Growth Suppression of Lung Cancer Cells by Targeting Cyclic AMP Response Element-Binding Protein

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Abstract

Genes regulated by cyclic AMP–response element-binding protein (CREB) have been reported to suppress apoptosis, induce cell proliferation, and mediate inflammation and tumor metastasis. However, it is not clear whether CREB is critically involved in lung carcinogenesis. We found that non–small cell lung cancer (NSCLC) cell lines exhibited elevated constitutive activity in CREB, in its immediate upstream kinases (ribosomal s6 kinase and extracellular signal kinase), and in the CREB-regulated cell survival proteins Bcl-2 and Bcl-xL. We hypothesized that constitutively active CREB is important to lung cancer cell growth and survival and therefore could be a potential therapeutic target for NSCLC. Ectopic expression of dominant repressor CREB and transfection with small interfering RNA against CREB suppressed the growth and survival of NSCLC cells and induced apoptotic cell death. Furthermore, treating H1734 NSCLC cells with an inhibitor of the CREB signaling pathway Ro-31-8220 inhibited CREB activation by blocking the activity of extracellular signal kinase and ribosomal s6 kinase, arrested the cell cycle at the G2-M phase, and subsequently induced apoptosis with the suppression of Bcl-2 and Bcl-xL expression. Ro-31-8220 suppressed both the anchorage-dependent and independent growth of NSCLC cells, but its cytotoxic effect was much less prominent in normal bronchial epithelial cells. Our results indicate that active CREB plays an important role in NSCLC cell growth and survival. Thus, agents that suppress CREB activation could have potential therapeutic value for NSCLC treatment. [Cancer Res 2008;68(4):981–8]

Introduction

Despite the availability of assorted standard treatments, such as surgery, radiotherapy, chemotherapy, or combined regiments, non–small cell lung cancer (NSCLC) remains an aggressive lung cancer associated with a poor patient survival. Hence, there is an imminent need for better therapies for NSCLC. Recently, the advent of targeted therapy offers new hope to various subsets of cancers by targeting specifically the signal transduction involving carcinogenesis and tumor growth (1–3). Thus, identifying new molecular targets for treatment and/or prevention of NSCLC is warranted and urgently needed to control the proliferation of lung cancer.

Research during the past few years has shown that transcription factor cyclic AMP response element-binding protein (CREB) regulates the expression of a repertoire of genes related to cell survival (4, 5), inflammation (6), and proliferation (7), such as Bcl-2, Bcl-xL, cyclooxygenase-2, and tumor necrosis factor-α. CREB has also been shown to involve the carcinogenesis of several types of cancer. For example, inhibition of CREB-dependent transcriptional activity using CRE-decoy oligonucleotide caused antiproliferative effects on cancer cells by inhibiting aromatase expression in breast adipose tissue (8). Furthermore, studies using ectopic expression of dominant-repressor CREB (KCREB) showed that in androgendependent prostate cancer cells, dihydrotestosterone stimulation caused an antiapoptotic effect through the phosphorylation of CREB (9). CREB was found to be overexpressed in bone marrow cells from patients with acute lymphoid or myeloid leukemia, suggesting that CREB is involved in leukemogenesis and that its overexpression can be a biomarker for leukemia (7, 10–12). Finally, in human melanoma cells, CREB has been reported to be a mediator of tumor growth and metastasis, and the expression of KCREB sensitizes melanoma cells to apoptosis and inhibits their growth and metastasis (13–17).

Although it is not known whether CREB is directly involved in lung cancer, several lines of evidence have supported this possibility. For example, a murine spontaneous lung tumors model induced by transgenic over expression of insulin-like growth factor-II (IGF-II) displayed high levels of phosphorylated CREB (p-CREB) in such tumor tissue, and IGF-II–induced CREB phosphorylation played an important role in survival of lung cancer cell line (18, 19). NSCLC cells often overexpress Bcl-xL and Bcl-2 (20), which are regulated by CREB, and their suppression can result in apoptosis. Moreover, a recent study exploring the role of neurotransmitter receptor on tumorigenesis have found that blockade of the receptor suppressed the growth of lung carcinoma cells by reducing the phosphorylation of CREB and the expression of CREB-regulated genes, such as c-fos, c-jun, bcl-2, and cyclin D1 (21). Thereof, we aim to determine whether constitutively active CREB (p-CREB) is a potential target for treating NSCLC and whether its inhibition blocks cell proliferation and induces apoptosis in NSCLC cells.

CREB is an effector for a variety of receptors, such as receptors for growth factors, hormones, retinoids, cytokines, and prosta-glandins. It can be activated via multiple pathways by various upstream kinases, including protein kinase A (PKA; refs. 22, 23), PKC (24), mitogen-activated protein kinase (MAPK)–activated protein-2 (25), Akt (26), and CaM KII and IV (27, 28). Ro-31-8220 is a well-known inhibitor of PKC, and it was also found to inhibit p90 ribosomal S6 kinase (p90Rsk) and mitogen and stress-activated kinase (Msk; refs. 29, 30). As PKC, Rsk, and Msks are all important upstream activators of CREB, we surmise that this compound would in effect inhibit CREB. We use this compound in addition to other genetic tools to study the effect of CREB on tumor cell growth and to evaluate the potential of targeting CREB signaling as a strategy for cancer therapy.
Materials and Methods

Cell culture. We obtained four human NSCLC cell lines, H1734 (lung adenocarcinoma), H226 (lung squamous cell carcinoma), A549 (alveolar lung epithelium cell, poorly differentiated), and H292 (pulmonary mucopidermoid carcinoma) from the American Type Culture Collection. Cells were cultured in RPMI containing 10% fetal bovine serum (FBS). Normal human tracheobronchial epithelial (NHTBE) cells (Clonetics), which were used as the control, were cultured by a three-dimensional organotypic air-liquid interface method as described previously (31–35). Ro-31-8220 was purchased from Calbiochem and prepared in DMSO.

Western blot analysis. The whole-cell lysate was prepared by lysing the cells in SDS lysis buffer [250 mmol/L Tris-Cl (pH 6.5), 2% SDS, 4% β-mercaptoethanol, 0.02% bromophenol blue, 10% glycerol] containing protease and phosphatase inhibitors. Standard SDS-PAGE and Western blotting procedures were used to analyze the cell lysate. Blots were probed with anti-CREB and anti–p-CREB (Ser133; Upstate Biotechnology); anti-Bcl-2, anti-Bcl-xL, anti–phosphorylated extracellular signal-regulated kinase 1/2 (Erk1/2), and anti-Erk1/2 (Santa Cruz Biotechnology); and anti-Rsk and anti–phosphorylated Rsk (Cell Signaling Technology). To detect the cleavage products of apoptosis, blots were probed with anti–poly(ADP-ribose) polymerase (PARP), anti–casparase–9, and anti–casparase-3 antibodies (New England Biolabs). Anti-actin antibodies were from Sigma-Aldrich, and the caspase-3 inhibitor Ac-DEVD-CHO was from Promega.

Electrophoretic mobility shift assay. Isolation of nuclear extracts and preparation of CRE oligonucleotide probes were conducted as previously described (36). For supershift analysis, the nuclear extracts from H1734 cells were incubated with radiolabeled oligonucleotide probes in the presence of antibodies against CREB or p-CREB for 30 min at 37°C. Unlabeled (cold) probe and a CRE mutant oligonucleotide 5′-AGAGATTGCCGTGGTGCA-AGAGGCTAG-3′ (bold face, mutated bases; Santa Cruz Biotechnology; 100-fold) was used to check the specificity of the probes. The radioactive bands on the dried gels were visualized and quantitated with Phospholmager (Molecular Dynamics) using ImageQuant software (Amersham Biosciences).

Immunocytochemistry for CREB localization. H1734 cells (1 × 10⁵ cells/mL) were plated on a glass chamber slide (Falcon; BD Biosciences) and treated the next day for 4 h with Ro-31-8220. The chambers were removed, and cells were fixed with cold acetone. After a brief washing with PBS, the slides were blocked with 5% normal goat serum in PBS for 1 h and then incubated for 4 h with rabbit anti-p-CREB antibody (1:100 dilution). The slides were washed, incubated with goat anti-rabbit IgG-Alexa 594 (Molecular Probes; 1:100 dilution) for 1 h, and counterstained for nuclei with 4′,6-diamidino-2-phenylindole, dihydrochloride (DAPI; 50 ng/mL; Molecular Probes) for 15 min. The slides were mounted, and confocal images were captured with an Olympus FV500 confocal microscope by using a Plan Apo 60× oil objective.

Transfection and cytotoxicity assay. H1734 cells (10,000/0.5 mL) were plated in triplicate in 24-well plates and transfected with plasmid DNA (50 ng/well) of wild-type CREB (CREBwt), KCREB, and CREB133 using Lipofectamine 2000 (Invitrogen). For RNA interference, H1734 cells were transfected with a final concentration of 100 nmol/L small interfering RNA (siRNA) SMARTpool sequences targeting human CREB or nonspecific control pool (Dharmacon RNA Technologies) using siIMPORTER siRNA transfection reagent (Upstate Biotechnology). The transfection efficiencies of the control plasmid were consistently above 80%. After 48 h of expression of CREBwt, KCREB, CREB133, or siCREB, the cytotoxic effect was determined with the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) method as described by the manufacturer (Sigma). The cytotoxic activity of Ro-31-8220 was also determined on the all four NSCLC cell lines. Briefly, the cells (2,000 per well) were incubated in triplicate in 96-well plates in the presence or absence of indicated agent in a final volume of 0.2 mL for different days at 37°C. Afterwards, we performed the MTT assay.

Flow cytometric analysis. H1734 cells were synchronized by serum starvation overnight before exposure to Ro-31-8220 in the presence of 5% serum. NHTBE cells were grown in air-liquid interface and treated with Ro-31-8220 in their normal medium. After different lengths of time, cells were washed, trypsinized, and fixed in 70% ethanol for 1 h at −20°C. Finally, cells were washed with PBS and stained with propidium iodide (25 μg/mL) in the presence of 1 μg/mL RNase for 30 min at room temperature. The distribution of cells in the cell cycle was then analyzed with a FACScalibur flow cytometer (Becton Dickinson).

Soft agar colony formation assay. Single-cell suspensions of the H1734 and H226 cells were treated with or without different concentrations of Ro-31-8220 and then mixed with agarose to a final concentration of 0.35%. Aliquots of 1.5 mL containing 10⁴ cells and 10% FBS were plated in triplicate in six-well plates over a base layer of 0.7% agarose and allowed to gel. The number of colonies at ≥60 μm was counted after 28 days of incubation.

Apoptosis assay. H1734 cells (200,000) were plated in chamber slides; the next day, they were transfected with plasmids encoding CREBwt, KCREB, or CREB133 (100 ng DNA per chamber) or with 100 nmol/L siCREB. The terminal transferase dUTP nick-end labeling (TUNEL) assay was performed according to the manufacturer’s instructions (Promega). Briefly, 48 h after transfection, the cells were fixed in 4% formaldehyde and permeabilized with 0.5% Triton X-100. The cells were then incubated with terminal deoxynucleotidyl transferase and fluorescein-dUTP and costained with DAPI and visualized with an Axioskop 40 fluorescence microscope (Carl Zeiss). Three random fields were counted for each sample. The images were captured with an Olympus FV500 confocal microscope by using a Plan Apo 60× oil objective.
were captured at a magnification of 400× and stored using Axiovision software (Carl Zeiss).

**Statistical analysis.** Statistical analysis was performed with Prism program (GraphPad Software). For multiple groups comparison, one-way ANOVA was used, followed by Dunnett’s test for comparing experiment groups against a single control. For single comparison between two groups, Student’s t test was used.

**Results**

**CREB signaling is constitutively overactivated in NSCLC cells compared with NHTBE cells.** To compare the constitutive CREB signaling between tumor and normal cells, we measured the expression level of CREB and its activation status among different cell lines under unstimulated normal growth condition. Western blot analysis showed that both CREB and p-CREB levels were substantially higher in all four NSCLC cell lines compared with NHTBE cells (Fig. 1A).

To determine whether such elevation in CREB phosphorylation was indeed translated into the CRE-dependent transcriptional activity, we performed an electrophoretic mobility shift assay (EMSA) with radiolabeled oligonucleotide probes containing consensus CRE motif (5'-TGACGTCA-3'). We found that nuclear extracts from all four NSCLC cell lines contained higher amount of CRE-binding proteins than that from NHTBE cells as indicated by the intensity of the single retarded band (Fig. 1B). The specificity of the probes was verified with 100-fold excess of unlabeled (cold) consensus CRE and mutant CRE oligonucleotides (Fig. 1C, lanes 3 and 4) using the nuclear extract from H1734 cells. Further retention of the radiolabeled band (super shift) by anti-CREB and anti–p-CREB but not control IgG (Fig. 1C, lanes 2, 5, and 6) confirmed that the previous single band resulted from the interaction between CRE oligonucleotide and activated CREB.

**CREB activity is inhibited by Ro-31-8220 in H1734 cells.** Ro-31-8220 substantially suppressed CREB activation in a time-dependent and dose-dependent manner in the H1734 cells (Fig. 2A). Moreover, the CRE-binding capacity of nuclear extract from H1734 cells was also suppressed by Ro-31-8220 in a time-dependent and dose-dependent manner (Fig. 2B). H1734 cells
treated with or without Ro-31-8220 for 4 h were fixed and immunocytochemically stained with anti-p-CREB antibody to analyze the cellular distribution of p-CREB. Confocal images of the staining showed that Ro-31-8220 induced the nuclear disappearance of p-CREB in the H1734 cells (Fig. 2C).

**Figure 3.** Upstream and downstream components of CREB signaling are constitutively overactivated in NSCLC cells, and their activation can be inhibited by Ro-31-8220. A, whole-cell lysates from NSCLC cell lines (H1734, H226, H292, and A549) and NHTBE cells were analyzed with Western blot for the levels of phosphorylated Rsk relative to the NHTBE cells (Fig. 3A, top). Incubation of the H1734 cells with Ro-31-8220 (20 μmol/L) suppressed the phosphorylated Rsk level within 2 h (Fig. 3B, top); such suppression became noticeable at a concentration of 5 μmol/L for 4 h of treatment of Ro-31-8220 (Fig. 3C, top). Moreover, Erk1/2, an important upstream kinase for Rsk activation, is also constitutively overactivated in all four NSCLC cell lines compared with the NHTBE cells (Fig. 3A, middle). The phosphorylated Erk1/2 level was decreased by Ro-31-8220 treatment within 30 min in H1734 cells (Fig. 3B, middle); this decrease was detectable at 5 μmol/L of Ro-31-8220 treatment (Fig. 3C, middle). The cell survival signaling regulated by CREB transcription factor was also examined. Western blot results showed that all four NSCLC cell lines constitutively overexpressed Bcl-xL and Bcl-2 compared with the NHTBE cells (Fig. 3A, bottom). Such overexpression can be suppressed by Ro-31-8220 treatment in a time-dependent and dose-dependent fashion (Fig. 3B and C, bottom).

**Figure 4.** The effect of Ro-31-8220 on cell proliferation was assessed for the levels of signaling components mentioned above. Equal sample loading is indicated by the band intensity of the inactive form of each protein or β-actin (bottom of each figure).
Ro-31-8220 (Fig. 5C, lane 3) through the cleavage of a 37-kDa band to a 16-kDa band. These findings show that Ro-31-8220 induced apoptosis in the H1734 cells. To determine whether caspase activation is required for Ro-31-8220–induced suppression of cell growth, we used a caspase-3 inhibitor, Ac-DEVD-CHO, to block caspase activation. The effectiveness of Ac-DEVD-CHO in blocking the Ro-31-8220–induced caspase-3 cleavages was confirmed on Fig. 5C. H1734 cells were then treated with Ro-31-8220 in the presence of different concentrations of Ac-DEVD-CHO, and cell viability was assessed with MTT assay. The caspase-3 inhibitor effectively protected the cells from Ro-31-8220 induced cytotoxicity at a concentration as low as 0.01 μmol/L (Fig. 5D). These results suggest that caspase-3 activation is essential for Ro-31-8220 induced cytotoxicity.

Suppression of CREB expression and activation inhibits cell proliferation and induces apoptosis in NSCLC cells. We have shown that Ro-31-8220 inhibited constitutively active CREB, suppressed cell proliferation, and induced apoptosis. To test whether the inhibition of constitutively active CREB is accountable for the antitumorigenesis effect of Ro-31-8220, we suppressed the constitutive CREB activity in H1734 cells by knockdown of CREB and the ectopic expression of KCREB and CREB133 were confirmed by Western blot analysis (Fig. 6C, top). Next, we examined whether such genetic quenching of constitutive CREB activity induced apoptosis. We found that suppression of CREB activity induced cleavage of both PARP and caspase 3 as did in Ro-31-8220 treatment (Fig. 6C). To confirm the effect of suppression of CREB activity on apoptosis, we performed a TUNEL assay. As expected, suppression of constitutive CREB activity caused a significant increase in the percentage of TUNEL-positive cells in H1734 cells — 44% for CREB-siRNA, 35% for KCREB, and 39% for CREB133, respectively — compared with controls (6% for CREBwt and 8% for nontarget siRNA; Fig. 6D). Meanwhile, treatment with 5 μmol/L Ro-31-8220 for 48 h induced apoptosis in 52% of the cells. These data suggest that the depletion of CREB in the H1734 cells sensitized the cells to apoptosis.

Discussion

CREB is an important transcription factor that involves numerous physiologic processes, including differentiation of bronchial epithelial cells (36, 37). Aside from the physiologic importance, the role of CREB in tumorigenesis has also been indicated lately (see Introduction). In the present study, we found that CREB is overexpressed and constitutively active in several human NSCLC cell lines. Moreover, we found that direct and/or indirect suppression of constitutively active CREB inhibits cell proliferation and induces apoptosis in NSCLC cells.
Several different upstream pathways have been known to lead to CREB activation. Among them, PKC pathway has been shown to induce CREB activation via a MAPK cascade (36, 37). Based on the inhibitory effect of Ro-31-8220 on several components along the PKC-CREB pathway, we used this compound to suppress CREB activation and found that Ro-31-8220 effectively inhibited the CREB activity (Fig. 2) and the growth of all four NSCLC cell lines we tested (Fig. 4A). Furthermore, the upstream and downstream signaling of CREB, including the phosphorylation of Erk and Rsk and the expression of Bcl-2 and Bcl-xL, are also effectively suppressed (Fig. 3B and C). These results not only showed the importance of CREB but also indicated that CREB may be constitutively activated by the PKC branch of its upstream pathway in the NSCLC cells. This assumption is further supported by the observation that the activity of two signaling components in the PKC-CREB pathway, ERK1/2 and RSK, are also markedly higher in the four tumor cell lines compared with normal cells (Fig. 3A). Our results agree with the report that phosphorylated Rsk and phosphorylated Erk1/2 are involved in the CREB activation (38, 39) and our own studies that PKC is involved in CREB signaling pathway (36).

As mentioned earlier, CREB plays a pivotal role in cellular signaling, and several upstream signaling pathways converge on CREB (40). Therefore, regardless the upstream pathways, CREB seems to be the most effective target for inhibiting the CREB-associated tumor cell growth. In addition, the expression of CREB gene can be up-regulated by the activation of CREB per se (41). Such an effect might account for the higher level of CREB observed in the NSCLC cells (Fig. 1A) and would also make the CREB level more effectually modulated. Other than the strategic advantage, the most compelling rationale for CREB targeting is the mechanism by which CREB supports tumor cell growth. We found that the expression of the CREB-regulated antiapoptotic proteins, Bcl-2 and Bcl-xL, is significantly higher in NSCLC cells.
compared with NHTBE cells (Fig. 3A), and such overexpression can be effectively suppressed by blocking the CREB signaling (Fig. 3B and C). Our findings agree with other reports that Bcl-2 and Bcl-xL are regulated by CREB (42). Moreover, the inhibition of CREB activity either by knockdown of CREB expression level with siCREB or expression of dominant-negative form of CREB mutants (KCREB and CREB133) induced apoptosis in NSCLC cells. We verified this apoptotic effect with various assays, including flow cytometry analysis, the signature cleavage of PARP and caspases, and TUNEL assay (Figs. 5 and 6). The rescue of such cell death by a caspase inhibitor, Ac-DEVD-CHO, affirmed that the major cause of cell death is apoptosis (Fig. 5C and D). Other studies have shown that the expression of KCREB decreases the tumorigenicity and tumor metastatic potential in nude mice (15, 16, 43), reduces the resistance of human melanoma cells to radiation (13), and reduces adipogenesis (44). In addition, the ability of forming colony in soft agar, a measure of aggressive cell growth, was clearly inhibited in NSCLC cells at a lower concentration of Ro-31-8220 (Fig. 4C). Conversely, NHTBE cells are not as susceptible as NSCLC cells to the cell death induced by the inhibition of CREB (Fig. 4B).

Concomitantly, we have observed in archived lung tumor specimens that the expression levels of CREB and p-CREB are distinctively higher in tumor tissues relative to the adjacent normal tissues and that such overexpression is inversely correlated with the survival duration of a subset of NSCLC patients. Our results indicate that NSCLC cells are highly dependent on the elevated CREB activity for their survival and cell growth and inhibition of CREB effectively suppress the growth of NSCLC cells. Taken together, over-activation of CREB confers a CREB-dependent survival and cell growth on NSCLC cells. Such dependence on the excessive CREB activity furnishes an extended therapeutic window for targeting CREB as a strategy for treating NSCLC tumors.

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References


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