810 cells (Fig. 3E). As shown in Fig. 3F, enhanced cell invasion by BDNF treatment was interrupted by K252a, suggesting the invasive potential of LCNEC cells may be mediated through BDNF/TrkB signaling. To verify the direct link of BDNF/TrkB signaling to the phenotypic alterations in LCNEC, we carried out the inhibition experiments using TrkB-siRNA or BDNF-siRNA LCNEC cell lines. Western blotting shows the inhibition of TrkB and endogenous BDNF by the siRNA knockdown (Fig. 3G). TrkB and BDNF-siRNAs significantly inhibited the invasion of NCI-H460 and NCI-H810 cells (Fig. 3H). Exogenous BDNF addition had little effect on the invasion of LCNEC cell lines transfected with TrkB-siRNA, but reversed the invasive ability of LCNEC cells downregulated by BDNF-siRNA transfection. TrkB and BDNF co-knockdown significantly inhibited the invasion even in the presence of exogenous BDNF.

3.4. BDNF/TrkB-induced invasion is mediated through MMP-2 and MMP-9

To explore the underlying mechanism mediating invasion by BDNF/TrkB signaling in LCNEC cells, we examined the effect of BDNF ligand on the activities of MMP-2 and MMP-9 in NCI-H460 and NCI-H810 cells. The increased expression and activities of MMP-2 and MMP-9 by BDNF treatment were identified in NCI-H460 and NCI-H810 by quantitative RT-PCR (Fig. 4A), Western blotting (Fig. 4B) and zymography (Fig. 4C). On the other hand, TrkB or BDNF knockdown significantly decreased the expression of MMP-2 and MMP-9 (Supplementary Fig. S1). The decreased expression in MMP-2 and MMP-9 with TrkB-siRNA transfection was not recovered by exogenous BDNF treatment (Fig. 4D and 4E), whereas the decreases with BDNF-siRNA were compensated by exogenous BDNF in LCNEC cells. We further investigated the effect of MMP-2 or MMP-9 knockdown on the invasion of LCNEC cells. In a preliminary experiment (Supplementary Fig. S2), MMP-2-siRNA or MMP-9-siRNA transfection induced over 80% inhibition of MMP-2 or MMP-9, respectively. MMP-2 or MMP-9 knockdown significantly inhibited the invasion of NCI-H460 and NCI-H810 (Fig. 4F) irrespective of exogenous BDNF addition. MMP-2 and MMP-9 concurrent knockdown inhibited the invasion more than MMP-2 or MMP-9 knockdown alone. These data suggest enhanced cell invasion by BDNF/TrkB signaling is through the upregulation of MMP-2 and MMP-9 pathway in LCNEC.

3.5. *BDNF/TrkB signaling augments colony formation in LCNEC cells*

We next investigated the role of BDNF/TrkB signaling on anchorage-independent growth of LCNEC cells. As shown in Fig. 5A and 5B, TrkB and BDNF-siRNAs significantly inhibited the colony formation of NCI-H460 and NCI-H810 cells. Exogenous BDNF addition had little effect on the colony formation of LCNEC cell lines transfected with TrkB-siRNA, but reversed the decrease in colony formation of LCNEC cells transfected with BDNF-siRNA. TrkB and BDNF co-knockdown significantly inhibited the colony formation even in the presence of exogenous BDNF. These results suggest BDNF/TrkB signaling mediate the anchorage-independent growth of LCNEC cells.

3.6. *Inhibition of TrkB suppresses tumorigenicity in vivo*

To determine whether the observed anchorage-independent growth by BDNF/TrkB signaling could be reflected *in vivo*, we investigated tumorigenicity of LCNEC cells with or without TrkB silencing in athymic nude mice. Subcutaneous tumors were developed in four out of six mice after implantation of cells transfected with control siRNA (Fig. 5C and 5D). In contrast, all the mice received cells transfected

with TrkB-siRNA showed no sign of tumor development throughout the observation period until three months after the cell implantation. There were significant differences in tumor growth between TrkB-siRNA and control siRNA groups (Fig. 5D). We confirmed TrkB and BDNF were highly expressed in tumor cells transfected with control siRNA (Fig. 5E).

3. Discussion

The present study was firstly designed to investigate biological significance of BDNF/TrkB signaling for NET: LCNEC and SCLC of lung cancer. We at first examined BDNF and TrkB expression status in lung cancer specimens. Both TrkB and BDNF expression levels in LCNEC were significantly higher than SCLC or non-NET tumor types of lung cancer. Furthermore, a significant correlation between BDNF and TrkB expressions was noted in LCNEC, but not in SCLC. It is sometimes difficult to histologically differentiate between LCNEC and SCLC, because they share several histological features, such as rosette formation, moulding of nuclei, and lack of apparent glandular formation and keratinization (28). Then, BDNF/TrkB signaling may be a diagnostic aid for differentiation between LCNEC and SCLC. However, whether low TrkB and BDNF expression in LCNEC correlates with good prognosis was not

observed. The reason may be that there were high TrkB and BDNF expression in all 11 patients with LCNEC. The incidence of LCNEC is only about 2% of resected lung cancers (29, 30), and the number of LCNEC patients in this study could not be over 11 cases. To define whether low TrkB and BDNF expression correlate with good prognosis in LCNEC, would require further investigation in a larger cohort of patients.

Metastasis is the most critical determinant for postoperative prognosis of patients with lung cancer. We investigated the significance of BDNF/TrkB signaling in LCNEC progression, firstly with respect to the effect on invasion. Degradation of the extracellular matrix and the basement membranes by proteases promotes the detachment of tumor cells, their crossing of tissue boundaries, and invasion into adjacent blood or lymphatic vessels and tissue compartments. Recent studies have demonstrated the important role of MMPs in cancer invasion and metastasis for a variety of solid malignant tumors (31). Especially, MMP-2 and MMP-9 (72 kDa and 92 kDa type IV collagenases or gelatinase A and gelatinase B) are associated with the malignant phenotype of tumors because of their unique ability to degrade type IV collagen (32). In the present study, BDNF/TrkB signaling enhanced invasive phenotype of LCNEC cells, which is consistent with the previous reports in non-SCLC (24) and head and neck tumor (22). We hypothesized MMP-2 and MMP-9 may be downstream mediators for

BDNF/TrkB signals in LCNEC cells, and verified this hypothesis with the data that exogenous BDNF increased MMP-2/-9 activities and cell invasion and that TrkB-siRNA and MMPs-siRNA abolished the enhanced MMP activities and invasion by BDNF.

Once cancer cells invade into blood or lymphatic vessels, the attachment to metastatic niche and anchor-independent growth are required to form the metastatic tumors. Thus, we investigated the effect of BDNF/TrkB signaling on anchor-independent colony formation of LCNEC cells, and found the anchorage-independent growth was enhanced by exogenous BDNF and suppressed by TrkB inhibition, despite the anchor-dependent (dish-attached) growth of LCNEC cells was not affected by the BDNF/TrkB modulation (Fig. 3C). To determine whether the observed anchorage-independent growth by BDNF/TrkB signaling could be reflected *in vivo*, we implanted TrkB-silenced LCNEC cells in athymic nude mice, and observed inhibition of TrkB completely disturbed the tumor formation of the LCNEC cells *in vivo*. The prophylactic effect of TrkB-silencing in this mouse model suggests BDNF/TrkB pathway may be a potential therapeutic target for LCNEC.

Our data indicate that the TrkB and BDNF pathway provides critical signals for not only MMP-mediated invasion but also for survival and tumor formation of LCNEC,

as shown in Supplementary Fig. S3. In conclusion, our data indicate BDNF and TrkB are overexpressed in LCNEC type of lung cancer, and BDNF/TrkB signaling is involved in invasiveness and tumorigenicity of LCNEC.

Conflict of interest statement

None declared.

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References

- [1] Bodey B, Bodey B Jr, Gröger AM, Siegel SE, Kaiser HE. Invasion and metastasis: the expression and significance of matrix metalloproteinases in carcinomas of the lung. *In Vivo* 2001;15:175-80
- [2] Asamura H, Kameya T, Matsuno Y, Noguchi M, Tada H, Ishikawa Y, et al. Neuroendocrine neoplasms of the lung: a prognostic spectrum. *J Clin Oncol* 2006;24:70-6.
- [3] Simon GR, Wagner H. Small cell lung cancer. *Chest* 2003;123:295S-71S.
- [4] Klein R, Parada LF, Coulier F, Barbacid M. TrkB, a novel tyrosine protein kinase receptor expressed during mouse neural development. *EMBO J* 1989;8:3701-9.
- [5] Klein R, Smeyne RJ, Wurst W, Long LK, Auerbach BA, Joyner AL, et al. Targeted disruption of the trkB neurotrophin receptor gene results in nervous system lesions and neonatal death. *Cell* 1993;75:113-22.
- [6] García-Suárez O, Pérez-Pinera P, Laurà R, Germana A, Esteban I, Cabo R, et al. TrkB is necessary for the normal development of the lung. *Respir Physiol Neurobiol* 2009;167:281-91
- [7] Matsumoto K, Wada RK, Yamashiro JM, Kaplan DR, Thiele CJ. Expression of

brain-derived neurotrophic factor and p14STrkB affects survival, differentiation, and invasiveness of human neuroblastoma cells. *Cancer Res* 1995;55:1798-806.

[8] Dionne CA, Camoratto AM, Jani JP, Emerson E, Neff N, Vaught JL, et al. Cell cycle-independent death of prostate adenocarcinoma is induced by the trk tyrosine kinase inhibitor CEP-751 (KT6587). *Clin Cancer Res* 1998;4:1887-98.

[9] Miknyoczki SJ, Lang D, Huang L, Klein-Szanto AJ, Dionne CA, Ruggeri BA. Neurotrophins and Trk receptors in human pancreatic ductal adenocarcinoma: expression patterns and effects on in vitro invasive behavior. *Int J Cancer* 1999;81:417-27.

[10] Au CW, Siu MK, Liao X, Wong ES, Ngan HY, Tam KF, et al. Tyrosine kinase B receptor and BDNF expression in ovarian cancers – Effect on cell migration, angiogenesis and clinical outcome. *Cancer Lett* 2009;281:151-61.

[11] Han L, Zhang Z, Qin W, Sun W. Neurotrophic receptor TrkB: is it a predictor of poor prognosis for carcinoma patients? *Med Hypotheses* 2007;68:407-9.

[12] Eggert A, Grotzer MA, Ikegaki N, Zhao H, Chnaan A, Brodeur GM, et al. Expression of the neurotrophin receptor TrkB is associated with unfavorable outcome in Wilms' tumor. *J Clin Oncol* 2001;19:689-96.

[13] Tanaka K, Mohri Y, Nishioka J, Kobayashi M, Ohi M, Miki C, et al. Neurotrophic

receptor, tropomyosin-related kinase B as an independent prognostic marker in gastric cancer patients. *J Surg Oncol* 2009;99:307-10.

[14] Yu X, Liu L, Cai B, He Y, Wan X. Suppression of anoikis by the neurotrophic receptor TrkB in human ovarian cancer. *Cancer Sci* 2008;99:543-552.

[15] Li Z, Jaboin J, Dennis PA, Thiele CJ. Genetic and pharmacologic identification of Akt as a mediator of brain-derived neurotrophic factor/TrkB rescue of neuroblastoma cells from chemotherapy-induced cell death. *Cancer Res* 2005;65:2070-75.

[16] Huang YT, Lai PC, Wu CC, Hsu SH, Cheng CC, Lan YF, et al. BDNF mediated TrkB activation is a survival signal for transitional cell carcinoma cells. *Int J Oncol* 2010;36:1469-76.

[17] Kawamura N, Kawamura K, Manabe M, Tanaka. Inhibition of brain-derived neurotrophic factor/tyrosine kinase B signaling suppresses choriocarcinoma cell growth. *Endocrinology* 2010;151:3006-14.

[18] Nakamura K, Martin KC, Jackson JK, Beppu K, Woo CW, Thiele CJ. Brain-derived neurotrophic factor activation of TrkB induces vascular endothelial growth factor expression via hypoxia-inducible factor-1 α in neuroblastoma cells. *Cancer Res* 2006;66:4249-55.

[19] Lam CT, Yang ZF, Lau CK, Tam KH, Fan ST, Poon RT. Brain-derived

neurotrophic factor promotes tumorigenesis via induction of neovascularization:

implication in hepatocellular carcinoma. Clin Cancer Res 2011;17:3123-33.

[20] Esposito CL, D'Alessio A, de Franciscis V, Cerchia L. A cross-talk between TrkB and Ret tyrosine kinases receptors mediates neuroblastoma cells differentiation. PLoS One 2008;3:e1643.

[21] Pearse RN, Swendeman SL, Li Y, Rafii D, Hempstead BL. A neurotrophin axis in myeloma: TrkB and BDNF promote tumor-cell survival. Blood 2005;105:4429-36.

[22] Kupferman ME, Jiffar T, El-Naggar A, Yilmaz T, Zhou G, Xie T, et al. TrkB induces EMT and has a key role in invasion of head and neck squamous cell carcinoma. Oncogene 2010;29:2047-59.

[23] Douma S, Van Laar T, Zevenhoven J, Meuwissen R, Van Garderen E, Peeper DS. Suppression of anoikis and induction of metastasis by neurotrophic receptor TrkB. Nature. 2004;430:1034-9.

[24] Zhang S, Guo D, Luo W, Zhang Q, Zhang Y, Li C, et al. TrkB is highly expressed in NSCLC and mediates BDNF-induced the activation of Pyk2 signaling and the invasion of A549 cells. BMC Cancer 2010;10:43.

[25] Terry J, De Luca A, Leung S, Peacock G, Wang Y, Elliot WM, et al. Immunohistochemical expression of neurotrophic tyrosine kinase receptors 1 and 2 in

lung carcinoma: potential discriminators between squamous and non squamous subtypes. Arch Pathol Lab Med 2011;135:433-9.

[26] Kai M, Onishi H, Souzaki M, Tanaka H, Kubo M, Tanaka M, et al.

Semi-quantitative evaluation of CD44(+) /CD24(-) tumor cell distribution in breast cancer tissue using a newly developed fluorescence immunohistochemical staining method. Cancer Sci 2011;102:2132-8.

[27] Onishi H, Kai M, Odate S, Iwasaki H, Morifuji Y, Ogino T, et al. Hypoxia

activates the hedgehog signaling pathway in a ligand-independent manner by upregulation of Smo transcription in pancreatic cancer. Cancer Sci 2011;102:1144-50.

[28] Jones MH, Virtanen C, Honjoh D, Miyoshi T, Satoh Y, Okumura S, et al. Two

prognostically significant subtypes of high-grade lung neuroendocrine tumors independent of small-cell and large-cell neuroendocrine carcinomas identified by gene expression profiles. Lancet 2004;363:775-81.

[29] Iyoda A, Hiroshima K, Toyozaki T, Haga Y, Baba M, Fujisawa T, et al. Adjuvant

chemotherapy for large cell carcinoma with neuroendocrine features. Cancer 2001;92:1108-12.

[30] Iyoda A, Hiroshima K, Nakatani Y, Fujisawa T. Pulmonary large cell

neuroendocrine carcinoma: its place in the spectrum of pulmonary carcinoma. Ann

Thorac Surg 2007;84:702-7.

[31] Stack MS, Ellerbroek SM, Fishman DA. The role of proteolytic enzymes in the pathology of epithelial ovarian carcinoma. Int J Oncol 1998;12:569-76.

[32] Nelson A. R., Fingleton B., Rothenberg M. L., Matrisian L. M. Matrix metalloproteinases: biologic activity and clinical implications. Int J Oncol 2000;18:1135-49.

[32] Warren WH, Faber LP, Gould VE. Neuroendocrine neoplasms of the lung. A clinicopathologic update. J Thorac Cardiovasc Surg 1989;98:321-32.

Figure Legends

Fig. 1. TrkB and BDNF expression in lung cancer of patients.

(A) Kaplan-Meier survival curve for neuroendocrine tumor (NET) type lung cancers (n=19, LCNEC and SCLC) and non-neuroendocrine tumor (non-NET) type lung cancers (n = 85, large cell carcinoma, adenocarcinoma and squamous cell carcinoma).

(B), (C), (D) Lung cancer tissues of patients were immunostained with an antibody for human TrkB or BDNF , and the expression level was evaluated as an index of total score (= % score × intensity score) in “Materials and Methods”. TrkB and BDNF expression levels evaluated as an index of percentage scores (B), intensity scores (C), total scores (D) were compared between normal bronchial epithelial (NBE), non-NET and NET. * $P < 0.001$. NS, not significant.

(E) Immunohistochemical staining for TrkB in lung cancer specimens, adenocarcinoma (upper left); squamous cell carcinoma (upper right, lower left); LCNEC (lower right). Original magnification: ×400.

(F) Immunohistochemical staining for BDNF in lung cancer specimens, adenocarcinoma (upper left, lower right); squamous cell carcinoma (upper right); LCNEC (lower left). Original magnification: ×400.

(G) A correlation between TrkB and BDNF expression in NET (n=19).

Fig. 2. TrkB and BDNF expression and its correlation with prognosis for small cell-type and LCNEC-type lung cancers.

(A) TrkB and BDNF expression levels evaluated as an index of total scores were compared between SCLC and LCNEC. * $P < 0.001$.

(B) A correlation between TrkB and BDNF expression in SCLC (n=8, left) and LCNEC (n=11, right).

Fig. 3. BDNF/TrkB signal enhances invasive phenotype of LCNEC cells.

(A) Protein lysates extracted from lung cancer cells (NCI-H460, NCI-H810, LU99, A549, SBC-3) were subjected to Western blot analysis for TrkB and BDNF. Mouse brain lysate was used as the positive control.

(B) LCNEC cells were immunostained with fluorescence-labeled (green) TrkB or BDNF antibodies, followed by counterstained with DAPI (blue). Histograms represent the expression intensities of TrkB or BDNF (green) and DAPI (blue). Original magnification: $\times 200$.

(C) NCI-H460 and NCI-H810 were seeded onto 96-well plates at a density of 5000

cells/well and incubated with recombinant human BDNF or a TrkB tyrosine kinase inhibitor K252a for 24 and 48 hours. Cell proliferation was determined by the absorbance counts at 492 nm (ref. 620nm) using Cell Count Reagent SF (Nacalai Tesque, Kyoto, Japan). BDNF or K252a treatment did not affect the growth of NCI-H460 and NCI-H810 cells analyzed by cell proliferation assay

(D), (E), (F) NCI-H460 and NCI-H810 cells were seeded onto matrigel-coated invasion chambers. After incubation for 24 hours in the presence of BDNF (10, 100 or 1000 ng/ml) (D), K252a (100, 500 or 1000 nM) (E), and BDNF (100ng/ml) and K252a (1000nM) (F), migrated cells were stained with Diff-Quick reagent and quantified by bright-field microscopy. Error bars represent standard deviations. * $P < 0.05$. ** $P < 0.001$.

Original Magnification: $\times 100$.

(G) NCI-460 and NCI-H810 were transfected with the indicated siRNA (50 nM), and 48 later protein lysates (60 μ g) were extracted from cells and subjected to Western blot analysis.

(H) NCI-H460 and NCI-H810 cells were transfected with the indicated siRNA and then seeded onto matrigel-coated invasion chambers. After incubation with BDNF (100 ng/ml) for 24 hours, migrated cells were quantified by bright-field microscopy. Error bars represent standard deviations. * $P < 0.05$. ** $P < 0.01$. NS, not significant.

Fig. 4. BDNF/TrkB signal-induced invasion is mediated through MMP-2 and MMP-9 in LCNEC cells.

(A), (B), (C) Quantitative RT-PCR (A), Western blotting (B) and gelatin zymography using a gelatin-zymography kit (Primary Cell, Sapporo, Japan) (C) represent the upregulated expression and activities of MMP-2 and MMP-9 by BDNF stimulation in NCI-H460 and NCI-H810 cells.

(D) (E) NCI-H460 (D) and NCI-H810 (E) were incubated with BDNF (100 ng/ml) for 24 hours after transfection with TrkB-siRNA and BDNF-siRNA. Total RNA was extracted from the cells and subjected to quantitative RT-PCR for MMP-2 and MMP-9 expression.

(F) NCI-H460 and NCI-H810 cells were transfected with the indicated siRNA and then seeded onto matrigel-coated invasion chambers. After incubation with BDNF (100 ng/ml) for 24 hours, migrated cells were quantified by bright-field microscopy. Error bars represent standard deviations. * $P < 0.05$. ** $P < 0.01$. § $P < 0.005$. §§ $P < 0.001$. NS, not significant.

Fig. 5. BDNF/TrkB signal augments colony formation *in vitro* and tumorigenicity *in*

vivo for LCNEC cells.

(A), (B) NCI-H460 (A) and NCI-H810 (B) cells were transfected with the indicated siRNA. Cells were resuspended in a 0.35% agar solution, and 0.7% agar layer without cells was overlayed. After incubation with BDNF (100 ng/ml) for 14 days, the colonies were stained by crystal violet and counted under a bright microscopy. Error bars represent standard deviations. * $P < 0.05$. ** $P < 0.01$. § $P < 0.005$. §§ $P < 0.001$. NS, not significant.

(C), (D) NCI-H810 cells were transfected with control-siRNA or TrkB-siRNA, and then implanted into flank regions of athymic nude mice. Subcutaneous tumor formation was observed in mice with control-siRNA, but not with TrkB-siRNA (C). Tumorigenic ability evaluated by tumor volume (D) was significantly inhibited in TrkB-siRNA group (n=6) compared with the control (n=6). Error bars represent standard deviations.

* $P = 0.025$, ** $P = 0.019$, *** $P = 0.014$.

(E) TrkB (left) and BDNF (right) expressions were confirmed by immunohistochemistry in tumor tissues of nude mice implanted with NCI-H810 cells with control-siRNA. Original magnification: $\times 400$.

Table 1. Clinicopathological profiles of LCNEC, SCLC and non-NET in patients with lung cancer.

Profile	Histologic Type			Total (n=104)	P-value
	LCNEC (n=11)	SCLC (n=8)	non-NET (n=85)		
Age					
~67 years	4	2	48	54	0.13
68 years~	7	6	37	50	
Gender					
Male	8	7	60	75	0.59
Female	3	1	25	29	
Tumor size					
T1	5	3	41	49	0.39
T2	4	4	35	43	
T3	2	0	3	5	
T4	0	1	6	7	
Lymph node metastasis					
N0	7	4	65	76	0.33
N1	2	1	10	13	
N2	2	3	10	15	
Lymphatic invasion					
-	9	6	74	89	0.61
+	2	2	11	15	
Venous invasion					
-	9	5	79	93	0.019*
+	2	3	6	11	
Stage					

I	6	2	57	65	0.094
II	2	1	11	14	
III	3	5	17	25	
Postoperative therapy					
-	3	0	35	38	0.055
+	8	8	50	66	
Postoperative recurrence					
Without	5	4	60	69	0.15
With	6	4	25	35	

LCNEC; large cell neuroendocrine carcinoma, SCLC;small cell lung carcinoma,
non-NET; non neuroendocrine tumor (large cell carcinoma, adenocarcinoma and
squamous cell carcinoma)

*Significant

Supplementary Figure Legends

Supplementary Fig. S1. TrkB or BDNF knockdown significantly decreased the expression of MMP-2 and MMP-9.

NCI-H460 and NCI-H810 were transfected with the indicated siRNA (50 nM) and then incubated with BDNF (100 ng/ml) for 24 hours. Cells were collected and quantitative RT-PCR was performed to determine the induction of MMP expression. Error bars represent standard deviations. * $P < 0.05$. ** $P < 0.01$.

Supplementary Fig. S2. MMP-2 and MMP-9 knockdown by siRNA transfection.

NCI-460 and NCI-H810 were transfected with siRNA targeting MMP-2 and MMP-9, and mRNA of MMP-2 and MMP-9 were analyzed by quantitative RT-PCR.

Supplementary Fig. S3. Schematic BDNF/TrkB signaling model for invasiveness and tumorigenicity of LCNEC cells.

BDNF and its receptor TrkB are overexpressed in LCNEC cells. Secreted BDNF binds to TrkB in an autocrine fashion, and activated TrkB signal enhances cell invasion, anchorage-independent growth and tumorigenicity. Exogenous BDNF from stromal cells also interacts and activates TrkB pathway. K252a: inhibits phosphorylation of

TrkB tyrosine kinase.

Figure 1

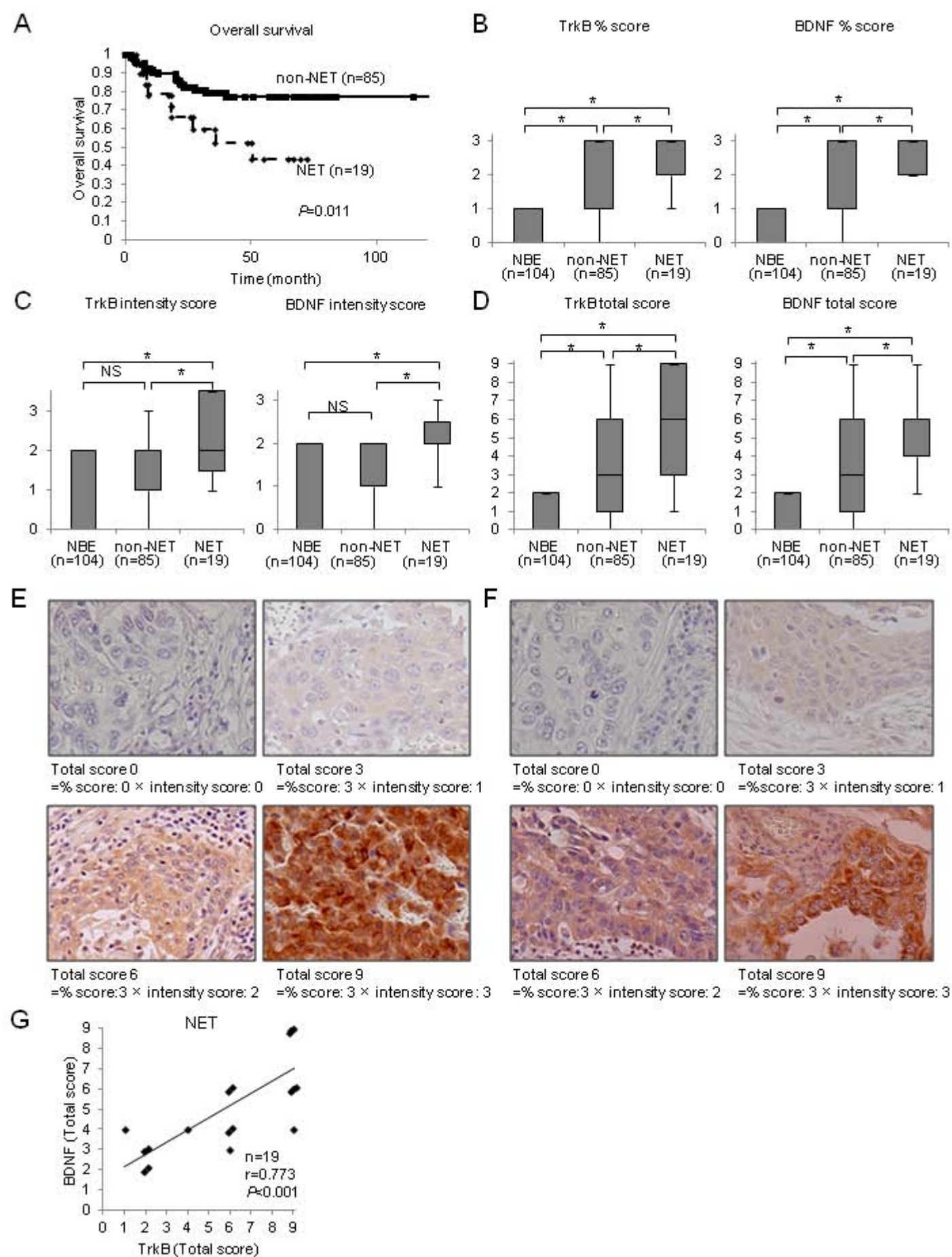
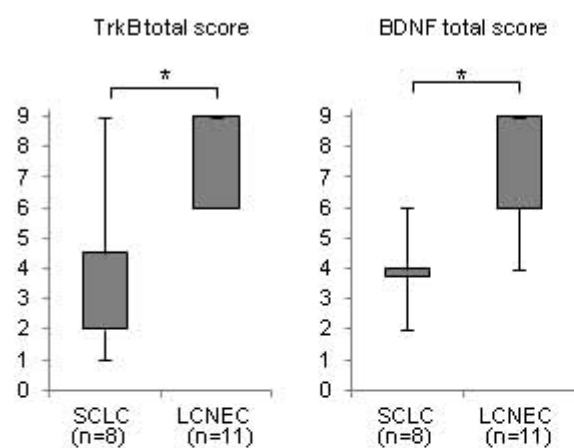


Figure2

A



B

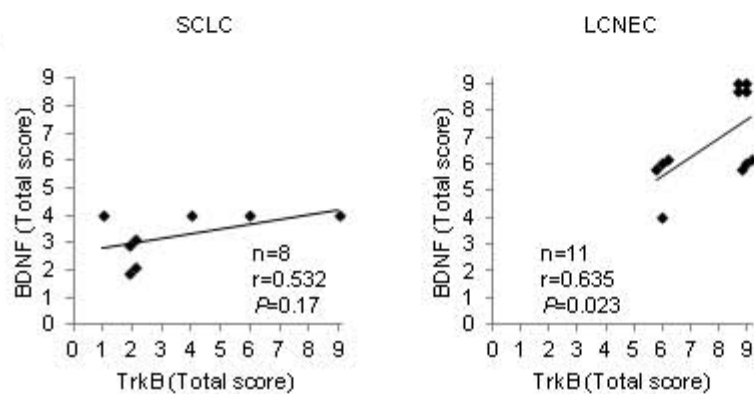


Figure 3

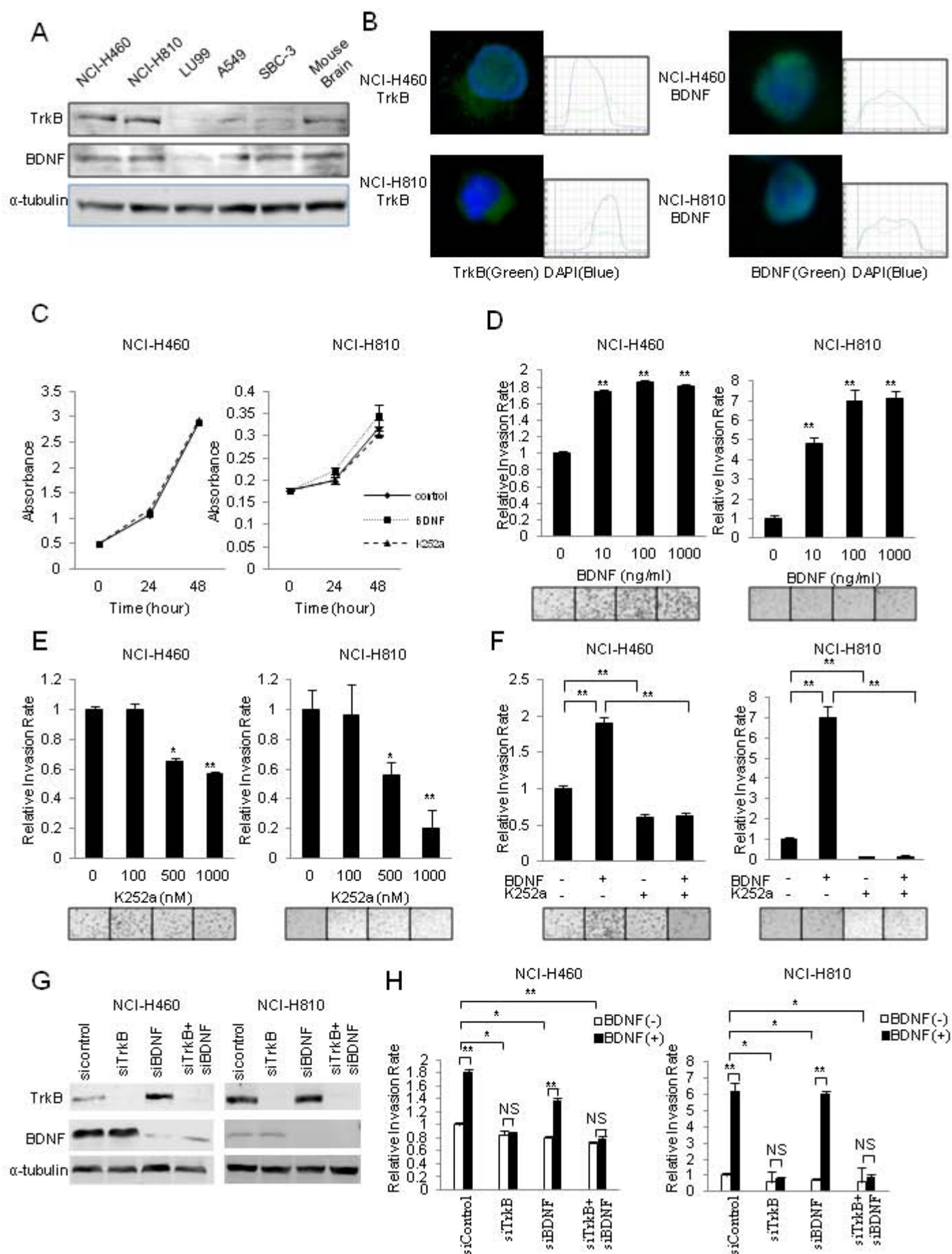


Figure 4

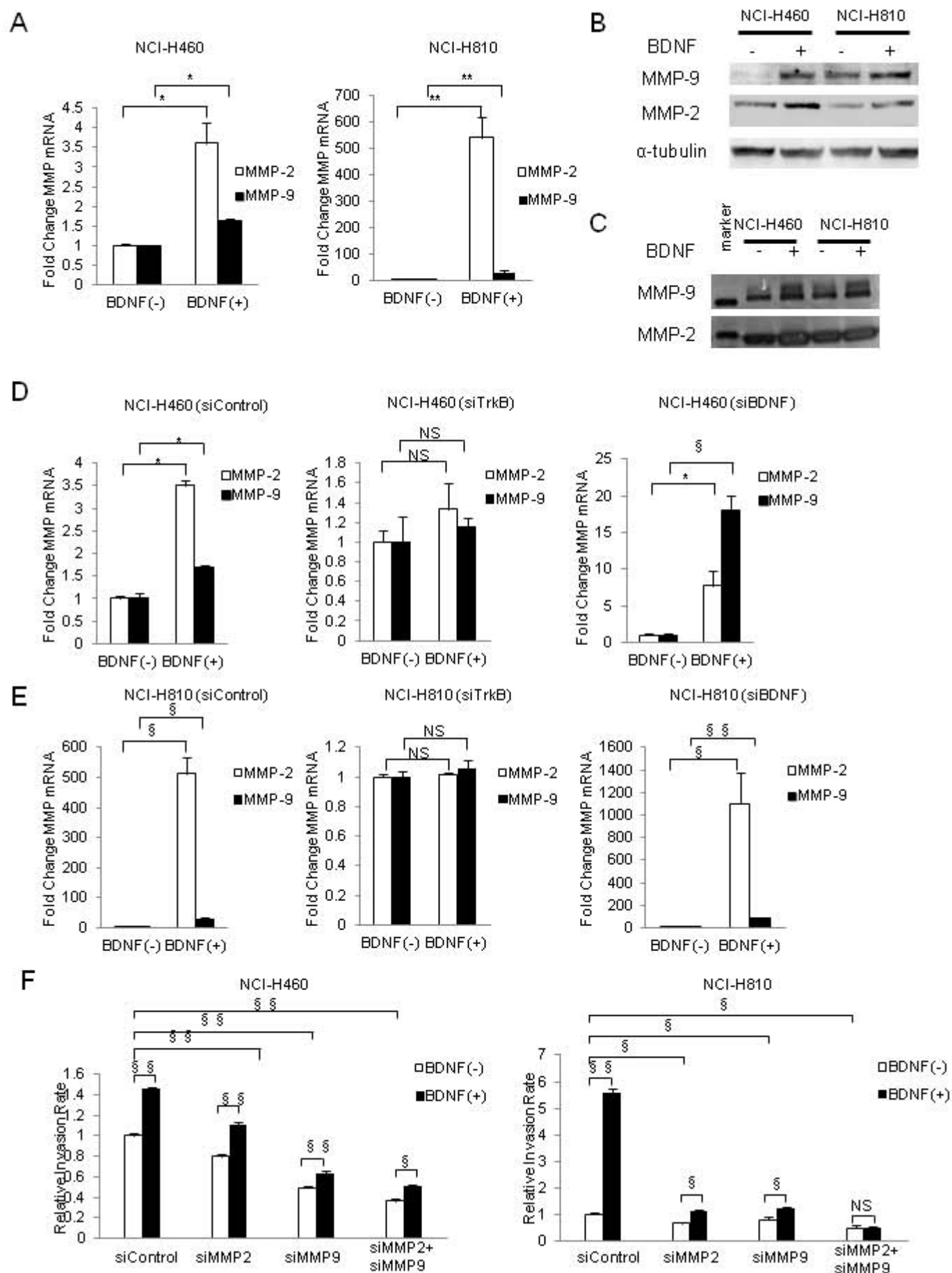
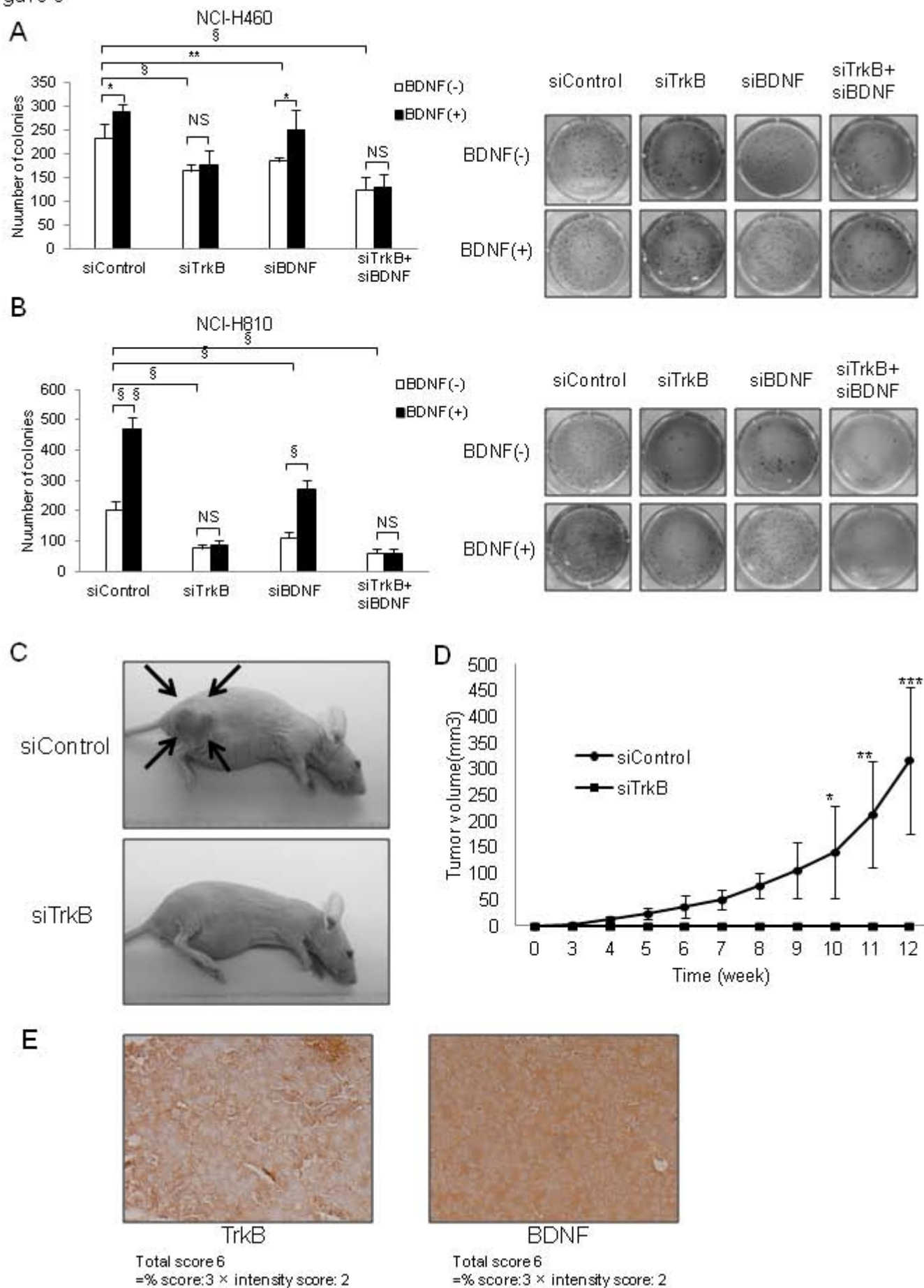
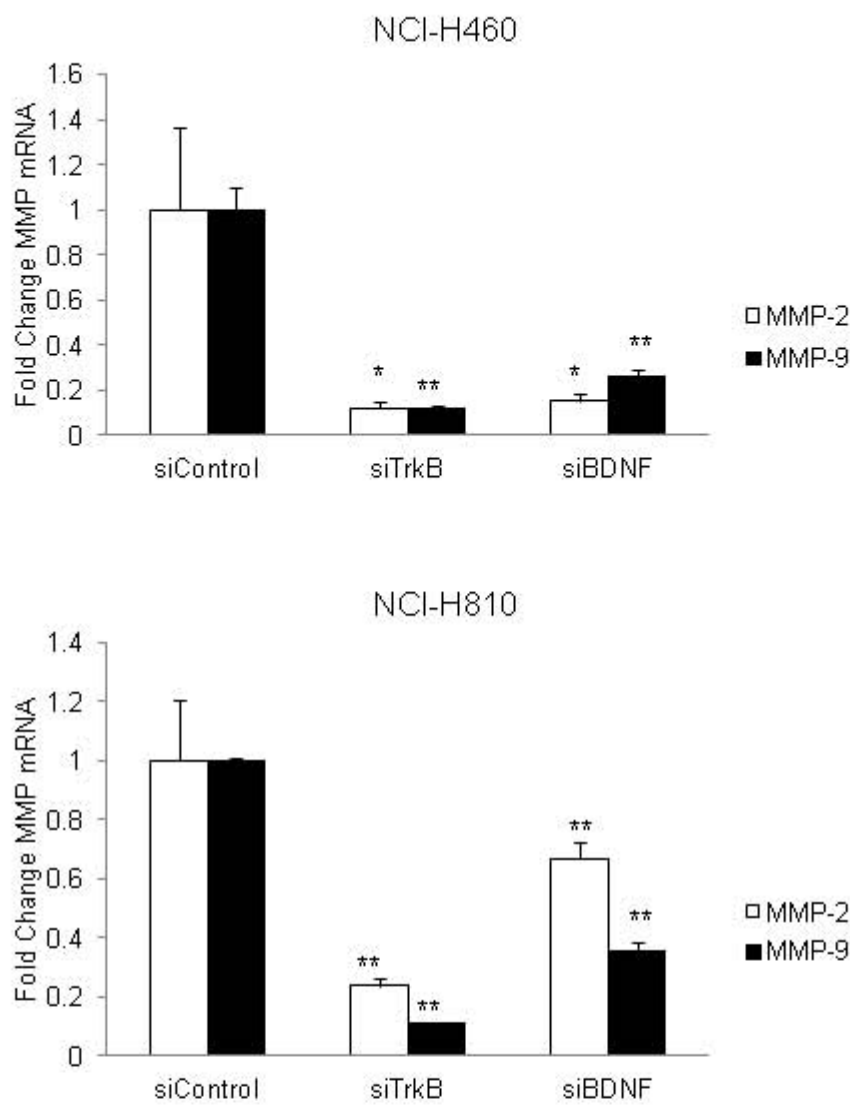


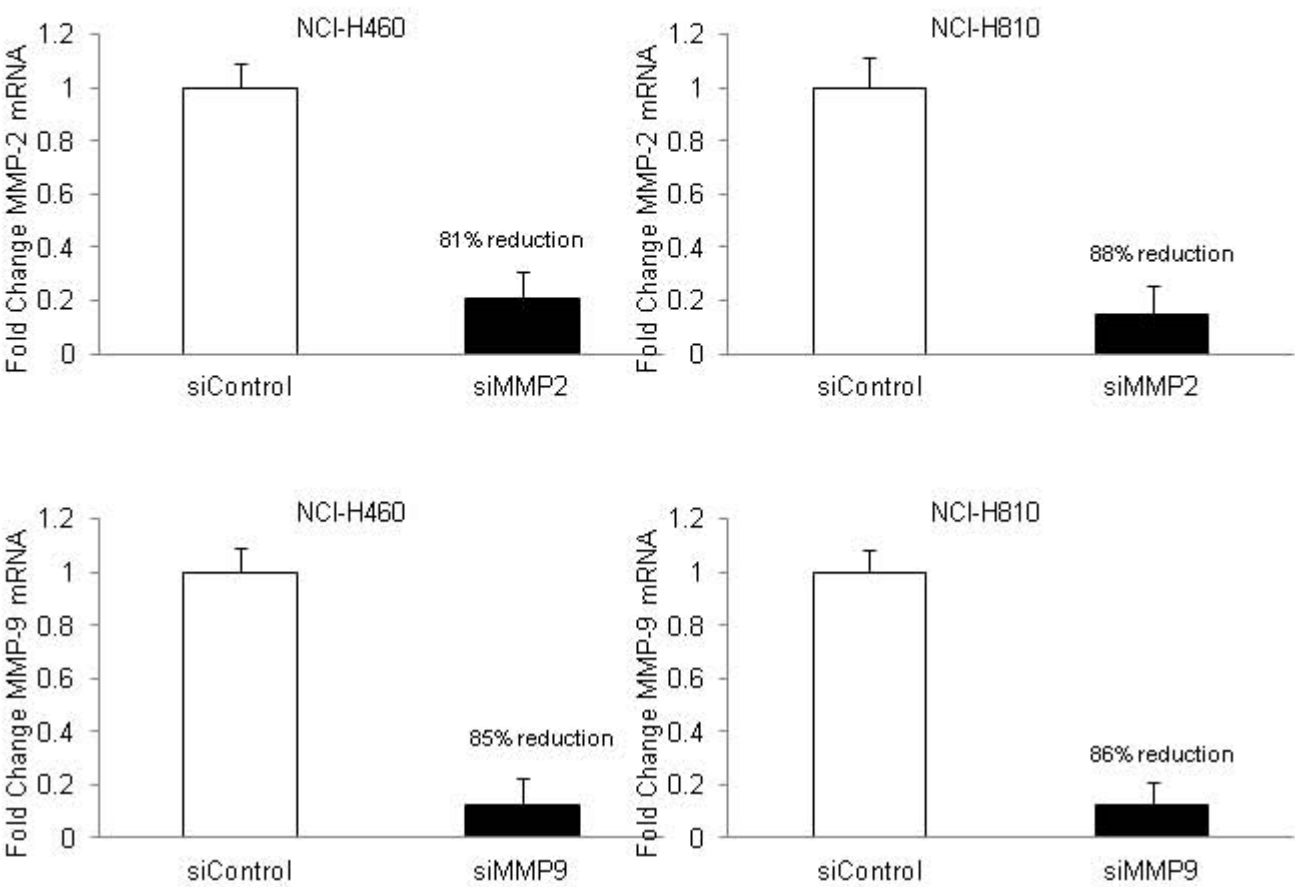
Figure 5



Supplementary Figure S1



Supplementary Figure S2



Supplementary Figure S3

