Transposon Mutagenesis Screen Identifies Potential Lung Cancer Drivers and CUL3 as a Tumor Suppressor

Casey Dorr1,2,3, Callie Janik1, Madison Weg1, Raha A. Been2,4, Justin Bader5, Ryan Kang1, Brandon Ng1, Lindsey Foran1, Sean R. Landman6, M. Gerard O’Sullivan7,8, Michael Steinbach9, Aaron L. Sarver1, Kevin A.T. Silverstein9, David A. Largaespada2,10, and Timothy K. Starr1,2,10

Abstract

Non–small cell lung cancers (NSCLC) harbor thousands of passenger events that hide genetic drivers. Even highly recurrent events in NSCLC, such as mutations in PTEN, EGFR, KRAS, and ALK, are detected, at most, in only 30% of patients. Thus, many unidentified low-penetrant events are causing a significant portion of lung cancers. To detect low-penetrance drivers of NSCLC, a forward genetic screen was performed in mice using the Sleeping Beauty (SB) DNA transposon as a random mutagen to generate lung tumors in a Pten-deficient background. SB mutations coupled with Pten deficiency were sufficient to produce lung tumors in 29% of mice. Pten deficiency alone, without SB mutations, resulted in lung tumors in 11% of mice, whereas the rate in control mice was approximately 3%. In addition, thyroid cancer and other carcinomas, as well as the presence of bronchiolar and alveolar epithelialization, in mice deficient for Pten were also identified. Analysis of common transposon insertion sites identified 76 candidate cancer driver genes. These genes are frequently dysregulated in human lung cancers and implicate several signaling pathways. Culin3 (Cul3), a member of a ubiquitin ligase complex that plays a role in the oxidative stress response pathway, was identified in the screen and evidence demonstrates that Cul3 functions as a tumor suppressor.

Implications: This study identifies many novel candidate genetic drivers of lung cancer and demonstrates that CUL3 acts as a tumor suppressor by regulating oxidative stress. Mol Cancer Res; 13(8):1238–47. ©2015 AACR.

Introduction

Most lung cancers are caused by smoking, which explains the higher mutation load in lung cancer compared with most other major epithelial cancers (1). Even though individual lung cancers harbor a large number of mutations, comprehensive genetic analyses of these cancers have identified few recurrent drivers, such as activating mutations in EGFR and KRAS, inactivating mutations in TP53, and translocations affecting ALK. Except for TP53, the percentage of tumors with either one of these driver mutations is less than 25% (2, 3). Another recurrent event found in non–small cell lung cancers (NSCLC) and small cell lung cancers (SCLC) is activation of the P13K/AKT pathway (3–5), which is frequently caused by loss of PTEN (6). Because of this confusing abundance of genetic mutations and other genetic anomalies, it is difficult to pinpoint specific drivers in any given patient and many lung cancer genetic drivers have yet to be identified (7).

Mouse models have been used to confirm that these altered proteins result in increased rates of lung cancer. For example, loss of Trp53 in the lungs results in adenocarcinomas after a long latency and, if Rb is simultaneously deleted in the lungs, tumor latency is decreased and the tumor phenotype switches to SCLC (8). If loss of one or both alleles of Pten are introgressed into this model, tumor latency is reduced even further (9). Decreasing Pten protein levels in wild-type mice by introducing a hypomorphic Pten allele also results in lung cancer in 28% of mice (10). Interestingly, lung-specific deletion of Pten in mice did not result in tumors, but when combined with lung-specific activation of Kras1,10, tumor latency was significantly decreased (11).

The aim of our experiments was to discover new genetic drivers of lung cancer by performing forward genetic screens in mice using the SB DNA transposon as a mutagen in lung epithelial cells. We performed one genetic screen on a wild-type background and three additional screens using mice with predisposing mutations...
in Trp53, p19ARF, and Pten. Contrary to our expectations, the only screen that produced at least twice as many lung tumors in the experimental animals compared with controls was in mice deficient for Pten. We sequenced the tumors that arose in these mice and identified 78 common transposition insertion sites (CIS) and were able to identify 76 candidate cancer genes. Over 85% of these candidate genes have documented alterations in ten or more human lung cancers, and several have been strongly implicated as drivers of lung cancer. The three genes identified with the most transposition insertions were Serinc3, Magi1, and Nckap5. There is evidence that Serinc3 is oncogenic, while Magi1 has tumor-suppressive activities (12, 13). We performed functional tests on another of our candidate cancer genes, CUL3, and found that reducing levels of CUL3 and/or PTEN resulted in cancer phenotypes in human lung cancer cell lines. Furthermore, analysis of gene expression patterns in cells deficient for CUL3, PTEN, or both CUL3 and PTEN suggests that this phenotype may be due to alterations in the NRF2 signaling pathway.

Materials and Methods
Mice
Pten floxed mice (Pten<sup>loxP<sub>129</sub></sup>/loxP<sub>129</sub>; ref. 14) on the C57Bl6/J background were a generous gift of Pier Pandolfi (Memorial Sloan Kettering, New York, New York) and National Cancer Institute, Frederick, MD. Trp53<sup>fl<sub>01XM3</sub>/fl<sub>01XM3</sub></sup> mice [129S4-Trp53<sub>01XM3</sub>/Nci] strain 01XM3 and Trp53<sup>fl<sub>01XG7</sub>/fl<sub>01XG7</sub></sup> mice [B6.129-Cdkn2atm1Cjs/Nci] strain 01XG7 were purchased from the National Cancer Institute Mouse Repository. Both Trp53<sup>fl<sub>01XM3</sub>/fl<sub>01XM3</sub></sup> and Trp53<sup>fl<sub>01XG7</sub>/fl<sub>01XG7</sub></sup> mice were a generous gift of Adam Dupuy (University of Iowa, Iowa City, IA). Lung-specific Cre recombinase mice (Spc-Cre; ref. 16) on the ICR × FVB/n background were a generous gift of Brigid Hogan (Duke University, Durham, NC). Spc-Cre mice were backcrossed to C57Bl6/J wild-type mice > 10 generations. T2/Onc15 mice were generated as described (rosa 68; ref. 17) and backcrossed to C57Bl6/J background. Conditional Sleeping Beauty transposase mice (RosaSBaseLsL; ref. 15) and backcrossed to C57Bl6/J wild-type mice > 10 generations. T2/Onc4 mice were generated on the C57Bl6/J background as described (TG6070; ref. 18). Mice were genotyped using DNA from tail biopsies. PCR protocols and primer sequences are available in Supplementary Data. All mice protocols were approved by the University of Minnesota’s Institutional Animal Care and Use Committee.

Cells
All cell lines, except HBEC, were obtained from ATCC and the authenticity of these cell lines was verified by short tandem repeat analysis (Johns Hopkins, Baltimore, MD). Human bronchial epithelial cells immortalized with CDK4 and hTERT were provided by John Minna (UT Southwestern; Dallas, TX). Functional assays were conducted in stage II lung cancer cells A549 or H522. 293T human embryonic kidney cells were transfected with OpenBiosystems lentiviral packaging mix and transduced with lentivirus that harbors CUL3-specific shRNA sequence. Cells were transduced according to the Open Biosystems' lentivirus production protocol. To make stable CUL3 knockdown cells, CUL3-specific shRNA encoding lentivirus was used to transduce A549 or H522 cells. The cells were then grown under puromycin selection in RPMI. A549 cells with stable CUL3 knockdown, or expressing the nonsilencing control, were then transfected with SABiosciences SureSilencing shRNA plasmids for human PTEN (catalog number KH03271H) or with the negative shRNA encoding plasmid control. The cells were maintained in RPMI with 1µg/mL puromycin, and 32µg/mL hygromycin at 37°C, and 5% CO<sub>2</sub>.

Histopathology and IHC
Formalin-fixed tissues were embedded in paraffin, and stained with H&E. IHC for CC10 was performed using a goat anti-mouse C-terminus peptide CC10 polyclonal antibody (Santa Cruz Biotechnology) with detection by a horseradish peroxidase (HRP) Polymer Kit (Biocare) using diaminobenzidine (DAB) as the chromogen. IHC for SPC was performed using a rabbit anti-proSP-C polyclonal antibody (Millipore); detection was with a rabbit EnVision+ HRP-polymer kit (Dako) as DAB as the chromogen. IHC for SB was performed using goat polyclonal anti-SB (R&D Systems). More details are provided in Supplementary Methods.

Transposon insertion analysis
Detailed methods are available in Supplementary Materials. Briefly, LM-PCR was performed on DNA isolated from tumors. PCR ampiclons were sequenced using the Illumina GAIIx sequencing platform. Sequences were mapped to the genome and CISs were identified using the TAPDANCE bioinformatics pipeline.

Western blotting
Cells were lysed in standard RIPA buffer and loaded onto 12.5% SDS–PAGE gels. Lysates were transferred to PVDF membranes and blocked in 5% milk TBS-T. The following primary antibodies were used: anti-CUL3 (Bethyl Labs A301-109A), anti-PTEN (138G6; Cell Signaling Technology #9559S), anti-NRF2 (D1C9; Cell Signaling Technology #8882S), anti-KEAP1 (D1G10; Cell Signaling Technology #7705S), and anti-GAPDH (14C10; Cell Signaling Technology #2118L). Goat–anti-rabbit IgG–HRP was used to detect primary antibodies (Santa Cruz Biotechnology SC-2004). HRP was detected using SuperSignal West Femto Maximum Sensitivity Substrate (Thermo Scientific, product #34096) and visualized using a FluorChemE imager (Protein Simple). Densitometry was measured using ImageJ software.

Cell proliferation assay
Cell proliferation was measured using an MTS assay for 5 to 6 days (Cell Titer 96 Aqueous One Solution Cell Proliferation Assay, Promega). Cells (3,500) were plated in 96-well plates and OD490/650 levels were measured after 1 hour using a spectrophotometer (Epoch BioTek). Data were analyzed using GraphPad Prism.

 Colony formation assay
Cells were grown in between layers of 0.5% Sea Plaque Low Melt Agarose (Lonza Cat. # 50101) in RPMI supplemented with 10% FBS, penicillin, streptomycin, and antibiotic selection for 3 weeks. Colonies were fixed, stained with crystal violet, and imaged. Colony counts were analyzed using ImageJ software.
Wild-type recombinase Rosa26-LsL-SB11 transposase allele (aMedian survival of wild-type mice was not determined because the majority lived longer than the endpoint of 1.5 years.

Lung tumor penetrance and median survival in four SB screens consisted of the following three alleles: (i) a conditional SB11 transposase enzyme (Rosa26-LsL-SB11; refs. 15, 19); (ii) a Cre-recombinase cDNA driven by the Surfactant Protein-C promoter (Spc-Cre; ref. 16); and (iii) a concatamer of oncogenic transposons (T2/Onc; refs. 17, 18; Supplementary Fig. S1A–S1C). In these mice, SB mutagenesis occurs in lung epithelial cells because SB11 transposase enzyme is activated by the lung-specific Cre recombinase (Supplementary Fig. S2). Control mice consisted of littermates with two of the three alleles. We also conducted three additional screens using the same three alleles introgressed into additional screens using the same three alleles introgressed into mice, except in one strain, there were roughly 25 copies of the transposon linked as a concatamer and resident on chromosome 15 (T2/Onc(15); ref. 17), whereas the second strain contained approximately 215 copies of the transposon as a concatamer on chromosome 4 (T2/Onc(4); ref. 18). The difference in lung tumor penetrance between these two experimental lines was 23% for T2/Onc(4) and 37% for T2/Onc(15). Of the three control groups, the two with wild-type Pten had a tumor penetrance of 3% for T2/Onc(4) and 4% for T2/Onc(15), whereas the control group with loss of Pten had an intermediate penetrance of 11% (Table 2). Interestingly, we expected a higher penetrance in the experimental group with the larger number of transposons (T2/Onc(4)), but this group actually had a lower penetrance than the low-copy group (T2/Onc(15)). It is possible that the higher number of transposon insertions was detrimental to cell survival, and thus resulted in a lower tumor penetrance. Survival correlated with the presence or absence of Pten, as the Pten WT control group became moribund at the same rate as the experimental group (Pten WT and SB mutagenesis; Fig. 1). Upon histologic examination, both the Pten WT control group and the experimental group had extensive bronchial epithelial hyperplasia, which may be the reason why morbidity was similar between these two groups. There was no difference in survival between the mice carrying the different transposon alleles (Supplementary Fig. S3).

Because of the small size of the tumors that developed (Supplementary Fig. S4), in most cases, the entire tumor was excised and used for extracting DNA. In those cases where microscopic examination of lung lesions was performed, a spectrum of lesions was observed, including bronchiolar and alveolar epithelial

The experimental genotype, number of mice, lung tumor penetrance, and median survival in the four screens are displayed in Table 1. Potential neoplasms in other tissues were also detected at necropsy (Supplementary Table S1), which may have resulted from leaky or non-lung-specific expression of the Spc-Cre transgene. Lung tumor penetrance in the wild-type, p19 and p53 screens, was not substantially higher in the experimental groups compared to the control groups, so we did not analyze these tumors. Instead, we focused on tumors arising in the Pten pre-disposed background, as there was a large difference in penetrance between all controls (6%) and experimental animals (29%).

The Pten cohort consisted of five different genotypes (Table 2). All animals were homozygous for the Pten WT knock-in allele and contained the conditional SB11 transposase. Because SB transposon mobilization in some cases is biased toward reinsertion into the donor chromosome, we used two strains of T2/Onc transgenic mice. In one strain, there were roughly 25 copies of the transposon linked as a concatamer and resident on chromosome 15 (T2/Onc(15); ref. 17), whereas the second strain contained approximately 215 copies of the transposon as a concatamer on chromosome 4 (T2/Onc(4); ref. 18). The difference in lung tumor penetrance between these two experimental lines was 23% for T2/Onc(4) and 37% for T2/Onc(15). Of the three control groups, the two with wild-type Pten had a tumor penetrance of 3% for T2/Onc(4) and 4% for T2/Onc(15), whereas the control group with loss of Pten had an intermediate penetrance of 11% (Table 2). Interestingly, we expected a higher penetrance in the experimental group with the larger number of transposons (T2/Onc(4)), but this group actually had a lower penetrance than the low-copy group (T2/Onc(15)).

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### Results

SB Mutagenesis drives lung tumor formation

We conducted four forward genetic screens in mice to identify genes involved in lung cancer. Our screen in wild-type mice consisted of the following three alleles: (i) a conditional SB11 transposase allele (Rosa26-LsL-SB11; refs. 15, 19); (ii) a Cre-recombinase cDNA driven by the Surfactant Protein-C promoter (Sp-Cre; ref. 16); and (iii) a concatamer of oncogenic transposons (T2/Onc; refs. 17, 18; Supplementary Fig. S1A–S1C). In these mice, SB mutagenesis occurs in lung epithelial cells because SB11 transposase enzyme is activated by the lung-specific Cre recombinase (Supplementary Fig. S2). Control mice consisted of littermates with two of the three alleles. We also conducted three additional screens using the same three alleles introgressed into mice with the following predisposing alleles: (i) p19ARF+/−/− (ii) p53+/−/−/− (Supplementary Fig. S1D–S1F). These mice are referred to as p19, p53, and Pten. The p19ARF+/−/− allele is a germline knockout. The initial report describing these mice found that roughly 30% of these mice develop tumors within 6 months and the majority of these tumors are blood tumors or sarcomas (20). The p53+/−/−/− allele is a dominant negative p53 allele that is not expressed in cells unless Cre recombinase is present. Therefore, these mice are heterozygous for p53, except in Cre-expressing cells. In the absence of Cre, these mice develop tumors due to p53 heterozygosity; while in animals expressing a germline Cre, the tumor spectrum changes slightly to favor carcinomas (21). Pten+/−/−/− mice lose expression of Pten in cells expressing Cre recombinase and this allele had been used to study brain and prostate cancer (14, 22).

The experimental genotype, number of mice, lung tumor penetrance, and median survival in the four screens are displayed in Table 1. Potential neoplasms in other tissues were also detected at necropsy (Supplementary Table S1), which may have resulted from leaky or non-lung-specific expression of the Spc-Cre transgene. Lung tumor penetrance in the wild-type, p19 and p53 screens, was not substantially higher in the experimental groups compared to the control groups, so we did not analyze these tumors. Instead, we focused on tumors arising in the Pten pre-disposed background, as there was a large difference in penetrance between all controls (6%) and experimental animals (29%).

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### Table 1. Lung tumor penetrance and median survival in four SB screens

<table>
<thead>
<tr>
<th>Screen</th>
<th>Genotype</th>
<th>Exp mice with lung tumors, % (d)</th>
<th>Median survival of exp mice (d)</th>
<th>Control mice with lung tumors, % (d)</th>
<th>Median survival of ctrl mice (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td>Rosa26-LsL-SB11 × T2/Onc × Spc-Cre</td>
<td>12 (95)</td>
<td>6 (99)</td>
<td>303</td>
<td>29 (62)</td>
</tr>
<tr>
<td>p19</td>
<td>Rosa26-LsL-SB11 × T2/Onc × Spc-Cre × p19ARF+/−/−</td>
<td>17 (55)</td>
<td>303</td>
<td>14 (87)</td>
<td>443</td>
</tr>
<tr>
<td>p53</td>
<td>Rosa26-LsL-SB11 × T2/Onc × Spc-Cre × p53+/−/−/−/−</td>
<td>22 (176)</td>
<td>6 (94)</td>
<td>303</td>
<td>326</td>
</tr>
<tr>
<td>Pten</td>
<td>Rosa26-LsL-SB11 × T2/Onc × Spc-Cre × Pten+/−/−/−/−</td>
<td>29 (62)</td>
<td>419</td>
<td>6 (94)</td>
<td>415</td>
</tr>
</tbody>
</table>

*Median survival of wild-type mice was not determined because the majority lived longer than the endpoint of 1.5 years.

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hyperplasia attributable to proliferation of club cells, primary pulmonary adenoma and adenocarcinomas (Fig. 2). The diagnosis of pulmonary adenomas and adenocarcinomas was based on the criteria recommended by the Mouse Models of Human Cancers Consortium (23), and expression of prosurfactant on the criteria recommended by the Mouse Models of Human Cancers Consortium (23), and expression of prosurfactant fi
t in the broad category of human non–small cell lung carcinomas. In addition to primary pulmonary lesions, several mice had metastatic adenocarcinomas in the lung of diverse primary origins (e.g., thyroid, mammary, preputial etc., or of undetermined origin; Supplementary Fig. S5). CIS data were generated from single, discrete tumors that had a gross appearance similar to those lesions diagnosed as primary pulmonary adenomas or adenocarcinomas; however, we cannot completely exclude the possibility that our CIS data may include some data that were derived from one or more metastatic tumors.

CIS analysis identifies candidate lung cancer genes

To identify the genes driving tumorgenesis in our mice, we performed linker-mediated PCR (LM-PCR) using DNA isolated from 23 lung tumors from 13 mice. We then subjected the LM-PCR amplicons to high-throughput sequencing and analyzed the sequences using the TAPDANCE bioinformatics pipeline that we developed (24). Over 18 million sequences were assigned to the 23 tumors based on the barcodes attached during the LM-PCR process. Of these, six million mapped to non-repeat regions in the mouse genome. Combining redundant sequences and insertions that occurred within 100 base pairs of each other reduced this number to 178,028 unique 100 bp regions, or an average of approximately 7,740 regions per tumor. The depth of sequence reads using the Illumina platform allowed us to filter regions based on the number of sequence reads that mapped to the region. We reasoned that regions with only one or a few reads could either be artifacts or only present in a minority of cells, whereas regions with a larger number of reads were more likely to be present in a majority of tumor cells (25). We set a read threshold of 0.01% of total reads mapping in a single tumor for each region. Out of the 178,028 nonredundant regions, 27,077 unique regions met the threshold (Supplementary Table S2).

In previous screens, we noted that transposon insertions mapping to the donor chromosome, where the original transposon concatamer was located, constituted up to half of all the mapped transposon insertions, a phenomenon referred to as "local hopping." In this experiment, we generated experimental mice using either the T2/Onc(4) or the T2/Onc(15) concatamers, which reside on chromosome 4 and 15, respectively. In this study, we did not see as large of a bias of insertions, with only 11% of insertions in chromosome 4 with T2/Onc(4) and 18% of insertions in chromosome 15 with T2/Onc(15). On the basis of the distribution of TA dinucleotides in the genome, the preferred SB integration site, we would expect 6% in chromosome 4 and 4% in chromosome 15. Nevertheless, to avoid this bias when determining CIS loci, we did not include insertions in these chromosomes in the analysis. After eliminating these insertions, we identified 78 CISs, or regions of the mouse genome interrupted by transposon insertions at a rate higher than expected. Manual analysis of each CIS region allowed us to identify 76 genes most likely to be affected in these regions, as three of the regions were all in the same gene, Magi1 (Supplementary Table S3). On the basis of the pattern of transposon insertions, we could also predict whether the genes acquired loss- or gain-of-function mutations (see Supplementary Methods). The majority (66%) appeared to be loss-of-function mutations, while 12% had a pattern suggestive of gain-of-function mutations. Of the 76 mouse candidate genes, 75 had human orthologs (Supplementary Table S3).

Candidate cancer genes are dysregulated in human lung cancers

To determine the relevance to human cancer, we analyzed the overlap of the 75 human CIS orthologs with various lists of human cancer genes. The current version of the Cancer Gene Census lists 522 functionally validated cancer genes (26). Nine of the CIS human orthologs overlapped with these documented cancer genes, an overlap that would not be expected by chance ($P < 0.0001$; Supplementary Table S4). The majority of cancer genes reported in the census are linked to hematopoietic cancers. To determine the specific relevance to lung cancer, we compared our CIS list to two major sources documenting somatic lung cancer mutations, The Cancer Genome Atlas (TCGA) and the Catalog of Somatic Mutations in Cancer (COSMIC). The vast majority of all annotated genes have a documented somatic mutation in human lung cancer based on these two sources (>18,000 genes in COSMIC and >17,000 genes in TCGA). If we limit our analysis to genes with at least 10 reported mutations (COSMIC = 7,209 and TCGA = 5,513), we find a significant overlap with our CIS genes [COSMIC overlap = 52 ($P$ value 5.3e–8). TCGA overlap = 44 ($P$ value 3.5e–11), Supplementary Table S4 and Supplementary Methods].

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Table 2. Lung tumor penetrance in Pten screen

<table>
<thead>
<tr>
<th>Group Genotype</th>
<th>Mice with tumors, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctrl 1 Ptenlox/lox x Rosa26-LsL-SB11 x T2/Onc(4)</td>
<td>3 (3)</td>
</tr>
<tr>
<td>Ctrl 2 Ptenlox/lox x Rosa26-LsL-SB11 x T2/Onc(15)</td>
<td>4 (26)</td>
</tr>
<tr>
<td>Ctrl 3 Ptenlox/lox x Rosa26-LsL-SB11 x Spc-Cre</td>
<td>11 (37)</td>
</tr>
<tr>
<td>Exp 1 Ptenlox/lox x Rosa26-LsL-SB11 x T2/Onc(4) x Spc-Cre</td>
<td>23 (35)</td>
</tr>
<tr>
<td>Exp 2 Ptenlox/lox x Rosa26-LsL-SB11 x T2/Onc(15) x Spc-Cre</td>
<td>37 (27)</td>
</tr>
</tbody>
</table>

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Figure 1.

Kaplan–Meier survival curves

Kaplan–Meier survival curves for two control groups (Pten$^{-/-}$ and Pten$^{+/+}$) and the experimental group (Pten$^{-/-}$ and SB). (Log-rank Mantel-Cox test $P$ values $< 0.0001$ for Pten$^{-/-}$ vs. Pten$^{+/+}$ and SB vs. Pten$^{-/-}$).
Lung cancer has one of the highest mutation rates among all types of cancer making it difficult to discern cancer-associated genetic mutations from background mutations. Factors including heterogeneity between cancer patients and differences in mutation rates within the genome due to transcription-coupled repair (27) and DNA replication timing (28) also confound analyses. Two recent large-scale genomic analyses of human lung squamous cell carcinoma (SCC; ref. 3) and adenocarcinoma (AC; ref. 2) published lists of significant amplifications/deletions, mutations, and genomic rearrangements based on exome and whole-genome sequencing. These analyses used algorithms that took into account some of the confounding factors. Our list of CIS human orthologs was significantly enriched in all three categories of genes determined in those studies to be possible drivers based on amps/dels, mutations, and rearrangements (Supplementary Table S4; P 0.001–0.018).

Pathway analysis

We used Ingenuity Pathway Analysis (Ingenuity Systems, www.ingenuity.com) to analyze canonical pathways enriched in our list of 75 CIS genes. As might be expected, the canonical pathway identified with the lowest P value was Molecular Mechanisms of Cancer (Supplementary Table S5). This association was based on seven genes (GAB2, TAB2, CREBBP, CTNNAL1, RBPF1, SMAD4, and GSK3B). Other canonical signalling pathways that were associated with these genes included the NF-κB, RANK, Integrin, and NGF pathways.

Our mouse model generates cancers by creating multiple random mutations in a single cell, as every cell contains either approximately 25 (T2/Onc(15)) or ~215 (T2/Onc(4)) transposons that can be mobilized to create mutations. We reasoned that the cancers arising in these mice are likely generated from multiple independent transposon insertions, but the frequency of each of these mutations in the different mice might not reach the level of significance required for classification as a CIS. To find combinations of insertions that may be cooperating to cause tumorigenesis, we adapted an algorithm called frequent itemset mining (29, 30). The algorithm identifies combinations of insertions that frequently co-occur in multiple tumors. These groups of genes can reach statistical significance, even though they do not individually reach significance as a CIS. All transposon insertions were associated with the nearest annotated gene and frequent itemset mining was used to determine sets of genes co-occurring in tumors from at least three different mice (Supplementary Methods). The 10 sets of genes with -Log (P value) >5 are listed in Supplementary Table S6. All of the sets were coordinately mutated in 3 separate mice and half of the sets consist of three genes, whereas the other half consisted of four genes. There were 23 unique genes included in the 10 gene sets, and only six of these reached significance as an individual CIS. The majority of these genes are associated with cancer and we propose that the mutations caused by the transposon insertions in or near these sets work together to cause tumorigenesis.

Cul3 functions as a tumor suppressor gene in human lung cancer cells

In addition to demonstrating a strong correlation between our CIS list of candidate driver genes and genes frequently disrupted in human lung cancer, it is important to demonstrate that these genes functionally act as driver genes. To this end, we choose to analyze one of the candidate drivers discovered in our screen, Culin3 (Cul3). We selected Cul3 for several reasons. First, TCGA analysis of lung SCCs identified the oxidative response pathway, specifically KEAP1/CUL3/NFE2L2, as a potential driver in this cancer (3). Second, CUL3 was mutated in 10 human lung adenocarcinomas as reported in the COSMIC database (31). Finally, we wanted to validate a “middle of the list” gene and Cul3 was identified in 25% of the mice in our screen. Approximately half of our CIS genes were identified in a larger percentage, and half in a smaller percentage of mice. On the basis of the location and orientation of the transposon insertions in the Cul3-mutant tumors (Supplementary Fig. S6), we predict that the transposon is causing a loss-of-function mutation. In humans, the protein product of CUL3 is a core scaffolding protein in an E3 ubiquitin ligase complex that includes KEAP1 and RBX1. Known substrates of this complex include NRF2 (gene name NFE2L2), IKKβ, and other proteins (32, 33). This complex is important in regulating oxidative stress and the recent TCGA analysis of lung SCC indicates that members of the complex may be disrupted in a significant percentage of these lung tumors (3).

In support of our hypothesis that Cul3 is a tumor suppressor, a trend toward reduced levels of Cul3 protein was seen in a series of cancer cell lines compared with a normal human bronchiolar epithelial cell line (HBEC; ref. 34; Fig. 3). Two of the cell lines analyzed were from patients with stage II cancer (A549 and H522) and one line was from a patient with stage IV cancer (H2030).
The mutational status of A549 and H522 has been analyzed by whole-genome sequencing (35). CUL3, PTEN, and RBX1 were wild-type in both cell lines, whereas A549 had a nonsynonymous mutation in KEAP1. Surprisingly, we found that further reduction of CUL3 levels in these lines using shRNA resulted in an increased growth rate compared with control lines (Figs. 4 and 5, \( P \) value day 5 < 0.05 both graphs). Knockdown of CUL3 in the stage IV line, H2030, did not have a significant effect on growth (data not shown). Because our mouse model was predisposed to cancer using a conditional Pten knockout allele, we generated A549 cell lines stably expressing shRNA targeting CUL3 alone, PTEN alone, or both CUL3 and PTEN (Supplementary Fig. S7). Consistent with our hypothesis that loss of CUL3 cooperates with loss of PTEN, the double knockdown cells grew faster than the control line or either of the single knockdown lines (Fig. 5, \( P \) value day 5 < 0.01).

To test the role of CUL3 and PTEN in anchorage-independent growth, we grew the cell lines in soft agar. Similar to the proliferation assay, the CUL3/PTEN double knockdown line formed the most colonies in soft agar compared with the single knockdown lines and the control line, although the difference between the CUL3 single and the double knockdown was not significant (Fig. 5).

Loss of CUL3 and PTEN activates the NRF2 signaling pathway

We measured changes in gene expression in the A549 cell strains with reduced levels of CUL3, PTEN, or both CUL3 and PTEN using the Illumina BeadArray platform. Interestingly, knockdown of PTEN resulted in changes in expression of only 11 genes (fold change > 2.0, FDR < 0.05), whereas knockdown of CUL3 caused changes in 87 genes, with the majority (59) being downregulated (Supplementary Table S7). Knockdown of both CUL3 and PTEN resulted in changes in expression of 120 genes, also with a majority (76) being downregulated.

Knockdown of CUL3 could affect many proteins regulated by ubiquitination because CUL3 is a scaffolding component of BTB–CUL3–RBX1 ubiquitin ligase complexes. The BTB protein functions as the targeting protein in this complex, and CUL3 can...
Knockdown of CUL3 and PTEN in A549 cells increases cell proliferation and anchorage-independent growth. A, Western blot analysis showing knockdown of PTEN, CUL3, or PTEN and CUL3 in A549 cells. B, Soft Agar Assay shows that knocking down both PTEN and CUL3 in A549 cells leads to increased colony formation compared with controls. In addition, the single CUL3 knockdown formed more colonies than the PTEN knockdown (t-test \( P < 0.01 \), \( P < 0.001 \), \( P < 0.0001 \)). C, MTS-based cell proliferation assay indicates that knocking down both CUL3 and PTEN leads to increased cell growth compared with knocking down CUL3 or PTEN or the negative control. CUL3 knockdown also led to increased growth compared with knocking down PTEN or the negative control (t-test \( P \) values day 5 < 0.01, all comparisons).

Discussion

It is likely that multiple agents targeting several pathways will be required to extend the survival of lung cancer patients. For this strategy to work, new targets must be identified and validated. To this end, we have developed a method of identifying novel drivers of lung cancer using SB mutagenesis in forward genetic screens in mice. Using this method, we were able to identify 76 potential lung cancer drivers. A caveat to any mouse study is that the lung tumors generated may not be genetically or physiologically equivalent to human tumors. Unfortunately, identifying driver genes in human lung cancer is particularly problematic due to the large number of background passenger mutations. If our forward genetic screen in mice were identifying bona fide drivers of human lung cancer, we would expect to find the orthologous genes mutated or altered to a significant extent in human lung cancer. Analysis of large-scale genomic datasets on human lung cancer indicates that almost 90% of the orthologous human genes we identified in our mouse screen are mutated or present in genomic regions of amplification, deletion, or rearrangement in a significant portion of human lung cancers (Supplementary Table S4). This suggests that these genes are likely drivers of human lung cancer and warrant further investigation as potential targets for therapy.

The first screen we performed was on a wild-type background, and although we saw a slight increase in lung tumor penetrance than 2-fold in the CUL3/PTEN double knockdown cells were not identified with a 2-fold change in CUL3 or PTEN single knockdown cells. The two highest upregulated genes were OSGIN1 and HMOX1, both of which are activated by the oxidative stress response (39, 40).

Further support that loss of PTEN and CUL3 synergizes to activate NRF2 signaling comes from Ingenuity Pathway Analysis (Ingenuity Systems, www.ingenuity.com). The canonical pathway identified by IPA with the lowest \( P \) value using the CUL3/PTEN gene list was the NRF2-mediated oxidative stress response pathway, while this pathway was not in the top 50 significant canonical pathways in the CUL3 list (Supplementary Tables S9 and S10).

To understand the mechanism of synergy between CUL3 and PTEN, we identified genes that were discordantly regulated when CUL3, PTEN, or CUL3/PTEN were knocked down compared with control cells. Only one gene had a greater than 2-fold change in all three comparisons that was discordant. The gene, DKK1, is a secreted inhibitor of Wnt signaling and DKK1 downregulation is associated with poor prognosis in lung cancer (41, 42). DKK1 was increased over 3-fold when PTEN was knocked down, but in CUL3 or CUL3/PTEN knockdown cells, DKK1 mRNA was decreased over 3-fold.

To measure the functional effect of CUL3 and PTEN in regulating oxidative stress, we incubated A549 control and knockdown cells with MitoSOX Red, a dye that fluoresces in response to levels of superoxide. As predicted, A549 cells with reduced levels of CUL3 and/or PTEN had significantly less fluorescence than control cells (Fig. 6, \( P < 0.005 \)). Although there was no significant difference between the three knockdown lines in three replicate experiments, the CUL3 single knockdown A549 cells consistently had the lowest amount of fluorescence. These results suggest that reduced levels of PTEN and/or CUL3 result in decreased production of superoxide, which could be protective for cancer cells.
Knockdown of CUL3 and/or PTEN in A549 cells results in reduced superoxide production. Representative brightfield (left) and red fluorescent (right, converted to grayscale) images of (A and B) A549 control cells and (C and D) A549 CUL3/PTEN knockdown cells treated with MitoSOX. E, graph of average MitoSOX fluorescence/field of view/cell comparing control cells with PTEN, CUL3, and CUL3/PTEN knockdown A549 cells. **, t test P < 0.01; ***, t test P < 0.001.

Figure 6.

over controls (17% vs. 12%), we believe that the SB system did not provide enough mutations per cell to actively accelerate lung tumorigenesis. To overcome this, we decided to use mice with common predisposing mutations for lung cancer. Interestingly, we found the highest lung tumor penetrance in mice with conditional ablation of Pten in the lungs, whereas mice with a conditional dominant negative Tp53 or a germline loss of p19ARF had lung tumor rates similar to controls. It is possible that p19 and p53 mice would have developed more lung tumors if they survived longer (Table 1), but instead became moribund due to other neoplasms caused by Tp53 heterozygosity or germline loss of p19ARF, respectively (Supplementary Table S1). This suggests that tumor initiation is accelerated by loss of Pten, while Tp53 mutations are probably not required for the early stages of cancer formation. In previous screens using the same approach in the intestines and the liver, tumor latency was shorter than that in our study, which could be related to a slower turnover rate and lower absolute numbers of cells being targeted using the Spc promoter (43).

Three genes were identified in our screen in more than 30% of mice: Magi1, Nckap5, and Serinc3. MAGI1 is a scaffold protein that plays a role in maintaining tight junctions in epithelial cells. There is evidence that MAGI1 may be playing a role in human lung cancer, as there are more than 10 patient samples with mutations in MAGI1 in both the COSMIC database and TCGA datasets (Supplementary Table S4). Furthermore, whole-genome sequencing revealed a genomic rearrangement in MAGI1 in a human lung cancer (2). SERINC3 belongs to a family of proteins that have the ability to incorporate serine into lipid membranes. On the basis of the pattern of transposon insertions in our screen, we predict that Serinc3 is being activated in the mouse tumors (Supplementary Table S3). Supporting the hypothesis that SERINC3 is an oncogene, overexpression in rat fibroblast cells increased their resistance to apoptosis and enhanced their tumorigenicity in a xenograft model (12). Similar to MAGI1, SERINC3 is mutated in more than 10 lung cancer patients in COSMIC (Supplementary Table S4) and was found at a rearranged genomic locus (2). Relatively little is known about the SH3-domain containing NCKAP5, except that mutations are found in patients with melanoma (44). On the basis of the results of our mouse screen, the known biochemical function of these proteins, and their presence in human tumor genomes, we believe further study is warranted.

New approaches are being developed to mine transposon insertion data to find combinations of genes that cooperate in tumorigenesis (24, 45, 46). We used a form of frequent itemset mining to identify sets of genes that are recurrently mutated in more than one mouse tumor (47). Using this method, we identified 10 sets of genes that were mutated in three different mice [−Log(P value) > 5.0; Supplementary Table S6]. There were 20 annotated protein-coding genes identified in these ten gene sets and all 20 are associated with cancer (www.ingenuity.com), whereas 15 have been functionally identified as tumor suppressors or oncogenes (CADM2, CDH6, CNTNAP5 CUX1R1, FOXA2, GRB14, LRLP1B, PSME4, ROCK1, SERINC3, SOCS6, SVIL, TCF4, and WNK1). Interestingly, nine out of ten of the gene sets included at least one member with a demonstrated functional role in cell adhesion (Svil, Cntnap5a, Cadm2, Cdh8, Flt2, Foxa2). In addition to cell adhesion, the majority of these gene sets include a gene that protects from apoptosis and enhances tumorigenicity (Serinc3; ref. 12). Each gene set also typically contained a gene that functions in a signaling pathway known to be important in cancer. Examples include, Socs6 regulating STAT signaling, Magi3 regulating PTEN signaling, Wnk1 regulating WNT signaling, and Soil regulating p53 signaling. To prove these genes function cooperatively will require simultaneous alterations in their expression levels. Once validated, the findings could be used to design combinations of targeted therapies attacking the cooperating pathways.

To functionally validate one of our candidate CIS genes, we used shRNA to decrease CUL3 expression in stage II lung cancer cell lines and demonstrated that these cells grew faster and were able to form more colonies in soft agar than control cells (Figs. 4 and 5). We analyzed gene expression patterns in A549 human lung cancer cell lines with CUL3, PTEN, or both CUL3 and PTEN knocked down. This analysis indicated that the NRF2 oxidative...
stress pathway is activated in CUL3/PTEN double knockdown cells, which could explain how these cancer cells are able to withstand the strong oxidative stress generated in cancer. We also measured the effect of knocking down CUL3 and PTEN in the human lung cancer cell line and noted a significant decrease in the production of reactive oxygen species in cells with reduced CUL3 and PTEN. Our results indicate that loss of CUL3 and PTEN may synergize to produce some phenotypes, including proliferation (Fig. 5C) and oxidative stress gene expression regulation, while other phenotypes, including anchorage-independent growth (Fig. 5B) and superoxide production (Fig. 6) do not demonstrate a synergistic effect in the double knockdown.

In conclusion, this study has identified a large number of potential genetic drivers of lung cancer. Furthermore, we have shown that loss of CUL3 and PTEN may be driving tumorigenesis by activating the NRF2 oxidative stress pathway.

Disclosure of Potential Conflicts of Interest

D. Largaespada has ownership interest (including patents) and is a consultant/advisory board member for Discovery Genomics, Inc. No potential conflicts of interest were disclosed by the other authors.

Authors’ Contributions

Conception and design: C. Dorr, D. Largaespada, T.K. Starr
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): C. Dorr, C. Janik, M.T. Weg, R.A. Been, R. Kang, B. Ng, L. Foran, T.K. Starr
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): C. Dorr, S.R. Landman, M.G. O’Sullivan, A.L. Sarver, T.K. Starr
Writing, review, and/or revision of the manuscript: C. Dorr, M.T. Weg, S.R. Landman, M.G. O’Sullivan, M. Steinbach, K.A.T. Silverstein, T.K. Starr
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): C. Dorr, R.A. Been, J. Bader, T.K. Starr
Study supervision: C. Dorr, R.A. Been, D. Largaespada, T.K. Starr

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