KrasG12D and Nkx2-1 haploinsufficiency induce mucinous adenocarcinoma of the lung

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Mucinous adenocarcinoma of the lung is a subtype of highly invasive pulmonary tumors and is associated with decreased or absent expression of the transcription factor NK2 homeobox 1 (NKX2-1; also known as TTF-1). Here, we show that haploinsufficiency of Nkx2-1 in combination with oncogenic KrasG12D, but not with oncogenic EGFRL858R, caused pulmonary tumors in transgenic mice that were phenotypically similar to human mucinous adenocarcinomas. Gene expression patterns distinguished tumor goblet (mucous) cells from nontumorigenic airway and intestinal goblet cells. Expression of NKKX2-1 inhibited urethane and oncogenic KrasG12D-induced tumorogenesis in vivo. Haploinsufficiency of Nkx2-1 enhanced KrasG12D-mediated tumor progression, but reduced EGFR-L858R-mediated progression. Genome-wide analysis of gene expression demonstrated that a set of genes induced in mucinous tumors was shared with genes induced in a nontumorigenic chronic lung disease, while a distinct subset of genes was specific to mucinous tumors. ChIP with massively parallel DNA sequencing identified a direct association of NKX2-1 with the genes induced in mucinous tumors. Here, we present what we believe to be a novel mouse model that develops mucinous adenocarcinoma of the lung, in which oncogenic KrasG12D is induced in the respiratory epithelium of Nkx2-1 heterozygous (Nkx2-1+/−) mice. Reduced expression of Nkx2-1 promoted initiation and progression of invasive KrasG12D, induced mucinous lung adenocarcinoma. Conversely, increased expression of Nkx2-1 in the respiratory epithelium inhibited carcinogen- or KrasG12D-induced lung tumor formation in vivo. A genome-wide gene expression study indicated that Nkx2-1 inhibited mRNAs involved in tumorigenesis and induced genes involved in apoptosis. Expression of Nkx2-1 sensitized lung carcinoma cells to cisplatin-induced apoptosis in vitro. ChIP sequencing (ChIP-seq) analysis indicated that Nkx2-1 directly associated with a set of genes induced in mucinous tumors. Bioinformatic analysis identified the AP-1 binding element (TGAnTCA) in a portion of the Nkx2-1 ChIP-seq peaks. Nkx2-1 inhibited AP-1-mediated activity and tumor colony formation in vitro, which suggested that Nkx2-1 suppresses lung tumorogenesis, at least in part, by inhibiting AP-1 activity. Our findings provide a molecular mechanism by which Nkx2-1 suppresses mutant Kras-driven mucinous adenocarcinoma.

Introduction

Mucinous adenocarcinoma of the lung (formerly known as mucinous bronchoalveolar cancer) is pathologically classified as tumor cells with goblet cell morphology containing abundant intracytoplasmic mucin (1). Invasive mucinous adenocarcinoma of the lung has a higher malignant potential than do the more common types of lung adenocarcinoma, such as acinar or papillary adenocarcinoma. Mucinous adenocarcinoma of the lung is associated with decreased or absent expression of the transcription factor NK2 homeobox 1 (NKX2-1; also known as TTF-1). NKX2-1 plays a critical role in lung morphogenesis and respiratory epithelial-specific gene expression, including activation of surfactant proteins and repression of mucus (3, 4). The potential oncogenic role of NKX2-1 in the pathogenesis of adenocarcinoma of the lung was proposed by findings that a region of 14q13.3 containing NKX2-1, NKX2-8, and PAX9 was amplified in approximately 10% of human lung adenocarcinoma (5–7). Loss-of-function and gain-of-function studies in human lung carcinoma and transformed cells supported a role of NKX2-1 as an oncogene (5–9); however, the KrasG12D/C57BL/6-p53−/− mouse model and a xenograft mouse model supported the concept that NKX2-1 is an anti-metastatic factor (10, 11).

Results

Haploinsufficiency of Nkx2-1 induced mucinous adenocarcinomas during KrasG12D tumorigenesis. In order to determine whether reduced expression of Nkx2-1 influences the pathogenesis of invasive mucinous adenocarcinoma of the lung, we created a mouse model...
in which mutated active Kras was conditionally expressed in the respiratory epithelium of wild-type or heterozygous Nkx2-1 mice. Mice were developed by crossing transgenic Scgb1a1-rtTA[tetO]-Kras4bG12D mice (12) with Nkx2-1 +/− mice (13). Nkx2-1 mRNA was significantly reduced in Nkx2-1+/− versus Nkx2-1+/+ mice (4, 14).

At 2 months after doxycycline (Dox) administration, the Kras transgenic mice with heterozygous Nkx2-1 (Scgb1a1-rtTA[tetO]-Kras4bG12D;Nkx2-1+/−; referred to herein as KrasG12D;Nkx2-1+/−) lost weight compared with the Kras transgenic mice with wild-type Nkx2-1 (Scgb1a1-rtTA[tetO]-Kras4bG12D;Nkx2-1+/+; referred to herein as KrasG12D;Nkx2-1+/+) and control littermates (Figure 1A). Average lung volume in KrasG12D;Nkx2-1+/− mice was increased compared with KrasG12D;Nkx2-1+/+ and control mice (Figure 1B). Tumor number and volume of KrasG12D;Nkx2-1+/− mice, as detected by microCT (Figure 1C), increased compared with those of KrasG12D;Nkx2-1+/+ and control mice (Figure 1, D and E). In the absence of KrasG12D weights of Nkx2-1+/− and Nkx2-1+/+ mice were similar (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI64048DS1). Nkx2-1−/− mice did not develop spontaneous lung tumors at 9 months of age (data not shown). Whereas KrasG12D;Nkx2-1−/− mice developed benign lung adenoma, KrasG12D;Nkx2-1−/− mice developed invasive lung adenocarcinoma within 2–8 months (Figure 2). Unlike tumor cells in KrasG12D;Nkx2-1−/− mice, tumor cells in KrasG12D;Nkx2-1−/− mice contained abundant intracytoplasmic mucin and lacked NKX2-1 staining (Figure 2A), consistent with the histochemical features of human mucinous adenocarcinoma of the lung (Supplemental Figure 2). Human mucinous adenocarcinomas often consist of a heterogeneous mixture of tumor cell types, including features of papillary or acinar adenocarcinoma (1). In the KrasG12D;Nkx2-1−/− mouse model, the percentage of tumor goblet cells (stained with the intracytoplasmic goblet cell marker anterior gradient homolog 2 [AGR2]) was 35% (Supplemental Figure 3). Cytokeratin 7 (CK7) and cytokeratin 20 (CK20), clinical biomarkers for mucinous adenocarcinoma of the lung (1), were expressed in KrasG12D;Nkx2-1+/− mice, whereas only CK7 was present in KrasG12D;Nkx2-1+/+ mice (Figure 2B). When Dox was administered for 2 months and then withdrawn for 2 weeks, tumors regressed (Figure 2C), which indicates that ongoing expression of mutant Kras is required for the maintenance of tumor goblet cells.

Tumor goblet cells were not dependent on the SPDEF/FOXA3 transcriptional program. Mucous metaplasia is a prominent feature of various chronic lung diseases, including asthma, chronic obstructive pulmonary disease (COPD), and cystic fibrosis (CF). Mucous metaplasia in these non-neoplastic disorders is associated with increased expression of the transcription factors Sam pointed domain Ets-like factor (SPDEF) and FOXA3, as well as various mucins, including MUC5AC, and mucin-associated genes, including AGR2 (15). To assess whether goblet cells associated with KrasG12D;Nkx2-1−/− induced tumors shared features with nontumor goblet cells, we
compared immunohistochemical findings of the mutant Kras-induced mucinous tumors with mucous metaplasia induced by house dust mite (HDM) allergen exposure (Figure 3). Mucus-associated proteins, including MUC5AC, MUC5B, and AGR2, were readily detected in goblet cells in lung tumors of KrasG12D;Nkx2-1+/– mice and in airways of HDM-challenged mice, but were absent in tumors induced in KrasG12D;Nkx2-1+/+ mice. In allergen-induced mouse models, NKX2-1 and FOXA2 inhibit goblet cell differentiation, whereas SPDEF is required for airway mucous metaplasia (4, 15, 16). Consistent with their inhibitory roles in goblet cell differentiation, both NKX2-1 and FOXA2 were decreased in tumor goblet cells in KrasG12D;Nkx2-1+/– mice. Both SPDEF and FOXA3 were highly expressed in airway goblet cells after HDM exposure, as previously reported (15, 17), but were not detected in the goblet cells in KrasG12D;Nkx2-1+/––induced tumors (Figure 3 and Supplemental Figure 4).

NKX2-1 inhibited mutant Kras–induced tumorigenesis in vivo. To directly assess the role of NKX2-1 in lung tumorigenesis, NKX2-1 was conditionally expressed in respiratory epithelial cells (4). This conditional system has been widely used to model lung tumorigenesis in mice (12, 18, 19). To assess whether increased NKX2-1 is sufficient to initiate tumor formation, Dox was administered to Scgb1a1-rtTA;[tetO]–Flag–Nkx2-1 mice for approximately 6–12 months, after which time none of the NKX2-1–expressing mice developed lung tumors (n = 19; data not shown). Kendall et al. reported that Nkx2-1, Nkx2-8, and PAX9 resided within the 14q13.3 locus and were amplified in approximately 10% of lung adenocarcinomas; in vitro data demonstrated that the combination of NKX2-1 with either Nkx2-8 or PAX9 was required for colony formation in virus-transformed human bronchial epithelial cells in vitro (5). We generated transgenic mice coexpressing NKX2-1 and Nkx2-8 or NKX2-1 and PAX9. Coexpression of NKX2-1 with either PAX9 or Nkx2-8 did not cause tumorigenesis after 4 months of Dox administration (Supplemental Figure 5).

To assess whether NKX2-1 influences tumorigenesis in Scgb1a1-rtTA;[tetO]–Flag–Nkx2-1 transgenic mice (both transgenic mice; FVB/N background), we treated the mice with urethane, a lung carcinogen. Urethane-induced tumors were readily detected on the lung surface of FVB/N control mice 16 weeks after administration (20). Expression of NKX2-1 decreased the number of urethane-induced tumors (Table 1 and Figure 4, A and B), which indicates that increased NKX2-1 suppresses tumor initiation. The few tumors seen in the NKX2-1–induced transgenic mouse group (Scgb1a1-rtTA;[tetO]–Flag–Nkx2-1 on Dox) did not express FLAG–NKX2-1 (data not shown), and they may be derived from lung epithelial cells that did not express the Scgb1a1-rtTA transgene. Since urethane induces lung tumors associated with Kras mutations (21), we assessed whether NKX2-1 inhibited mutant Kras–induced tumors by creating Nkx2-1;KrasG12D triple transgenic mice (Scgb1a1-rtTA;[tetO]–Flag–Nkx2-1;[tetO]–KrasG12D). Coexpression of NKX2-1 reduced the number and volume of KrasG12D–induced lung tumors (Figure 4, C and D), which indicates that increased expression of NKX2-1 inhibited mutant Kras–induced tumor initiation and progression in vivo.

We also assessed whether NKX2-1 influences proliferation of lung epithelial cells by using HBEC3 human bronchial epithelial cells generated by expression of hTERT and CDK4 (22). We infected HBEC3

Figure 2
Haploinsufficiency of Nkx2-1 caused mucinous adenocarcinoma of the lung in KrasG12D mice. (A) Lung sections were stained with H&E or with NKX2-1 and Alcian blue. Tumors in KrasG12D;Nkx2-1+/– mice (14 of 16) contained goblet cells with abundant intracytoplasmic mucin (Alcian blue positive, NKX2-1 negative). (B) CK7 and CK20, clinical biomarkers for human mucinous adenocarcinoma of the lung, were expressed in tumor cells of KrasG12D;Nkx2-1+/– mice. (C) Alcian blue–stained tumor cells in lungs of KrasG12D;Nkx2-1+/– mice 2 months after Dox administration (left; n = 6). Tumor cells in KrasG12D;Nkx2-1+/– mice regressed following withdrawal of Dox for 2 weeks after the 2-month administration (right; n = 8). Scale bars: 1 mm (A, top and middle); 100 μm (A, bottom, and B and C).
Figure 3
Tumor goblet cells are not dependent on the SPDEF/FOXA3 transcriptional program. Sections from control, $\text{Kras}^{G12D}/\text{Nkx2-1}^{+/+}$, $\text{Kras}^{G12D}/\text{Nkx2-1}^{-/-}$, and HDM-challenged lungs and normal intestine were stained for mucins MUC2, MUC5AC, MUC5B, and AGR2 and the transcription factors NKX2-1, FOXA2, FOXA3, and SPDEF. FOXA3 and SPDEF, which were seen in goblet cells of HDM-challenged lungs, were not expressed in the tumor goblet cells of $\text{Kras}^{G12D}/\text{Nkx2-1}^{-/-}$ mice. Scale bars: 100 μm.
cells with a lentiviral vector containing Flag–Nkx2-1 (4). Expression of Nkx2-1 significantly inhibited proliferation of HBEC3 cells (Supplemental Figure 6), which suggests that Nkx2-1 may influence tumorigenesis, at least in part, by suppressing cell proliferation.

Haplinsufficiency of Nkx2-1 did not induce mucinous adenocarcinomas during EGFR\textsuperscript{L858R} tumorigenesis. EGFR mutations are not associated with human mucinous adenocarcinoma (1). While mutant Kras–induced lung tumorigenesis was suppressed by Nkx2-1 in vivo (present study and ref. 10), whether mutant EGFR–induced lung tumorigenesis is influenced by Nkx2-1 in vivo is unknown. Mutated active EGFR\textsuperscript{L858R} was conditionally expressed in the respiratory epithelium of wild-type or Nkx2-1\textsuperscript{1/2} mice by crossing Scgb1a1-rtTA;[tetO]–Flag–Nkx2-1 mice with the Nkx2-1\textsuperscript{1/2} mice (13); these mice are referred to herein as EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} and EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2}, respectively. Unexpectedly, tumor number and volume were significantly decreased in EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} mice compared with EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} littermates (Figure 5A), which indicates that tumorigenesis mediated by mutant EGFR was enhanced by Nkx2-1. Consistent with the infrequent presence of EGFR mutations in human mucinous adenocarcinoma of the lung (1), neither EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} nor EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} mice developed mucinous adenocarcinomas (Figure 5B). Lung tumors in EGFR\textsuperscript{L858R},Nkx2-1\textsuperscript{1/2} mice stained for MUC5B, but not Alcian blue or MUC5AC. These results indicate that (a) Nkx2-1 enhances tumorigenesis in the context of an activated mutant EGFR, and (b) the mutant EGFR did not induce tumor goblet cells in Nkx2-1\textsuperscript{1/2} mice. Consistent with these mouse data, the majority of the KRAS mutation–associated human adenocarcinoma cell lines expressed high levels of MUC5AC mRNA, whereas all cell lines bearing EGFR mutations expressed little or no MUC5AC mRNA (Figure 5C). Of KRAS mutant cell lines, those lacking Nkx2-1 expressed higher levels of MUC5AC and MUC5B mRNA than did those positive for Nkx2-1 (Figure 5C), which suggests that Nkx2-1 suppresses mucin gene expression in mutant KRAS–associated tumors.

Nkx2-1 inhibited expression of a group of genes induced in mucinous tumors. To identify mechanisms underlying the pathogenesis of mucinous adenocarcinoma of the lung, genome-wide gene expression analysis was performed using Kras\textsuperscript{G12D},Nkx2-1\textsuperscript{1/2}–mouse lungs. A number of mRNAs that were increased in Kras\textsuperscript{G12D},Nkx2-1\textsuperscript{1/2}–lungs overlapped with those induced in a HDM model of asthma (HDM-challenged mice; ref. 23), including ADAM8, AGR2, ALOX15, CHI3L1, IGF1, MUC5AC, MUC5B, RETNL, and SAA3 (Figure 6, highlighted in blue and green, and Supplemental Table 2), which supports the concept that some of the aspects of goblet cell differentiation are shared among these lung diseases. In order to identify genes regulated by Nkx2-1 in the mucinous tumor model, mRNA analysis was performed in A549 human lung carcinoma cells, which bear a KRAS mutation and lack Nkx2-1 expression (Figure 5C). Nkx2-1 was expressed in the A549 cells with a lentiviral vector (Supplemental Table 3 and ref. 4). A group of Nkx2-1–inhibited genes induced in the lungs of the mucinous tumor model, but not in the asthma model, was identified (Figure 6, highlighted in red). Those genes may be tumor markers or function as tumor promoters. AGR2, LCN2, MUC5AC, MUC5B, and RBP4 were also Nkx2-1–inhibited genes; however, they were expressed in lungs of both the mucinous tumor and the HDM-induced mouse models (Figure 6, highlighted in green).

**Table 1**

<table>
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<th>Mouse group</th>
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<th>Dox</th>
<th>Tumor incidence(^a)</th>
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<tr>
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<td>Scgb1a1-rtTA</td>
<td>Yes</td>
<td>15/15</td>
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<tr>
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<tr>
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<td>Yes</td>
<td>6/16</td>
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</table>

\(^a\)Number of mice that developed lung tumors relative to total.

**Figure 7**. The profile of genes regulated by Nkx2-1 in A549 human lung carcinoma cells is shown in Figure 6, Figure 7A, and Supplemental Table 3. Nkx2-1 induced expression of SFTP\(_\alpha\), SFTP\(_\beta\), LAMP3, CEACAM6, and MYBPH (3, 11, 24). Expression of MUC5AC, MUC5B, and SERPINE1 (4, 25) was inhibited by Nkx2-1. Gene Ontology analysis revealed that expression of genes linked to protein kinase cascade and enzyme linked receptor protein signaling pathway was decreased, and expression of those related to programmed cell death was increased, by Nkx2-1 (Supplemental Figure 7). Nkx2-1 inhibited FGFR1, FGFR4, IGF1R, CCND3, CCNE2, and CDK6, which are associated with cancer (26–31), but induced expression of genes that induce programmed cell death, such as FAS and TIMP3 (32, 33). Although Nkx2-1 suppressed genes linked to tumorigenesis and induced genes linked to apoptosis, it did not alter viability of A549 carcinoma cells (data not shown). While expression of Nkx2-1 in human lung tumors is associated with better prognosis (34), we assessed whether Nkx2-1 influenced chemotherapy-induced cell death in A549 cells. Cisplatin is a chemotherapy drug clinically used to treat mutant KRAS–associated lung cancer (35). Nkx2-1 sensitized A549 cells to cisplatin-induced apoptosis, a finding confirmed by detection of cleaved PARP, an apoptosis marker (Figure 7, B–D).

ChIP-seq analysis identified Nkx2-1 binding sites in A549 lung carcinoma cells. ChIP-seq analysis was used to identify potential direct transcriptional targets of Nkx2-1 in chromatin from A549 cells expressing Nkx2-1. Sequence reads obtained from massively parallel sequencing were mapped onto the human genome. ChIP-seq analysis was validated by examining Nkx2-1 binding peaks in the promoter of SFTP\(_\alpha\), a known downstream target of Nkx2-1 (36, 37). Nkx2-1 was directly associated with the promoter of the SFTP\(_\alpha\) gene (Figure 8A). Nkx2-1 inhibited expression of MUC5AC (Figure 6 and Figure 7A) and was directly associated with the promoter of MUC5AC (Figure 8B), suggestive of its activity as a transcriptional suppressor. Nkx2-1 was also associated with the first and second introns of FGFR1 (Figure 8C), a known oncogene (26), and inhibited FGFR1 mRNA in A549 cells (Figure 7A).

Nkx2-1 binding elements were present in intergenic, intronic, 5′ untranslated (5′ UTR), and upstream regions (Supplemental Figure 8). The widespread distribution of Nkx2-1 binding sites observed in the present study is consistent with other ChIP-seq analyses identifying STAT1, GATA1, and MYOD binding elements in the genome. The potential regulatory role of the widespread binding of transcription factors in chromatin looping, chromatin organization, and nuclear structure has been proposed; however, their precise biological roles remain unknown (38). To assess the functional significance of direct associations of Nkx2-1 with chromatin, we analyzed ChIP-seq locations that occurred within 10 kb of those genes that were up- or down-regulated by Nkx2-1 (Figure 6, Figure 7A, and Supplemental...
The distribution of the locations within the subregions of each gene was obtained (Figure 8D). The first intron was treated as a separate region, as it is thought to be involved in transcription control in the human genome (39). In NKX2-1–upregulated genes, 46% of NKX2-1 peaks were located upstream of the second exon, including 10 kb upstream, 5′ UTR, and the first intron. Approximately 38% of the peaks were located in the other introns. In contrast, in NKX2-1–downregulated genes, 39% of NKX2-1 peaks were located upstream of the second exon, while 43% of the peaks were located in the other introns (Figure 8D), indicative of the presence of potential inhibitory NKX2-1 regulatory sites linked more closely to regions downstream of the second exon. Binding to 3′ proximal regions, including 3′ UTR and 10 kb downstream, was similar between upregulated and downregulated genes (14% vs. 15%). NKX2-1 binding sites were not detected in the first exons.

NKX2-1 associated with canonical AP-1 binding sites. Binding sequences that were associated with NKX2-1 were analyzed to identify overrepresented motifs. As expected, NKX2-1 associated with the motif CTTG (reverse complement CAAG), as seen in the promoter of SFTPA1 (Figure 8, A and E), consistent with previous studies (40). A high-frequency association of NKX2-1 with TGAGTCA (reverse complement TGACTCA), an established binding motif for the transcription factor AP-1 (Figure 8E and Supplemental Figure 9), was identified. Among the NKX2-1–targeted genes induced in the present mucinous tumor model (Figure 6), 43% of them (13 of 30) had the AP-1 motif identified in the NKX2-1–ChIP-seq peaks (Supplemental Figure 10). AP-1 is an oncoprotein strongly associated with lung cancer (41). AP-1 is also known to activate MUC5AC through the JNK–AP-1 pathway (42, 43). NKX2-1 was associated with an AP-1 binding site in the MUC5AC promoter (Figure 8B). In order to assess the functional relevance of the association of NKX2-1 with the AP-1 binding element, an AP-1 reporter luciferase construct containing AP-1 binding elements was cotransfected with a NKX2-1 expression vector. As shown in Figure 8F, AP-1 activity in H441 human lung adenocarcinoma cells was significantly inhibited by NKX2-1. Other lung epithelial transcription factors, including NKX2-8, CEBPA, FOXA2, or FOXJ1, did not influence AP-1 activity in this assay. The
Figure 5

EGFR\textsuperscript{L858R} mice did not develop mucinous adenocarcinoma of the lung regardless of Nkx2-1 expression. (A) Number and volume of lung tumors, measured by microCT, were decreased in EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/–} (n = 19) compared with EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/+} (n = 13) mice 4 months after Dox administration. n = 16 (control). (B) Lung sections were stained with Alcian blue, MUC5AC, and MUC5B. Mucinous tumors were not observed in EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/–} or EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/+} mice. Tumor cells in lungs of EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/+} and EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/–} mice did not stain with Alcian blue or MUC5AC, whereas tumor cells in lungs of EGFR\textsuperscript{L858R};Nkx2-1\textsuperscript{+/–} mice stained with MUC5B. (C) MUC5AC mRNA was highly expressed in NKX2-1-negative KRAS mutant lung carcinoma cell lines (H2122 and A549), but not in EGFR mutant lung carcinoma cell lines. MUC5B mRNA was expressed in both KRAS mutant (H2122 and A549) and EGFR mutant (H3255) cell lines. Shown is fold induction compared with mRNA expression of H3255 cells. Results are mean ± SEM (A) and mean ± SD of triplicates for each group (C). N.D., not detectable. *P < 0.05. Scale bars: 100 μm.
inhibitory effect of NKX2-1 on FGFR1 expression was blocked by PMA, an AP-1 inducer (Figure 8G). FOSL1 (a member of the AP-1 family; also known as FRA-1) induces colony formation of A549 cells (44). NKX2-1 inhibited FOSL1-mediated colony formation in A549 cells (Figure 8H). Thus, we concluded that NKX2-1 associates with AP-1 binding elements and inhibits both AP-1–mediated activity and tumor colony formation, providing a potential mechanism by which NKX2-1, at least in part, suppreses tumorigenesis.

Discussion
While the histology and prognosis of mucinous adenocarcinoma of the lung are well defined, experimental models for studying the pathogenesis and treatment of this cancer are lacking. In the present study, we created a mouse model of pulmonary mucinous adenocarcinoma by inducing mutant Kras in the respiratory epithelium of Nkx2-1+/- mice. Consistent with findings in human mucinous adenocarcinomas, these tumors contained numerous goblet cells that stained for mucins and expressed CK7 and CK20. Characteristics of the tumor-associated goblet cells were distinct from those in nontumorigenic intestine and airways. In contrast to findings in the KrasG12D;Nkx2-1+/- mice, expression of mutant EGFR in the respiratory epithelium of Nkx2-1+/- mice did not cause mucinous tumors. Although KRAS and EGFR signaling pathways are shared, our findings indicate that the Kras mutation defines distinctive mucinous lung tumor pathology (Figure 9). Thus, our mouse model provides an experimental tool to understand the pathogenesis of mucinous adenocarcinoma.
KrasG12D;Nkx2-1+/– mice, in which continuous (or chronic) reduction of Nkx2-1 was achieved. This finding is consistent with their loss in goblet cells being associated with chronic lung diseases (4, 45). In contrast, SPDEF and FOXA3, which are normally induced during non–tumor-associated mucous metaplasia in the lung (15, 17), were not expressed in tumor goblet cells in KrasG12D;Nkx2-1+/– mice, which indicates that mucin production in tumor goblet cells was not dependent on the SPDEF/FOXA3 transcriptional program. Likewise, this transcriptional program was not associated with goblet cell metaplasia in idiopathic pulmonary fibrosis (46).

Figure 7
NKX2-1 inhibited mRNAs associated with tumorigenesis and induced those related to apoptosis. (A) mRNAs were isolated from lentiviral Nkx2-1–expressing and control A549 cells and subjected to mRNA microarray analysis. A heat map of the mRNAs is shown. Green and red denote mRNAs decreased and increased, respectively, by NKX2-1. mRNAs associated with mucus (MUC5AC, MUC5B, MUC13, and AGR2) and oncogenes (FGFR1 and CDK6) were suppressed by Nkx2-1. Nkx2-1 induced surfactant protein genes (SFTPA1 and SFTPB) and apoptotic genes (FAS and TIMP3). (B) Lentiviral Nkx2-1–expressing and control A549 cells were treated with cisplatin (final concentration, 0–20 μM). 72 hours after treatment, MTS assay was used to measure cell viability (n = 3 per group). Cisplatin treatment reduced Nkx2-1–expressing A549 carcinoma cell viability significantly more than that of control A549 cells. (C) Phase-contrast images of control and Nkx2-1–expressing A549 cells 24 hours after 20 μM cisplatin (original magnification, ×20). (D) NKX2-1 sensitized A549 cells to cisplatin-induced apoptosis. 24 hours after cisplatin treatment (20 μM), proteins were extracted from control or Nkx2-1–expressing A549 cells. Induction of cleaved PARP, an apoptosis marker, was confirmed by IB. Results are mean ± SD. *P < 0.001 vs. control.
Figure 8
Identification of NKX2-1 binding sites by ChIP-seq. (A) NKX2-1 associated with the promoter and first intron of SFTPA1 at sites that contain canonical NKX2-1 binding motifs (CAAG and CTTG). (B) NKX2-1 associated with the promoter of MUC5AC that contains an AP-1 binding motif (TGACTCA). (C) NKX2-1 associated with the first and second introns of FGFR1. (D) Distribution of peaks of NKX2-1 binding sites in genes up- or downregulated by NKX2-1. (E) Motifs present in NKX2-1 ChIP-seq peaks. (F) H441 lung adenocarcinoma cells were transfected as described in Methods. Results are presented as fold activation of light unit, normalized to β-galactosidase activity, relative to control constructs. NKX2-1 inhibited AP-1 activity in H441 cells (n = 3 per group). (G) Lentiviral Nkx2-1–expressing and control A549 cells were treated with PMA, an AP-1 inducer, at a final concentration of 10 ng/ml. FGFR1 mRNA was measured as described in Methods. PMA rescued the inhibitory effect of NKX2-1 on FGFR1 mRNA expression. (H) A549 cells stably expressing Nkx2-1, FOSL1, or both were developed using lentiviral vectors. Protein expression of NKX2-1 and FOSL1 was confirmed by IB. FOSL1-induced colony formation was inhibited by NKX2-1, as determined by soft agar assays (see Methods) performed using the stably infected cells and A549 control cells. n = 3 per group. Results are mean ± SD of biological triplicates for each group. *P < 0.05; **P < 0.01; ***P < 0.001.
Inhibitory role of NKX2-1 in mucinous adenocarcinoma of the lung.

NKX2-1 functioned in a context-dependent manner to inhibit mutant KRAS tumorigenesis. The chromosomal region of 14q13.3 that is amplified in 10% of human lung adenocarcinoma (5–7) contains MBIP, STELLAR1, SP7A3, NKX2-1, NKX2-1-AS1, NKX2-8, and PAX9 (Ensembl genome browser; http://useast.ensembl.org/index.html). The role of this amplification in pulmonary oncogenesis has been of considerable interest. Loss-of-function and gain-of-function studies in vitro implicated NKX2-1 as a potential oncogene (5–9). Recent studies using lung cancer mouse models did not support the proposed role of NKX2-1 as a tissue-specific oncogene, but rather implicated NKX2-1 as an antimetastatic factor (10, 11). Furthermore, reduced expression of Nkx2-1 induced cell proliferation and promoted carcinogen-induced thyroid adenoma in vivo (47). In the present study, NKX2-1 suppressed Kras tumorigenesis, but promoted EGER tumorigenesis, in the transgenic mouse models. In KrasLSL-G12D/p53−/− mice, NKX2-1 functioned as an antimetastatic factor (10); however, in the present study, haploinsufficiency of Nkx2-1 did not induce metastasis in either the KrasG12D or the EGERLSL mouse model in vivo (data not shown). Kras mutation in combination with p53, p16NK4A, or Lkb1 deletion leads to lung tumor metastasis in mouse models (48). Since amplification of NKX2-1 at the 14q13.3 locus is associated with a poor prognosis, whereas NKX2-1 protein levels are associated with a favorable prognosis (49), we assessed whether other genes located at the 14q13.3 locus might contribute to lung tumorigenesis in the mouse model. Expression of NKX2-1 with either Nkx2-2 or PAX9 did not induce lung tumors in transgenic mice in vivo (Supplemental Figure 5). These results are consistent with prior reports that Nkx2-2 null mice develop airway dysplasia at 1 year of age (50) and that expression of Nkx2-2 inhibits growth of some lung cancer cells in vitro (51).

Identification of NKX2-1 downstream genes involved in mucinous tumorigenesis. The multiple genome-wide gene expression analyses combined with the NKX2-1 ChIP-seq analysis identified a set of NKX2-1–targeted genes involved in mucinous tumorigenesis. RASSF9, SCARA3, and RDH10 were selectively induced in the mucinous tumor model, but not in the HDM-induced asthma model (Figure 6). These 3 genes were previously identified as NKX2-1 target genes in KrasLSL-G12D/p53−/− mice (10), which perhaps indicates that they are involved in tumor progression, but not goblet cell metaplasia/hyperplasia. Among the same set of genes, the lineage-specific transcription factors HNF4A and SOX2 were also identified as genes suppressed by NKX2-1. NKX2-1 directly associates with the promoters of HNF4A and SOX2 genes (Figure 6, Figure 7A, and Supplemental Figure 10). Tissue distribution of both HNF4A and SOX2 is distinct from that of NKX2-1. HNF4A, required for liver function, is expressed in the gastrointestinal system, liver, kidney, white adipose tissue, and pancreas, but not in normal lung, thyroid, or brain, where NKX2-1 is expressed (www.nursa.org/10.1621/datasets.02001). Both SOX2 and NKX2-1 are expressed in the respiratory tract. However, SOX2 is limited to conducting airway epithelial cells, whereas NKX2-1 is expressed in both conducting airways and the alveoli (52). NKX2-1 directly suppressed expression of HNF4A and SOX2, which in turn may influence tissue-specific cell specification. Regarding lung tumorigenesis, SOX2 has been proposed as an oncogene in squamous cell lung carcinoma (53).

In summary, haploinsufficiency of Nkx2-1 combined with KrasG12D, but not EGERLSL, caused mucinous adenocarcinoma of the lung. The tumor goblet cells expressed a transcriptional program distinct from goblet cells induced by allergen exposure or those in intestine. NKX2-1 suppressed lung tumorigenesis caused by Kras mutation, but promoted lung tumorigenesis caused by EGER mutation. ChIP-seq and mRNA microarray analysis revealed that NKX2-1 served distinct inhibitory and stimulatory roles in regulating the expression of genes involved in mucus production and lung tumorigenesis. Our results demonstrated the context-dependent role of NKX2-1 in the regulation of pulmonary adenocarcinoma, indicating that distinct approaches may be required for treatment of mucinous adenocarcinoma of the lung.

Methods

Human specimens. Pathologic tissues from mucinous (n = 6) and nonmucinous (n = 1) adenocarcinomas of the lung were obtained in accordance with institutional guidelines for use of human tissue for research purposes. See Supplemental Table 1 for patient information.

Transgenic mice and animal husbandry. Nkx2-1+/− mice were provided by S. Kimura (NIH, Bethesda, Maryland, USA; ref. 13). Transgenic mice bearing [tetO]-EGFRLSL (18) were obtained from the National Cancer Institute Mouse Repository. Transgenic mice bearing Sgfl1a-ltTA, [tetO]-Kras(G12D) and [tetO]-Flag–Nkx2-1 were generated previously (4, 12). Transgenic mice bearing [tetO]–NKX2-8 (human) and [tetO]–PAX9 (human) were generated at the Transgenic and Gene Targeting Core at Cincinnati Children’s Hospital Medical Center. Transgenic mice were provided chow containing Dox (625 mg/kg chow) beginning at 4–5 weeks of age. For urethane-induced tumorigenesis, control and Nkx2-1 transgenic mice were injected i.p. with 1 mg/g body weight of urethane once weekly for 4 consecutive weeks after Dox administration. At 16 weeks after the first urethane injection, lungs were harvested, and tumors were counted using a dissecting microscope (20). See Supplemental Methods for animal maintenance.

MicroCT imaging and tumor count and volume measurement. See Supplemental Methods.

Tissue preparation, immunohistochemistry, and immunofluorescence microscopy. Staining (H&E, Alcian blue, and immunohistochemistry) was performed using 5-μm paraffin-embedded lung sections as previously described (15). See Supplemental Methods for antibody information.

Cell lines. See Supplemental Methods.

mRNA microarray and expression analyses. RNA isolation and microarray analysis were performed as previously described (4). Differentially expressed genes were identified using a random-variance t test (54). Gene identifications were considered statistically significant if their P value was less than 0.01, false discovery rate was less than 5%, and fold change was greater than 2.0. Microarray results were deposited in GEO (accession nos. GSE40508 and GSE40584). See Supplemental Methods for Gene Ontology analysis and quantitative RT-PCR.
Immunoblot assays. See Supplemental Methods.

Transient transfection assays. See Supplemental Methods.

Treatment of A549 cells with cisplatin or PMA. See Supplemental Methods.

ChIP-seq analysis. ChIP was performed using rabbit anti–NKX2-1 antibody (catalog no. WRAB-1231; Seven Hills Bioreagents) with chromatin from NKX2-1–expressing A549 lung carcinoma cells according to the manufacturer’s protocol (catalog no. 9003; Cell Signaling Technology). ChIP-enriched DNA (10 ng) or input DNA was used for high-throughput DNA sequencing. The samples were blunt ended, A-tailed, and ligated with adaptors, according to the library preparation protocol from Illumina. DNA fragments approximately 250 bp in length were size-selected and amplified. ChIP-enriched and input DNA samples were barcoded and sequenced simultaneously for 50 cycles using Solexa/Illumina Genome Analyzer II at the University of California, Riverside. Sequenced reads (6 bp linker plus 45 bp DNA) were demultiplexed based on the 6-bp barcodes, and barcodes were removed before alignment. Alignment of sequence reads to the human reference (assembly hg19) was performed using Bowtie (55). ChIP-seq read density files were generated and viewed in the Integrative Genome Viewer (IGV; ref. 56). To determine where NKX2-1 bound to the genome, enrichment peaks were detected and subsequently mapped to the nearest annotated genes using CisGenome software (57). See Supplemental Methods for motif frequency analysis. Consensus motifs (Figure 8E and Supplemental Figure 9C) were computed using Gibbs Motif Sampler provided by CisGenome using the default parameters.

Soft agar colony formation assays. See Supplemental Methods.

Statistics. Statistical differences were determined using Student’s t test (2-tailed and unpaired) or Mann-Whitney test. The difference between 2 groups was considered significant when the P value was less than 0.05 for all tests of mouse and in vitro experiments.

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Study approval. The animal protocol was reviewed and approved by the Institutional Animal Care and Use Committee at the Cincinnati Children’s Hospital Medical Center. Human specimen analysis was approved by the ethics committees of Nagasaki Graduate School of Biomedical Sciences (permission no. 05062433-2) and Kawasaki Medical School (permission no. 255), and written informed consent was obtained from all participants before study entry.

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