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Requirement of the NF-κB Subunit p65/RelA for K-Ras-Induced Lung Tumorigenesis

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Abstract

K-Ras-induced lung cancer is a very common disease, for which there are currently no effective therapies. Because therapy directly targeting the activity of oncogenic Ras has been unsuccessful, a different approach for novel therapy design is to identify critical Ras downstream oncogenic targets. Given that oncogenic Ras proteins activate the transcription factor NF-κB, and the importance of NF-κB in oncogenesis, we hypothesized that NF-κB would be an important K-Ras target in lung cancer. To address this hypothesis, we generated an NF-κB-EGFP reporter mouse model of K-Ras-induced lung cancer and determined that K-Ras activates NF-κB in lung tumors *in situ*. Furthermore, a mouse model was generated where activation of oncogenic K-Ras in lung cells was coupled with inactivation of the NF-κB subunit p65/RelA. In this model, deletion of p65/RelA reduces the number of K-Ras-induced lung tumors both in the presence and absence of the tumor suppressor p53. Lung tumors with loss of p65/RelA have higher numbers of apoptotic cells, reduced spread and lower grade. Using lung cell lines expressing oncogenic K-Ras, we show that NF-κB is activated in these cells in a K-Ras-dependent manner and that NF-κB activation by K-Ras requires IKKβ kinase activity. Taken together, these results demonstrate the importance of the NF-κB subunit p65/RelA in K-Ras induced lung transformation and identify IKKβ as a potential therapeutic target for K-Ras-induced lung cancer.

Keywords

Lung cancer; K-Ras; NF-κB; p65/RelA; IKKβ

INTRODUCTION

Lung cancer is the second most common type of cancer in the U.S., yet it is the leading cause of cancer deaths (1). Importantly, activating point mutations in the K-Ras GTPase gene occur in a large number of lung cancer patients (2–4). These mutations are not only associated with poor prognosis and therapy resistance (5,6), but have also been causally linked to the oncogenic process. In this regard, expression of mutant K-Ras in mice is sufficient to cause transformation and tumor formation (7,8). Effective abrogation of K-Ras activity reverts malignant cells to a

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non-malignant phenotype (9–12). Therefore, cancer therapy targeting K-Ras would be expected to produce a clinical benefit. Unfortunately, therapies aimed at inhibiting the biological activity of K-Ras have so far been unsuccessful (13). In order for more effective therapies for K-Ras-induced lung cancer to be generated, the critical K-Ras effectors involved in oncogenesis need to be identified.

The transcription factor NF-κB is a dimeric complex formed by members of a conserved family of proteins that share a motif designated as the Rel Homology Domain. NF-κB is expressed ubiquitously, and the primary NF-κB member responsible for transcriptional activation of target genes is the subunit p65/RelA (14,15). In unstimulated non-transformed cells, most NF-κB complexes are held in an inactive cytoplasmic form through interactions with the inhibitor of κB (IκB) proteins. Upon stimulation with cytokines or other relevant molecules, IκB is phosphorylated by the IκB kinase (IKK) complex and undergoes rapid ubiquitination and proteasome-mediated degradation. The NF-κB subunits are then released and accumulate in the nucleus to regulate target gene transcription (14,15).

Even though NF-κB has been reported to have a tumor suppressive role in certain specific settings (16), the majority of studies show that, when activated, NF-κB can contribute to oncogenic transformation (17). Indeed, NF-κB is important for cellular transformation induced by oncoproteins (18,19). Not surprisingly, constitutive NF-κB activation has been detected in a variety of human malignancies (17), including lung cancer (20).

Importantly, NF-κB is activated by oncogenic Ras. Studies from our group revealed that oncogenic H-Ras induces cellular transformation in fibroblasts by activating NF-κB (18); and NF-κB activation is required to suppress oncogenic H-Ras-induced apoptosis (21). Other studies have demonstrated a correlation between increased NF-κB activity and expression of oncogenic K-Ras (20,22). Duran et al (23) demonstrated a mechanistic link between K-Ras, IKK, and NF-κB through the signaling adaptor p62. Based on these cell-based studies, it is important to determine if NF-κB is required for development of K-Ras-induced tumors *in situ*.

Here we demonstrate that oncogenic K-Ras activates NF-κB in lung epithelial cells *in situ*. In addition, genetic deletion of the NF-κB subunit p65/RelA in a K-Ras induced lung cancer mouse model reduces lung tumorigenesis both in the presence and absence of the tumor suppressor p53. K-Ras-dependent NF-κB activity was observed in transformed human lung epithelial cells. Interestingly, NF-κB activity in both murine and human K-Ras-transformed cells requires IKKβ kinase activity. These results demonstrate NF-κB (p65/RelA) as an important K-Ras oncogenic effector in lung cancer and suggest pharmacological inhibition of IKKβ activity as a therapeutic approach for K-Ras-related malignancies.

METHODS

Animal husbandry and Cre-expressing adenovirus (adenocre) administration

Lox-stop-lox (LSL) K-Ras^{G12D} mice (24), cis-κB-EGFP mice (25), p65/RelA conditional mice (26), p53 conditional mice (27) and mice generated by inter-strain crossings were housed in pathogen-free conditions according to the protocols approved by the UNC Institutional Animal Care and Use Committee. Lung tumor induction was performed by intranasal administration of 1×10^7 plaque forming units (pfus) of adenocre (Gene Transfer Vector Core, University of Iowa, Iowa City, IA) in selected animals at 8 weeks of age, as described (24).

Histopathological analysis

Mice were euthanized by intraperitoneal administration of 250mg/kg avertin followed by surgical resection of the portal vein. Lungs were perfused with saline and inflation-fixed

overnight with formalin 10%. Fixed tissues were be embedded in paraffin, sectioned at 5 micrometer thickness and stained with hematoxylin/eosin.

Live imaging and laser scanning microscopy

The whole-body small animal fluorescence imaging system (Xenogen IVIS 100 system, Caliper Life Sciences, Hopkinton, MA) equipped with a charge-coupled device camera was used to visualize GFP fluorescence emission using GFP filter for excitation (445–490 nm) and emission (515–575 nm). Analysis of the images was performed using Living Image software (Caliper Life Sciences, Hopkinton, MA). Laser scanning microscopy was performed using a Nipkow-type spinning disk confocal scan head (CSU-10, Yokogawa Corporation, Newnan, GA) with a 10X objective, attached to an inverted microscope (model IX-81, Olympus, Center Valley, PA). Images were acquired using a CCD camera (model C4742-80-12AG, Hamamatsu, Bridgewater, NJ).

Western Blotting and Immunohistochemistry

Western Blotting and Immunohistochemistry were performed as described (26,28). The antibodies used and respective catalog numbers were as follows: anti-phospho-IκBα-Ser32/36 (9246), anti-IκBα (9242), anti-phosphoAKT-Ser473 (4058), anti-phospho-p44/42-MAPK-Thr202/Tyr204 (4370), anti-p44/42-MAPK (4696), anti-phospho-IKKα/β-Ser176/180 (2697) and anti-p65/RelA (4764) antibodies were from Cell Signaling (Danvers, MA); anti-pan-Ras^{12D} (PC10L) and anti-c-K-Ras (OP24) were from Calbiochem (San Diego, CA); we also used anti-GFP (JL-8, Clontech, Mountain View, CA), anti-β-tubulin (sc-9104, Santa Cruz Biotechnology, Santa Cruz, CA) and anti-IKKβ (05-535, Chemicon, Temecula, CA) antibodies.

Detection of Cre-mediated recombination

Cre-mediated recombination of the LSL-K-Ras allele and p65 conditional allele was detected by PCR amplification with primers flanking the deleted site (sequences available upon request). Amplification of the wildtype allele results a 3.9 kilobase product and amplification of the deleted allele results in a 1.3 kilobase product. Amplification was performed by denaturation at 95°C for 1min followed by 35 cycles of amplification at 98°C for 10 seconds, 52°C for 30 seconds and 72°C for 90 seconds with a final extension step of 10min at 72°C.

Terminal deoxynucleotidyltransferase-mediated dUTP-biotin nick end labeling (TUNEL) assay

Tissue sections were deparaffinized, rehydrated, and stained according to the ApopTag Plus in situ apoptosis detection kit(Millipore, Billerica, MA) instructions.

Tumor number and grade analysis

Tumor slides from each lung lobe (same orientation and level section used for each lobe) were scored for number, spread and grade blindly. For analysis of tumor spread, tumors were divided either into bronchial lesions or alveolar lesions according to the following criteria. Bronchial lesions were tumor masses either completely contained within the bronchial compartment or lesions where the spread into the alveolar compartment was smaller than the bronchial component. Alveolar lesions were lesions restricted to the alveolar compartment (excluding adenomatous alveolar hyperplasia), or lesions were the alveolar spread was larger than the bronchial component (including solid tumors). For analysis of tumor grade, each tumor was given a score of 1 to 5 based on previously described criteria (29).

Generation of KE67 cell line

Lung tumors from K-Ras/NF-κB mice were dissected under asseptic conditions and cut into small pieces (around 2mm in diameter). Each piece was placed in a 100mm cell culture dish with 2ml of 0.25% trypsin-EDTA (Invitrogen) and minced with a sterile razor blade. After trypsinization, 8ml of complete medium were added to the dish and cells were transferred to 15ml conical tubes. Untrypzinized tumor chunks and tissue debris were allowed to sediment for 10 min. Both the supernatant and sedimented fractions were collected and plated separately in 100mm dishes. Cells were then kept on culture and passed when confluency was reached. To inhibit fibroblast growth, the culture medium was supplemented with Mouse FibrOut™ 9 (Chi Scientific, Maynard, MA) for a week.

Cell culture

Cell passages were kept to a minimum and no cells were passaged continuously for more than six months. Low passage SALEB and SAKRAS cells were obtained from Dr. Scott Randell and cultured in serum-free bronchial epithelium growth medium (BEGM, Clonetics-Lonza, Allendale, NJ). These cells were originally selected in medium containing a triple antibiotic cocktail and subsequently characterized by real-time PCR for expression of the genes used for immortalization and transformation (30). Short Tandem Repeat-DNA profile authenticated NCI-H358 cells were obtained from ATCC (Manassas, VA) and maintained in RPMI 1640 (Invitrogen, Carlsbad, CA) supplemented with 10% FBS (Sigma-Aldrich, St. Louis, MO). KE67 cells were generated in the laboratory (as described above) and their origin was authenticated both by PCR of the excised K-Ras allele, as well as expression of EGFP from the reporter allele. They were maintained in Dulbecco's Modified Eagle's Medium (DMEM, Invitrogen, Carlsbad, CA) supplemented with 10% FBS and 0.5mM 2-mercaptoethanol (both from Sigma-Aldrich, St. Louis, MO).

Electrophoretic mobility shift assay (EMSA)

Cells were either transfected or treated with appropriate reagents, nuclear extracts were prepared and EMSA was performed as previously described (28), using ^{32}P-labeled oligonucleotide probes corresponding to an NF-κB site within the MHC class I promoter region.

RNA isolation and Real-time PCR analysis

Total RNA was prepared using TRIZOL reagent (Invitrogen) following the manufacturer's protocol and real-time PCR analysis was performed as previusly described (28) in an ABI 7000 Sequence Detection System using TaqMan Gene Expression Assay primer-probe sets (all from Applied Biosystems, Foster City, CA) for *IL-8* (Hs99999034_m1), *Bcl-xL* (Hs00236329_m1) and *MMP-9* (Hs00234579_m1). Relative quantitation was determined by the $\Delta\Delta C_t$ method using Gusb (Hs99999908_m1) as the endogenous control.

Transfections and Reporter Assays

siRNA transfections were performed as previously described (28) with 100nM of either a non-targeting siRNA control or siRNA smart pools targeting IKKβ or K-Ras (Dharmacon, Lafayette, CO). Reporter assays were performed as described (28). For genetic studies, cells were co-transfected with 100ng of either empty pcDNA3 vector (Invitrogen, Carlsbad, CA) for control or a pcDNA3 vector encoding the kinase mutant form of IKKβ (IKKβ-KM). For pharmacological studies, cells were treated treated as indicated (see figure legends). Relative light units were measured on an Lmax Microplate Luminometer (MolecularDevices, Sunnyvale, CA).

Flow Cytometry

2×10^5 KE67 cells plated in 6-well plates were treated with either 0.1% DMSO or 5uM IKKβ inhibitor CmpdA (31) for 16h. Cells were then scraped in PBS supplemented with 2% FBS (Sigma) and subsequently analyzed for GFP expression on a Beckman-Coulter Cyan ADP cytometer (Dako, Carpinteria, CA). Results were analyzed with FlowJo software (Tree Star, Ashland, OR).

Statistics

All values are presented either as mean ± SD or as representative images of at least three independent experiments. In the case of animal studies, five mice of each different genotype were analyzed. All comparisons were made using the unpaired Student *t* test for samples with unequal variance. Differences were considered statistically signi cant at $p \leq 0.05$ (indicated by asterisks).

RESULTS

Generation of a NF-κB reporter mouse model of K-Ras-induced lung cancer

In order to determine if NF-κB activity is induced in mouse lung tumors triggered by activation of oncogenic K-Ras, an NF-κB reporter mouse model of K-Ras-induced lung cancer was developed. To generate this model, we used oncogenic K-Ras inducible Lox-Stop-Lox (LSL) K-Ras^{G12D} mice (24), where expression of oncogenic K-Ras^{G12D} is triggered by Cre recombinase-mediated removal of the LSL element (Fig. 1A). The LSL-K-Ras^{G12D} mice were then bred to *cis*-NF-κB-EGFP knock-in mice, which express enhanced green fluorescent protein (EGFP) under the control of NF-κB *cis* elements (25). Mice positive for the conditional K-Ras allele and the NF-κB responsive EGFP reporter allele (referred to as K-Ras^{G12D}/NF-κB mice) were infected by intranasal administration of adenocre in order to activate oncogenic K-Ras^{G12D} specifically in lung epithelial cells and induce lung tumor formation.

NF-κB is activated in mouse K-Ras-induced lung cancers

NF-κB activity in K-Ras^{G12D}/NF-κB mice was evaluated by measuring the levels of EGFP expression in the lungs of tumor-bearing animals. First, non-invasive live fluorescence imaging was used to measure EGFP expression at 19 weeks post-infection, when lung adenocarcinomas can be detected (24). As can be seen in Fig. 1A, K-Ras^{G12D}/NF-κB mice have higher EGFP fluorescence emission levels in the chest area than K-Ras^{WT}/NF-κB mice (mice positive for the the NF-κB responsive EGFP reporter allele, but lacking the conditional K-Ras allele). Next, EGFP expression was measured directly in dissected lungs by laser scanning fluorescence microscopy. Lung tumors from K-Ras^{G12D}/NF-κB animals are EGFP positive (Fig. 1B). Importantly, the lungs of K-Ras^{WT}/NF-κB mice have only a few scattered EGFP positive cells (Fig. 1B). To rule out the possibility that the EGFP-positive cells within the lung tumors might be comprised of inflammatory cells (which are part of the tumor microenvironment and require NF-κB activation for their function (32)), we performed GFP immunohistochemistry. As can be seen in Figure 1C, many epithelial cells within the lung neoplastic lesions stain positive for EGFP (middle panel), whereas very few cells stain positive in K-Ras^{WT}/NF-κB mice (upper panel). As expected, the lung neoplastic cells from K-Ras^{G12D} positive mice lacking the EGFP reporter allele are negative for EGFP expression (bottom panel).

In addition to evaluating EGFP reporter activity, we measured levels of the phosphorylated form (phospho-ser32/36) of the IκBα protein, a marker of NF-κB and IKK activation (Fig. 1D). When compared to adenocre-infected K-Ras^{WT} lungs, the lungs of adenocre-infected K-Ras^{G12D} mice display increased levels of IκBα phosphorylation at Ser32/36 coupled with lower levels of total IκBα protein (consistent with IKK-induced degradation). In addition, consistent

with K-Ras activation, K-Ras^{G12D} mice display increased levels of phospho-AKT and phospho-p42/44). Finally, expression of the mutant 12D form of Ras was detected exclusively in K-Ras^{G12D} mice. These results support the EGFP analysis, indicating a higher degree of NF-κB activity in the lungs of K-Ras^{G12D} mice. Taken together these results confirm that NF-κB is activated in K-Ras-induced murine lung tumors *in situ*.

Deletion of the NF-κB p65/RelA subunit in the mouse lung decreases K-Ras-induced lung tumorigenesis

Given that K-Ras-induced lung tumorigenesis triggers NF-κB activation, we asked if genetic deletion of the NF-κB subunit p65/RelA in the LSL-K-Ras mouse model affects K-Ras-induced oncogenesis. To achieve p65/RelA inactivation we bred the LSL-K-Ras^{G12D} mice to p65$^{fl/fl}$ conditional mice (26) to obtain LSL-K-Ras^{G12D}/p65$^{fl/fl}$ mice. Lungs were then infected with adenocre to activate K-Ras^{G12D} and inactivate p65/RelA simultaneously (K-Ras^{G12D}/p65$^{\Delta}$ mice).

As evaluated by pathological examination of dissected lungs at 13 weeks post-infection, K-Ras^{G12D}/p65$^{\Delta}$ mice display a significantly reduced number of tumors than K-Ras^{G12D}/p65^{WT} mice (Figure 2A). In order to confirm that recombination of the conditional p65/RelA allele occurred in the lungs of K-Ras^{G12D}/p65$^{\Delta}$ mice, we measured excision by PCR (see fig. 2B and supplementary methods). In addition, as revealed by immunohistochemical studies, the neoplastic lung lesions found in K-Ras^{G12D}/p65$^{\Delta}$ mice lacked p65/RelA expression (Fig. 2C). Interestingly, loss of p65/RelA affected, not only the number of lesions formed, but also their spread. As can be seen in fig. 2D, most lesions formed in the presence of p65/RelA at 13 weeks post-infection have spread significantly into the alveolar compartment, whereas most lesions lacking p65/RelA at the same timepoint are still mostly contained within the bronchial epithelium. As these results indicate, although not absolutely required for tumor formation, p65/RelA greatly potentiates K-Ras-induced transformation in the lung *in situ*.

In order to gain insight into the role played by p65/RelA in potentiating K-Ras-induced oncogenesis, we investigated if loss of p65/RelA in this mouse model affects neoplastic cell survival. Relevant to this point, NF-κB has been shown, in cell-based studies, to be required to suppress Ras-induced apoptosis (21). Consistent with these previous findings, very few apoptotic cells were detected in K-Ras^{G12D}/p65^{WT} lesions, whereas a high number of apoptotic cells were seen in lesions of K-Ras^{G12D}/p65$^{\Delta}$ animals (Fig 3).

The ability of the NF-κB p65/RelA subunit to potentiate K-Ras-induced lung tumorigenesis does not depend on the status of the p53 tumor suppressor

The tumor suppressor p53 is a well-known activator of the apoptotic response triggered upon oncogene activation; it is also known that p53 activity can be negatively regulated by NF-κB and vice versa (33). Therefore, it would be reasonable to assume that NF-κB can potentiate K-Ras-induced oncogenesis by suppressing p53 activity. However, contrary to this assumption, we showed (21) that NF-κB regulates H-Ras-induced transformation in a p53-independent manner.

In order to address if p65/RelA potentiates K-Ras-induced oncogenesis by suppressing p53 activity, we generated a mouse model of K-Ras-induced lung cancer with combined loss of p65/RelA and p53 to ascertain whether loss of p53 would block the ability of p65/RelA to potentiate K-Ras transformation. For this purpose, we bred LSL- K-Ras^{G12D}/p65$^{WT/WT}$ and LSL-K-Ras^{G12D}/p65$^{fl/fl}$ models to p53$^{fl/fl}$ mice (27) to generate K-Ras^{G12D}/p53$^{\Delta}$/p65^{WT} and K-Ras^{G12D}/p53$^{\Delta}$/p65$^{\Delta}$ mice.

p53 is a strong tumor suppressor on its own, and its loss accelerates K-Ras tumor kinetics (29). We also observed this accelerated kinetics in animals with combined loss of p65 and p53. Even though loss of p53 did not seem to affect the number of lesions formed, p53 null tumors grew faster and progressed to a higher histological grade (not shown). Nonetheless, similar to what was observed in K-Ras^{G12D} mice, loss of p65/RelA in K-Ras^{G12D}/p53$^{\Delta}$ mice resulted in a lower frequency of lung tumors (Figure 4A). These data confirm previous cell-based studies (21) indicating that NF-κB potentiates K-Ras transformation in the lung independently of the status of p53.

Furthermore, loss of p65/RelA in K-Ras^{G12D}/p53$^{\Delta}$ mice resulted in lower grade tumors. As outlined in Fig. 4B, K-Ras^{G12D}/p53$^{\Delta}$/p65$^{\Delta}$ mice have a significantly higher percentage of grade 1 tumors than K-Ras^{G12D}/p53$^{\Delta}$/p65^{WT} mice. Conversely, Ras^{G12D}/p53$^{\Delta}$/p65$^{\Delta}$ mice have a significantly lower percentage of Grade 4 and 5 tumors. This indicates that p65/RelA regulates not only survival of lung cells upon K-Ras activation, but also that it regulates other cell properties that contribute to progression of the malignant phenotype

NF-κB is activated in human K-Ras-transformed lung epithelial cells and activation requires IKKβ activity

The above experiments demonstrate that K-Ras activates NF-κB in the mouse lung, but it is important to confirm that the same relationship exists in human lung cells. Therefore, NF-κB activity was measured in low-passage primary immortalized human small airway cells (SALEB) and their K-Ras-transformed counterparts (SAKRAS) (30). As can be seen in Fig. 5A, SAKRAS display p65-associated DNA binding activity (NF-κB band in untreated lane), whereas SALEB cells do not. SAKRAS cells also display increased sensitivity to cytokine-induced NF-κB activation (compare TNFα lanes). In addition, when compared to SALEB cells, SAKRAS display highly elevated expression of NF-κB target genes IL-8 and MMP-9 and slightly elevated expression of Bcl-XL (Fig. 5B). Finally, similar to the murine lung tumors, SAKRAS cells also have increased levels of phosphorylated IκBα (Fig. 5C). Importantly, SAKRAS cells exhibit elevated phosphorylated IKK (Fig. 5C, and see below).

In addition, we investigated NF-κB activity in H358 cells, a lung adenocarcinoma-derived cell line known to harbor a K-Ras oncogenic mutation (34). As shown in Fig. 6A (left panel), H358 cells exhibit constitutive NF-κB DNA binding activity that is suppressed upon siRNA-mediated knockdown of K-Ras expression, demonstrating that the majority of NF-κB DNA binding activity in these cells is derived downstream of K-Ras expression.

Because of the increased level of phospho-IκBα detected in mouse tumors (Fig. 1D) and the increased levels of phosphorylated forms of both IκBα and IKKα/β in SAKRAS cells (Fig. 5C), we asked if NF-κB activation induced by K-Ras is mediated by IKK. First, we tested a potent IKKβ inhibitor (cmpdA (31)) in SAKRAS cells. IKKβ inhibition, but not control treatment, blocked constitutive NF-κB DNA binding activity (Fig. 5A). Additionally IKKβ inhibition blocked K-Ras-induced target gene expression (Fig. 5B).

We then explored siRNA knockdown to IKKβ in H358 cells. Knockdown of IKKβ strongly suppressed NF-κB DNA binding activity in H358 cells, similar to siRNA-mediated knockdown of K-Ras (Fig. 6A). Additionally, H358 cells were either transfected with a kinase-inactive version of IKKβ (IKKβ-KM) or treated with CmpdA, and NF-κB-dependent reporter activity was measured using luciferase. Results from these experiments demonstrate that both kinase-inactive IKKβ and CmpdA block NF-κB activity (Figs. 6B and C), indicating the involvement of IKK in the K-Ras-induced pathway. Finally we investigated whether pharmacological inhibition of IKKβ would also affect NF-κB activity in mouse cells. For this purpose we used the KE67 cell line derived from lung tumors of our K-Ras^{G12D}/NF-κB EGFP reporter mice.

As can be seen on Fig. 6D, treatment of KE67 cells with CpA reduced the number of EGFP-positive lung tumor cells by almost 50%.

Taken together, these results indicate that IKKβ plays an important role in mediating NF-κB activation by K-Ras, supporting its inhibition in K-Ras-induced lung cancer as a potential new therapeutic approach.

DISCUSSION

Point mutations in K-Ras occur frequently in lung cancer and drive the oncogenic phenotype. Since there are no effective therapies for K-Ras-positive lung cancer (or for lung cancer broadly), new approaches for therapy must be identified. In this regard, current interest is focused on downstream oncogenic effectors of the activated Ras forms (35–38). Previously we had shown that the transcription factor NF-κB is critical for oncogenic transformation downstream of H-Ras (18,21). Furthermore, trying to dissect the role of the NF-κB subunits in Ras-transformation, our group also showed that the p65/RelA subunit contributes to efficient H-Ras-induced transformation (39). Additional studies have shown that p65/RelA is activated in tumor biopsies from K-Ras-induced lung cancer patients (20), in K-Ras positive prostate epithelial cells (22) and in both pancreatic cancer cells and melanoma cells in a Ras-dependent manner (40,41). Here we have analyzed a role for the p65/RelA subunit of NF-κB downstream of oncogenic K-Ras for the development of lung tumors *in situ*.

Using LSL-K-Ras^{G12D} mice (24), we show that K-Ras activates NF-κB in lung tumors *in situ* (Fig. 1). Recently, Meylan et al (42) reported that NF-κB activation in the LSL-K-Ras^{G12D} lung tumor model depends on deletion of p53. Our studies clearly show that NF-κB activation occurs when p53 is wildtype. Meylan et al (42) analyzed nuclear accumulation of p65/RelA as a marker of NF-κB activation, while our studies utilized NF-κB-dependent EGFP reporter and IκBα phosphorylation from *in situ* tumors (Fig. 1). Thus, the use of distinct assays with different sensitivity likely explain the differences in findings from the two papers, specially as loss of p53has been shown to further enhance NF-κB activation (43). More importantly, Meylan et al (42) reported that expression of a degradation-resistant form of IκBα (IκBα-SR) suppressed tumor formation in the K-Ras lung tumor model with deleted p53. Consistent with their findings, our results show that p65/RelA is needed for efficient lung tumor formation by K-Ras^{G12D} regardless of p53 status (Figs. 2 and 4).

Furthermore, consistent with the previous cell-based studies (21), cre-generated deletion of p65/RelA in parallel with K-Ras^{G12D} activation led, not only to reduced transformation (Fig. 2), but also to an apoptotic response in surviving tumors (Fig. 3). This result suggests that the reduction in lung tumor number in the p65/RelA null setting is caused through an apoptotic response, with the surviving tumors presumably undergoing less (but measurable) apoptosis, which suggests that a likely mechanism for p65/RelA's role in potentiating transformation is to promote cell survival. In this regard, we have not detected significant upregulation of traditional anti-apoptotic genes by oncogenic H-Ras (39) or by K-Ras (unpublished and Fig. 5B). Future experiments will address mechanisms of survival controlled by p65/RelA downstream of oncogenic Ras expression.

The loss of p65/RelA significantly reduces, but does not eliminate, tumorigenesis downstream of oncogenic K-Ras expression (Figs. 2 and 4). We have previously shown that Ras-induced transformation is also impaired in c-Rel null MEFs, and that impairment is highest in c-Rel/p65 double null MEFs (39), which suggests that both NF-κB subunits play an important role in Ras-mediated transformation. Consistent with our previous work, Barbie at al (44) have shown that c-Rel expression is important for survival of K-Ras-transformed cells. Meylan et al (2009) have detected both c-Rel and p65/RelA activation in the LSL-K-Ras^{G12D}/p53$^{\Delta}$ mouse

model. These studies, together with the results described in this manuscript are consistent with a model where both NF-κB subunits would be activated by K-Ras to promote oncogenesis.

Even though regulation of cell survival by p65/RelA certainly plays a role promoting K-Ras transformation, the reduced grade of p65/RelA null K-Ras/$p53^{\Delta}$ lung tumors (Fig. 4B) suggests that p65/RelA regulates additional aspects of the malignant phenotype. Interestingly, in the panel of genes analyzed in human primary cells, the two most strongly K-Ras-induced genes were found to be IL-8 and MMP-9 (Fig. 5B), both of which have been shown to be important in tumor progression. IL-8 was shown to promote Ras-induced angiogenesis (45), and MMP-9 has been shown to induce tumor invasion (46). Thus, in addition to controlling survival, NF-κB activation by oncogenic K-Ras likely involves additional oncogenic mechanisms, including enhanced invasion.

For therapy design purposes, it is important to identify mediators of K-Ras-induced NF-κB activation that can be pharmacologically targeted. Here we identify IKKβ as an important mediator of NF-κB activity in lung primary cells and lung cancer cell lines (Figs. 5 and 6). This is consistent with additional evidence that IKKβ is activated by oncogenic Ras (22,23, 41,47), as well as evidence that IKKβ promotes oncogenesis. Loss of IKKβ prevents tumorigenesis in a mouse model of colitis-associated cancer (48). Pharmacological inhibiton of IKKβ inhibits multiple myeloma cell growth *in vitro* and as xenograft tumors (49). Knockdown of IKKβ expression inhibits growth of H-Ras-driven melanomas (41). Finally, IKKβ not only activates mTOR in certain breast cancer cells, thereby promoting tumor angiogenesis, but its expression correlates with poor clinical outcome (50). Interestingly, the IKK-related kinase TBK1 has been recently implicated in K-Ras-induced transformation and NF-κB activation (44,51). It remains to be determined whether IKKβ and TBK1 contribute to K-Ras-induced NF-κB activation independently, or whether there is a functional connection between these two pathways. In this regard, TBK1 and IKKβ may contribute to different oncogenic phenotypes, with TBK1 serving as a stronger regulator of cancer cell survival.

In summary, our studies show that K-Ras triggers NF-κB activation in a mouse model of lung cancer *in situ*. NF-κB is an important K-Ras target in mediating the oncogenic process, because loss of the NF-κB subunit p65/RelA significantly impairs lung tumor formation in the presence or absence of p53. In addition, inhibiton of IKKβ expression or function blocks NF-κB activation in K-Ras-transformed lung cells, suggesting pharmacological targeting of IKKβ or other upstream regulators that control NF-κB as a potential therapeutic approach for K-Ras-induced lung cancer therapy.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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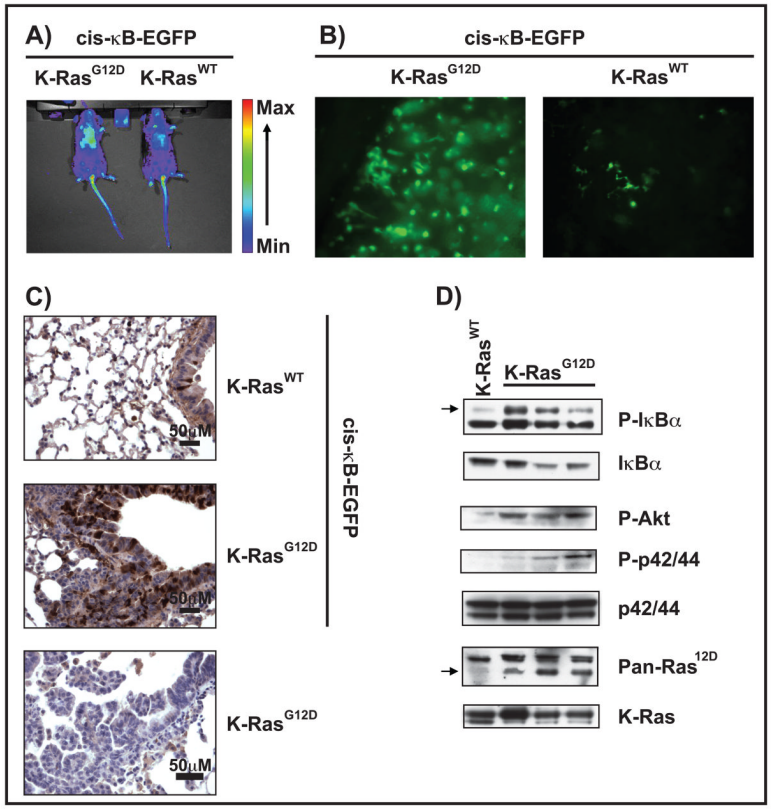

Figure 1. Oncogenic K-Ras activates NF-κB in lung tumors *in situ*

WT and K-Ras^{G12D}/NF-κB mice were analyzed at 19 weeks post-infection. **A)** *In vivo* live EGFP fluorescence emission. Color scale indicates the range of fluorescence intensity. **B)** Laser scanning microscopy of dissected lungs to measure EGFP fluorescence emission. **C)** Lung tissue sections of WT and K-Ras^{G12D}/NF-κB mice were analyzed by GFP immunohistochemistry (positive cells stain in brown). Slides were counterstained with hematoxylin (blue). **D)** Lung protein lysates from K-Ras^{G12D} or K-Ras^{WT} mice were submitted to western blotting with the indicated antibodies. Arrows indicate the specific immunodetected bands; additional bands in blots are non-specific.

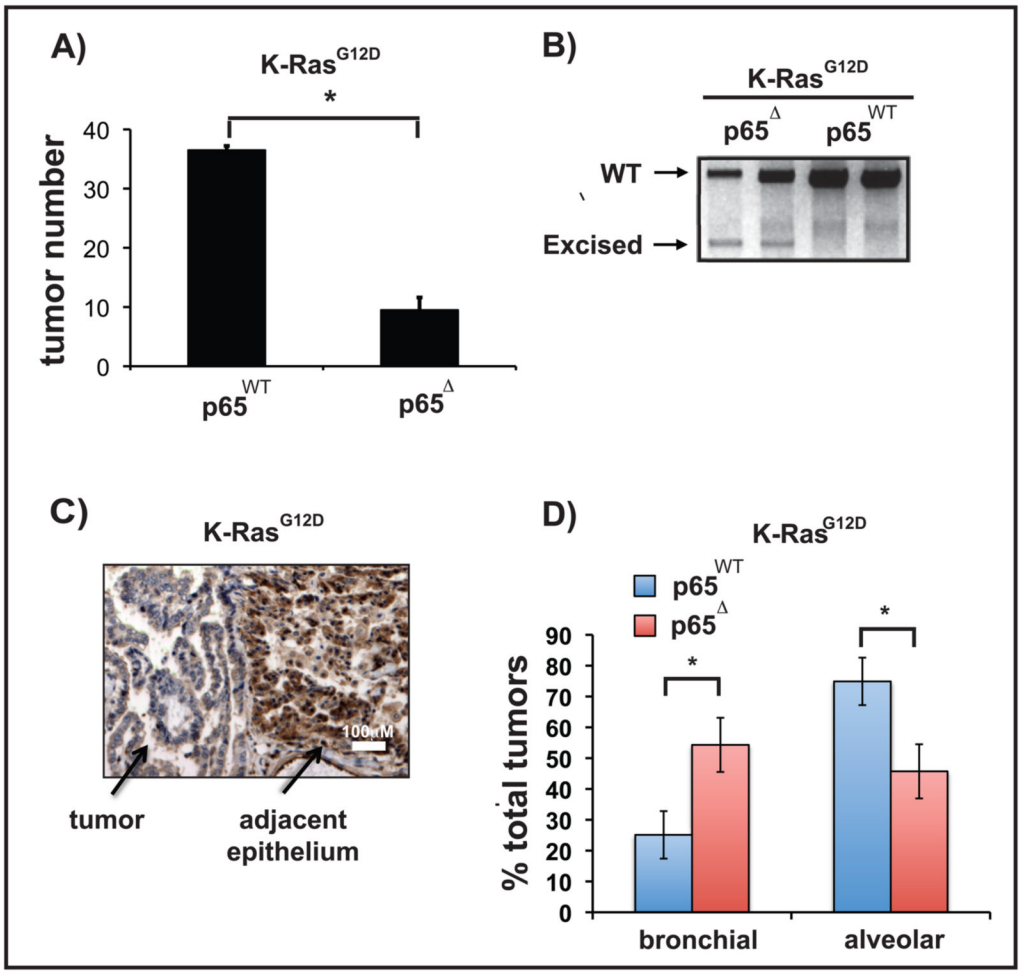

Figure 2. Loss of p65/RelA reduces formation and spread of K-Ras-induced lung tumors

K-Ras^{G12D}/p65^{WT} and K-Ras^{G12D}/p65$^{\Delta}$ mice were analyzed at 13 weeks post-infection. **A)** Number of K-Ras-induced neoplastic lesions was determined by counting lesions in Hematoxylin/Eosin stained lung sections as described (see methods). **B)** PCR to detect cre-mediated recombination of p65/RelA. Bands corresponding to the WT and excised alleles are indicated. **C)** Immunohistochemistry for p65/RelA (positive cells are brown). Neoplastic lesion and adjacent epithelium are indicated. **D)** Analysis of lung tumor spread was performed on Hematoxylin/Eosin stained lung sections as described (see methods).

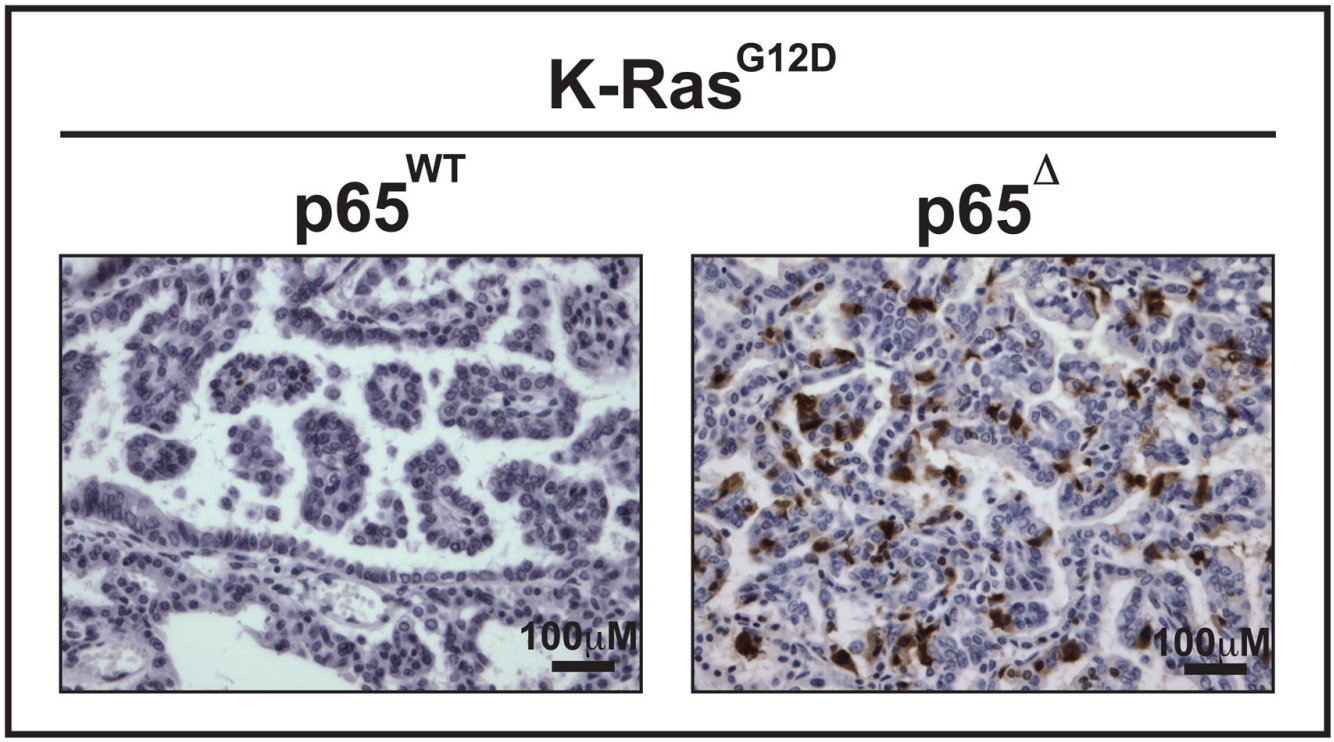

Figure 3. K-Ras^{G12D}/p65$^{\Delta}$ lung tumors have higher numbers of apoptotic cells

Apoptotic cells were detected by TUNEL staining of lung tissue sections (positive cells are brown).

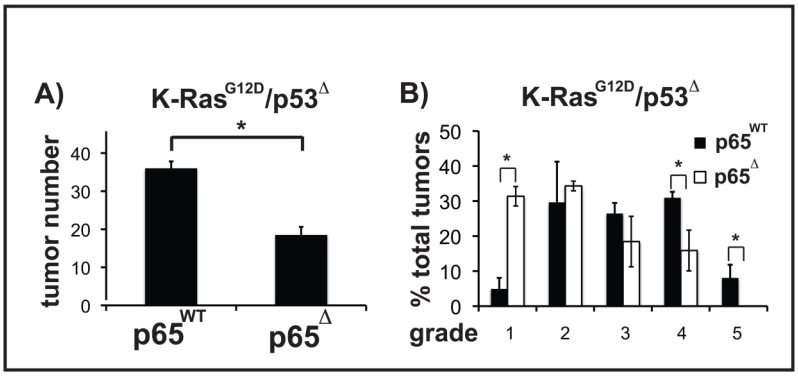

Figure 4. Loss of p65/RelA reduces formation and grade of K-Ras-induced lung tumors in the absence of p53

K-Ras^{G12D}/p53$^{\Delta}$/p65^{WT} and K-Ras^{G12D}/p53$^{\Delta}$/p65$^{\Delta}$ mice were analyzed at 19 weeks post-infection. **A)** Number of K-Ras-induced neoplastic lesions was determined by counting lesions in Hematoxylin/Eosin stained lung sections as described (see methods). **B)** Analysis of lung tumor grade was performed on Hematoxylin/Eosin stained lung sections as described (see methods).

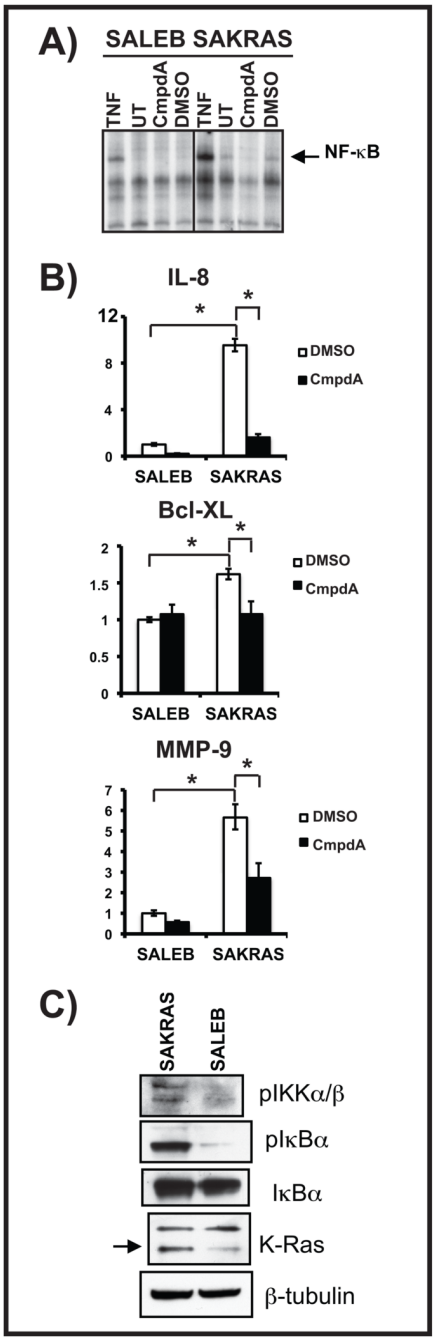

Figure 5. K-Ras-induced NF-κB activation in lung primary cells requires IKKβ activity

A) Nuclear extracts of lung primary SALEB and SAKRAS cells were analyzed by EMSA with a probe containing a canonical NF-κB DNA binding site. Cells were eiter left untreated (UT) or treated for 1h with 20ng/ml TNFα (TNFα), 1uM CmpdA (CmpdA) or 0.02% DMSO (DMSO). **B)** Expression of NF-κB target genes IL-8, Bcl-XL and MMP-9 was analyzed by real-time quantitative PCR in SALEB and SAKRAS cells treated with 0.02% DMSO (DMSO) or 1uM CmpdA (CmpdA) for 24h. **C)** Western blotting of total protein lysates from SALEB (SL) or SAKRAS (SK) cells probed with different antibodies as indicated.

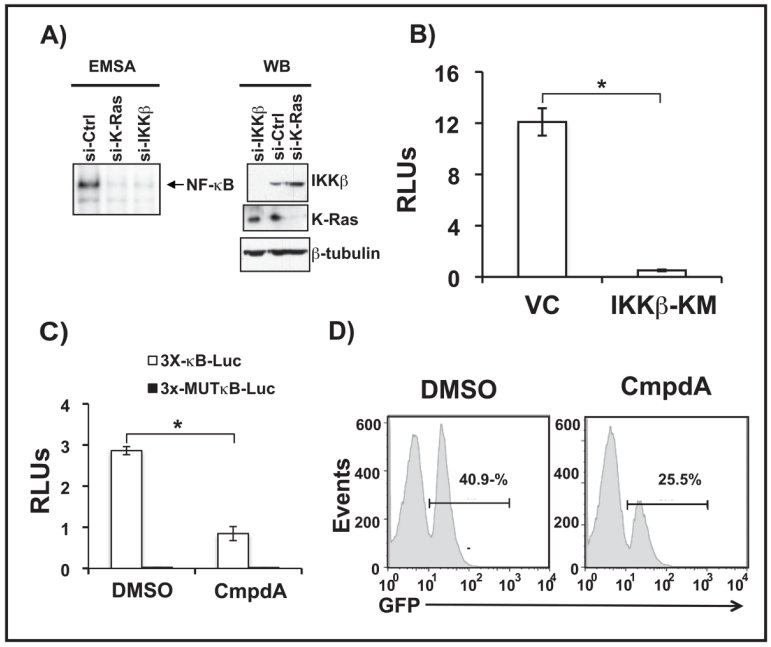

Figure 6. K-Ras-induced NF-κB activation in lung cancer cells requires IKKβ expression and activity

A) H358 cells were transiently transfected with siRNA targeted against K-Ras (siK-Ras), IKKβ (siIKKβ), and nontargeting control (siCtrl) and analyzed at 96h post-transfection for NF-κB DNA binding activity by EMSA (left panel) and efficiency of knockdown by Western Blotting (WB, right panel). NF-κB DNA binding complexes as well as antibodies used are indicated. **B and C)** Dual luciferase reporter assays were performed using an NF-κB-responsive firefly luciferase reporter (3x-κB-Luc, unfilled bars) or an NF-κB-unresponsive reporter (3X-MUTκB-Luc, black-filled bars). For panel B, H358 cells were either transfected with an empty pcDNA3 vector (VC) or with pcDNA3-IKKβ-KM. For panel C, H358 cells were either treated with 0.02% DMSO or treated 1uM CmpdA for 16h. **D)** DMSO or CmpdA-treated KE67 cells were analyzed by flow cytometry. Forward and side scatter (FS and SS) were used to gate on live cells. The single color histogram represents the number of events recorded in function of the level of GFP fluorescence emission using a logaritmic scale. A threshold for GFP-positive cells was arbitrarily set (linear gate) and the percentage of GFP positive cells is indicated.