SOX2 and p63 colocalize at genetic loci in squamous cell carcinomas

Hideo Watanabe,1,2,3 Qiuping Ma,1 Shouyong Peng,1,2 Guillaume Adelmant,4,5 Danielle Swain,1 Wenyu Song,1 Cameron Fox,1 Joshua M. Francis,1,2,3 Chandra Sekhar Pedamalulu,1,2 David S. DeLuca,2 Angela N. Brooks,1,2 Su Wang,6 Jianwen Que,7 Anil K. Rustgi,8 Kwok-kin Wong,1,9 Keith L. Ligon,1,10 X. Shirley Liu,1,6,11 Jarrod A. Marto,4,5 Matthew Meyerson,1,2,3,10 and Adam J. Bass1,2,3,9

1Department of Medical Oncology, Dana-Farber Cancer Institute, Boston, Massachusetts, USA. 2Cancer Program, The Broad Institute of MIT and Harvard, Cambridge, Massachusetts, USA. 3Center for Cancer Genome Discovery, Dana-Farber Cancer Institute, Boston, Massachusetts, USA. 4Department of Biological Chemistry and Molecular Pharmacology, Harvard Medical School, Boston, Massachusetts, USA. 5Department of Cancer Biology and Blais Proteomics Center, Dana-Farber Cancer Institute, Boston, Massachusetts, USA. 6Department of Biostatistics and Computational Biology, Dana-Farber Cancer Institute and Harvard School of Public Health, Boston, Massachusetts, USA. 7Division of Gastroenterology, Department of Medicine, Abramson Cancer Center, University of Pennsylvania Perelman School of Medicine, Philadelphia, Pennsylvania, USA. 8Department of Medicine and 9Department of Pathology, Harvard Medical School, Boston, Massachusetts, USA. 10Center for Functional Cancer Epigenetics, Dana-Farber Cancer Institute, Boston, Massachusetts, USA.

The transcription factor SOX2 is an essential regulator of pluripotent stem cells and promotes development and maintenance of squamous epithelia. We previously reported that SOX2 is an oncogene and subject to highly recurrent genomic amplification in squamous cell carcinomas (SCCs). Here, we have further characterized the function of SOX2 in SCC. Using ChIP-seq analysis, we compared SOX2-regulated gene profiles in multiple SCC cell lines to ES cell profiles and determined that SOX2 binds to distinct genomic loci in SCCs. In SCCs, SOX2 preferentially interacts with the transcription factor p63, as opposed to the transcription factor OCT4, which is the preferred SOX2 binding partner in ES cells. SOX2 and p63 exhibited overlapping genomic occupancy at a large number of loci in SCCs; however, coordinate binding of SOX2 and p63 was absent in ES cells. We further demonstrated that SOX2 and p63 jointly regulate gene expression, including the oncogene ETV4, which was essential for SOX2-amplified SCC cell survival. Together, these findings demonstrate that the action of SOX2 in SCC differs substantially from its role in pluripotency. The identification of the SCC-associated interaction between SOX2 and p63 will enable deeper characterization the downstream targets of this interaction in SCC and normal squamous epithelial physiology.

Introduction

More than 1 million people worldwide die each year from squamous cell carcinomas (SCCs), and there is a paucity of targeted therapies for these diseases (1). While these tumors emerge from various epithelial tissues, certain features are commonly seen across these tumors regardless of origin, including highly recurrent amplifications involving chromosome 3q. We previously investigated 3q amplifications in lung and esophageal SCCs and found in both variants that the focus of amplification lies at the locus of the developmental transcription factor SOX2, which we further demonstrated to serve as an essential SCC oncogene (2). SOX2 amplification and oncogenicity have since been reported in a spectrum of SCCs (3–8) and, more recently, small-cell lung cancer (9). The most comprehensive SCC genomic characterization effort to date, The Cancer Genome Atlas (TCGA) lung SCC study, identified high-level amplification/overexpression of SOX2 in 21% of tumors, the third most frequent genomic alteration after inactivation of TP53 and CDKN2A (10).

Despite the strong genomic evidence, the functional rationale for recurrent SOX2 amplifications in SCCs has not been established. SOX2 is largely studied in the context of pluripotency, as it is essential for ES cells and is able to cooperatively induce differentiated cells to become pluripotent stem cells (11). Because of this role in pluripotency, overexpression of SOX2 has been widely speculated to contribute to carcinogenesis by imparting upon cells stem-like properties, thus leading to the development of cancers characterized by aggressive clinical behavior and poor differentiation status (12–14). Indeed, we reported an expression signature of “ES cell–like” to be enriched in lung SCCs with higher SOX2 expression signature (2).

However, the hypothesis that oncogenic roles of SOX2 recapitulate its actions in pluripotency would not explain the preferential amplification of SOX2 in SCCs as opposed to adenocarcinomas (15). The predilection for SOX2 amplifications in SCC suggests that its contribution to SCC may reflect activities specific to the squamous epithelial lineage. Indeed, SOX2 has been recently noted to play essential roles in the development of squamous epithelial lineage and, in the adult, to mark precursor populations of both the esophagus and the large airways (16, 17). Therefore, it is plausible that SOX2’s actions in SCC reflect this lineage-specific program.

While it may appear paradoxical that SOX2 is essential for pluripotency, yet also regulates the development and maintenance of a specific developmental lineage, these distinct SOX2 actions may follow its ability to act jointly with distinct cofactors. SOX2...
SOX2 genomic occupancy in SCC cells is distinct from that in ES cells. (A) Correlation matrix depicting pairwise comparisons of identified SOX2 binding peaks in the 3 SOX2-amplified SCC lines and in the ES cell line H9. Color scale represents degree of correlation (red, positive; blue, inverse). (B) Appearance of OCT4 DNA binding motif, plotted around the SOX2 motif near the summit of SOX2 binding peaks in the H9 ES cell line and in the 3 SCC lines. The OCT4 motif was highly enriched within 10 bp from the SOX2 motif in SOX2 peaks in H9 cells, but not in the SCC lines. (C) OCT4 protein expression in H9 ES cells and the 3 SCC lines. OCT4 expression was not detectable in any of the SCC lines by immunoblots.

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belongs to a family of factors that largely bind to DNA as a heterodimer, typically with other transcription factors (18). Distinct SOX2 heterodimeric partners have been found in different lineages, such as SOX2-OCT4 pairing in ES cells (19, 20) and SOX2-BRN2 pairing in the neural lineage (21). However, unique SOX2 dimerization partners or protein complexes have not been identified in normal squamous epithelia or in SCC. We hypothesized that evaluating the genome-wide occupancy profile of SOX2 in SCCs compared with ES cells would enable us to identify the extent to which the actions of SOX2 in SCC recapitulates its roles in pluripotency. Furthermore, to the extent that SOX2’s genomic localization differs from ES cells, we hypothesized that identification of novel SOX2 collaborating transcription factors in SCC may allow us to begin to characterize its mechanisms of action in these deadly cancers.

Results

Genomic occupancy of SOX2 in SCC cells is distinct from that in ES cells. To compare SOX2’s genomic occupancy in SOX2-amplified SCCs and in ES cells, we performed ChIP-seq using an antibody against endogenous SOX2 in the esophageal SCC cell lines KYSE70 and TT and in the lung SCC line HCC95, all of which had genomic amplification at the SOX2 locus (Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI71545DS1), as well as in H9 human ES cells, in which SOX2 dimerizes with OCT4. Peaks of SOX2 binding were identified in each sample relative to input DNA using MACS algorithm (22). We confirmed strong enrichment of the presence of consensus SOX2 binding motifs in both SCC and ES cells (Supplemental Figure 1B) as well as a high degree of overlap (40.2%) between previously reported SOX2 occupancy in H1 ES cells (23) and our data from H9 ES cells (Supplemental Figure 1C). We then compared SOX2 binding peaks pairwise in these cells and found they were more similar across all 3 SCC cell lines — even between lines of lung and esophageal origin — than between the ES cells and any SCC cell line (Figure 1A). In addition, we found that overlaps of SOX2 occupancy in these 3 SCC cell lines with the published SOX2 occupancy in H1 ES cells were much less (4.9%–9.1%) than the H9 ES cells’ overlap with the H1 line (Supplemental Figure 1C).

It has been hypothesized that SOX2 and OCT4 may collaborate in cancers, where SOX2 acts as an oncogene (24). Therefore, we evaluated the presence of OCT4 motifs around the SOX2-occupied regions in the data from SCC and ES cells. As expected, we observed strong enrichment of OCT4 motifs immediately adjacent to the SOX2 motif near the peak center in ES cells (Figure 1B). Conversely, OCT4 motifs were not enriched at SOX2-occupied loci of the SCC cell lines (Figure 1B), which suggests that one or more different SOX2 partners exist in SCC. In fact, we found no detectable expression of OCT4 protein in the SCC lines (Figure 1C), which suggests that factors other than OCT4 act with SOX2 in SCC.

SOX2 interactome in chromatin of SCC cells includes p63 protein. To identify potential novel SOX2-interacting proteins in SCC, we performed tandem affinity purification (TAP) followed by liquid chromatography–tandem mass spectrometry (LC-MS/MS) in the 3 SOX2-amplified SCC cell lines uniformly expressing FLAG-HA–tagged SOX2 (FLAG-HA-SOX2) at near-physiological levels (Figure 2, A and B, and Supplemental Figure 2, B and C). To identify SOX2’s interacting partners in the context of DNA binding, we performed TAP from the chromatin fraction solubilized by micrococcal nuclease digestion on the insoluble fraction of isolated nuclei (Figure 2A, Supplemental Figure 2C, and Supplemental Table 1). We identified a subset of 45 SOX2-interacting proteins common to all 3 cell lines (Supplemental Figure 2D), 19 of which were previously identified as pluripotency-associated factors (25–27). We also found that SOX2 in SCCs was associated with members of the NuRD complex similar to protein complexes purified from neural stem cells (Figure 2A and ref. 28). These observations suggest that certain SOX2 functions may be similar across cell lineages.
Conversely, we reasoned that the novel subset of 26 SOX2 interactors, including 14 transcriptional regulators unique to SCCs (Figure 2A and Supplemental Figure 2D), may dictate lineage-specific functions. Among them, p63 (encoded by TP63) was estimated to be the most abundant transcription factor associated with SOX2 (Figure 2A). Moreover, inspecting data from the lung SCC TCGA project, we found that of the 14 transcriptional regulators, mRNA expression of TP63 showed the most significant positive correlation with SOX2 expression ($r = 0.629$; Figure 3A and Supplemental Table 2). In fact, the TP63 locus is frequently coamplified with SOX2 (2) and was coamplified in the 3 SCC cell lines used in this study (Supplemental Figure 1A). Expression of both SOX2 and TP63 correlated with copy number status in lung TCGA dataset (Supplemental Figure 3A). p63 is well recognized as a master squamous regulator and is the primary marker used to clinically diagnose SCCs (29). In normal squamous epithelia, SOX2 and p63 are coexpressed in the proliferative basal cell layer (6). In the large airways, SOX2 and p63 both mark a putative stem cell in normal physiology (30, 31). Based on the frequent coexpression of SOX2 and p63 and the biologic plausibility of this putative interaction, we pursued this candidate interaction in functional and mechanistic studies.

SOX2 interacts with ΔNp63α, and both are essential for SCC growth. The predominant p63 isoform expressed in the squamous basal layer lacks the full aminoterminal domain and is referred to as ΔNp63α. ΔNp63α may help maintain the proliferative potential of basal cells and is necessary for epithelial stratification (32, 33). As in basal cells, we found that the predominant isoform of p63 in the 3 SCC cell lines was ΔNp63α (Supplemental Figure 3B). Prelimi-
SOX2 associates with p63 in SCC. (A) Gene expression of SOX2 and TP63 in lung SCCs from TCGA. \( r = 0.629; P = 1.02 \times 10^{-9} \). (B) SOX2-p63 interaction, shown by co-IP of p63 using an antibody against endogenous SOX2 in KYSE70 cells. (C) Co-IP of SOX2 with FLAG-tagged ΔNp63α expressed in 293T cells. IPs by FLAG were immunoblotted with antibodies against SOX2 and p63. (D) Direct physical binding of SOX2 and GST-ΔNp63α in GST pulldown assay. Top: Expression of SOX2 protein in 20% of input and GST-ΔNp63α bound proteins, detected via immunoblotting with a SOX2 antibody. Bottom: GST and GST-ΔNp63α expression, assessed by Coomassie blue staining.

Figure 3

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nary evidence suggested a direct physical interaction of SOX2 and p63, obtained by co-IP of p63 with an antibody against endogenous SOX2 (Figure 3B); additional support for p63 as the immunoprecipitated protein was shown by co-IP after shRNA-mediated suppression of TP63 (shTP63; Supplemental Figure 3C). In addition, IPs with anti-FLAG antibody in 293T cells that were cotransfected with SOX2 and FLAG-tagged ΔNp63α were found by immunoblotting to contain SOX2 (Figure 3C), further supporting a physical interaction between the proteins upon ectopic expression. An in vitro assay, pulldown with GST-ΔNp63α, showed direct binding of SOX2 and ΔNp63α under these conditions (Figure 3D), which suggests that the potential physical interaction between these factors may not be necessarily mediated by DNA or other factors.

To determine the requirement for ΔNp63α expression for growth of SOX2-amplified SCC cells that predominantly express the ΔNp63α isoform, we tested KYSE70 cells with 3 doxycycline-inducible (Dox-inducible) TP63-directed shRNAs — 2 of which target all TP63 isoforms, including ΔNp63α (shTP63), and 1 of which specifically targets only the ΔNp63α isoform (shΔNp63) — relative to shLucZ. Suppression of TP63 reduced growth of the KYSE70 cells (Figure 4A), similar to suppression of SOX2 with Dox-inducible SOX2-directed shRNAs (shSOX2; Figure 4B), indicating that both SOX2 and ΔNp63α are essential for maintaining cell growth. Furthermore, combinato-
same direction. By integrating these data into ChIP data, we found that genes whose expression was downregulated by suppression of either SOX2 or TP63 in KYSE70 cells were significantly enriched with the genes near our high-confidence SOX2-p63–co-occupied regions \( (P = 6.35 \times 10^{-6} \text{ or } P = 7.66 \times 10^{-7}) \), respectively, and genes whose expression was downregulated by suppression of both SOX2 and TP63 were also significantly enriched with the presence of SOX2 and p63 co-occupancy \( (P = 2.04 \times 10^{-4}) \) (Supplemental Table 3). We next identified genes whose expression changed \( >1.5\text{-fold} \) relative to control after TP63 suppression as well as after SOX2 suppression. We then overlapped this gene list with 2,523 genes with transcriptional start sites \( (\text{TSSs}) \) within 50 kb of one of the 2,426 high-confidence SOX2-p63–co-occupied peaks (Supplemental Table 4). We identified 93 genes that were commonly downregulated, and another 95 that were commonly upregulated, after SOX2 and TP63 suppression (Figure 6B, Supplemental Figure 6A, and Supplemental Table 4). We identified 93 genes that were commonly downregulated, and another 95 that were commonly upregulated, after SOX2 and TP63 suppression (Supplemental Figure 6B). How - ever, ectopic expression of p63 was not itself sufficient to rescue ETV4, as they were diminished by shRNA-mediated suppression of ETV4 \( (\text{shETV4; Figure 7, C and D, and Supplemental Figure 6B}) \).

We identified that 2 loci near the ETV4 TSS were co-occupied by SOX2 and p63 (Figure 7A), at positions approximately 3 kb upstream and approximately 1 kb downstream of the TSS. Suppression of p63 by shTP63 led to decreased occupancy of SOX2 at the above-described positions in the ETV4 locus, as measured by ChIP-PCR (Figure 7B), which suggests that SOX2 binding to these regions depends on simultaneous binding of p63. Furthermore, consistent with previous reports \( (35) \), proliferation and anchorage-independent growth of SCC cell lines were dependent on ETV4, as measured by Dox-inducible shRNAs — shTP63 (1) and shTP63 (2) target all TP63 isoforms, whereas shΔp63 specifically targets ΔNp63α — is plotted as the ratio of Dox-treated to non–Dox-treated cell viability over time after seeding. Immunoblots show expression of p63 and β-actin as loading controls before and after Dox treatment. (B) Effect of shSOX2 on viable cell numbers over time. Growth of KYSE70 cells after suppression of SOX2 or LacZ by Dox-inducible shRNAs is plotted as in A. Immunoblots for SOX2 and β-actin are shown. (C) Effect of SOX2 and TP63 double suppression compared with suppression of each gene on viable cell numbers over time. Growth of KYSE70 cells and immunoblots after suppression of both SOX2 and TP63 by shSOX2 construct with puromycin resistance cassette and shTP63 construct with neomycin resistance as well as suppression of either SOX2 or TP63 alone are plotted as in A. Values are mean ± SD of cells plated in 6 wells. \( *P < 0.0001, \text{sum-of-squares F test for curve fitting.} \)

For those 93 genes with evidence for positive regulation by p63 and SOX2, we next evaluated their mRNA expression across primary SCCs from the lung SCC TCGA \( (10) \) and their correlation with SOX2 mRNA expression, with a focus on 5 genes present in the Cancer Gene Census \( (http://cancer.sanger.ac.uk/cancergenome/projects/census/#cl_analysis) \) (Figure 4C). Among them, ETV4, a member of the Ets family of transcription factors, was notable for both its correlation with SOX2 in primary SCCs and its previously reported role in SCC pathogenesis \( (35) \), ETV4 has also been reported to be overexpressed in airway basal cells \( (31) \), thus linking it to a SOX2-p63–positive cell population. We confirmed that ETV4 transcription was dependent on expression of both p63 and SOX2 by quantitative RT-PCR after treatment with Dox to induce shRNAs for the respective genes (Figure 6D).

Discussion

SOX2 is a frequently recurrent amplified oncogene in multiple forms of SCC and has been implicated in breast and prostate carcinomas and glioblastoma \( (12–14) \). Many have hypothesized that SOX2 and OCT4 act coordinately in cancer to induce “stem-like” tumors that are poorly differentiated and demonstrate poor sur -vival \( (36–38) \). In SCCs, in contrast, SOX2 amplification is largely a positive prognostic marker \( (2, 15) \). Together with the predilec -tion for SOX2 amplification in cancers of squamous cell origin, these associations suggest that SOX2’s oncogenic role in SCC may

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In summary, our present demonstration of cooperative regulation by SOX2 and p63 of a factor essential for SCC proliferation and anchorage-independent growth supports our hypothesis that joint function of SOX2 and p63 contribute to squamous epithelial neoplasia.

SOX2 and p63 are essential for SOX2-amplified SCC cell growth. (A) Effect of TP63-specific shRNA on viable cell numbers over time. Growth of KYSE70 cells after suppression of TP63 or LacZ control by Dox-inducible shRNAs — shTP63 (1) and shTP63 (2) target all TP63 isoforms, whereas shΔp63 specifically targets ΔNp63α — is plotted as the ratio of Dox-treated to non–Dox-treated cell viability over time after seeding. Immunoblots show expression of p63 and β-actin as loading controls before and after Dox treatment. (B) Effect of shSOX2 on viable cell numbers over time. Growth of KYSE70 cells after suppression of SOX2 or LacZ by Dox-inducible shRNAs is plotted as in A. Immunoblots for SOX2 and β-actin are shown. (C) Effect of SOX2 and TP63 double suppression compared with suppression of each gene on viable cell numbers over time. Growth of KYSE70 cells and immunoblots after suppression of both SOX2 and TP63 by shSOX2 construct with puromycin resistance cassette and shTP63 construct with neomycin resistance as well as suppression of either SOX2 or TP63 alone are plotted as in A. Values are mean ± SD of cells plated in 6 wells. \( *P < 0.0001, \text{sum-of-squares F test for curve fitting.} \)
reflect its physiologic function in squamous epithelium more than its role in pluripotency.

We demonstrated that SOX2 genome-wide occupancy in SCCs of esophageal and lung origin was distinct from that in ES cells, where SOX2 functioned in cooperation with the pluripotency factor OCT4. Instead, we discovered p63 as a novel collaborative interacting partner protein of SOX2 in SCCs. Our data further suggested that the differences in SOX2 occupancy between SCC and pluripotent ES cells likely largely reflect the presence of different SOX2 partners (i.e., p63 and OCT4, respectively). SOX2 and p63 coregulated scores of genes in SCC, including the previously described squamous cell oncogene ETV4 (35), which we confirmed to be essential for SCC proliferation. In light of our demonstration that amplification and overexpression of SOX2 and TP63 could be readily used as clinical markers, it would be interesting to identify additional target genes of functional collaboration between these 2 factors that may be more relevant to translational research.

Expression of p63 is accompanied by SOX2 expression in precursor populations of both the esophagus and the large airways, and expression of both factors is downregulated during cellular maturation, which suggests they may act to maintain an immature cell state (16, 17, 39, 40). Indeed, loss of function of ΔNp63 enhances terminal maturation in stratified squamous epithelium (41). On one hand, ΔNp63α overexpression has been shown in a rat cell line to accelerate tumor growth in nude mice (42), and transgenic mice overexpressing ΔNp63α develop epidermal hyperplasia (43). Tp63 was recently shown to be required for maintenance of tumors, as inducible genetic deletion of all its isoforms led to blockade of chemically induced SCC formation in mice (44). In vivo models have shown that ectopic overexpression of ΔNp63 cooperates with oncogenic Hras to induce

Figure 5
SOX2 genomic occupancy in SCC overlaps with p63 occupancy. (A) Appearance of p63 DNA binding motifs, plotted around the SOX2 motif near the summit of SOX2 peaks in the H9 ES cell line and the 3 SCC lines. The p63 motif was highly enriched within 50 bp from the SOX2 motif in SOX2 peaks in all 3 SCC lines, but not in H9 cells. (B) p63 protein expression in H9 cells and the 3 SCC lines. p63 expression was barely detectable in H9 cells by immunoblots. (C) Heatmap showing composite signals from SOX2 and p63 ChIP-seq data in the 3 SCC lines. ChIP signal intensity is shown by red shading. Shown are SOX2-p63–co-occupied loci, high-confidence SOX2 peaks without evidence of p63 binding, and high-confidence p63 peaks without evidence of SOX2 binding.
SCCs from keratinocytes by promoting progenitor cell expansion (45). On the other hand, ectopic SOX2 in the esophageal/forestomach epithelium has been demonstrated to induce basal cell hyperplasia with loss of maturation and, in cooperation with inflammation and STAT3 activation, lead to SCCs (8). These 2 squamous factors, however, have not been previously shown to functionally collaborate. Although we have not studied normal SOX2-p63–positive precursor cells, we speculate that these factors likely interact and may coregulate gene expression in this cell population as well.

While SOX2 plays pivotal roles in ES cell and adult stem cell maintenance across a diverse array of tissues, including eye lens, neurons, gastrointestinal glands, and squamous epithelia (16, 39, 46), the roles of p63 in development appear to be confined more to stratified squamous epithelia (33). Our findings of overlapping SOX2 and p63 localization and function within squamous epithelium may explain the distinct contributions of SOX2 across multiple tissue types, indicating that SOX2 cooperates with p63 in a manner analogous to its actions with OCT4 in ES cells, BRN2 in neural stem cells, and PAX6 in the eye lens.

While our data suggest novel direct collaborative functions of SOX2 and p63 in SCCs, we also demonstrated that SOX2 may additionally cooperate with AP-1 transcription complex in SCCs independent of p63 function. AP-1 complexes have been shown to function in normal squamous epithelial development to help prevent maturation (47). The degree to which SOX2 and AP-1 may jointly act in SCC and in normal squamous epithelial tissues will need to be addressed in future studies. Similarly, SOX2 may act with other factors in SCC and squamous development.

**Figure 6**
Identification of target genes coregulated by SOX2 and p63. (A) Gene expression changes by suppression of SOX2 and of TP63 in KYSE70 cells. Cloud color represents plot density. Changes were significantly positively correlated (trend line; \( r = 0.492 \)). (B) Overlap among genes with high-confidence SOX2-p63–co-occupied loci within 50 kb from their TSS, and genes whose expression was downregulated (>1.5 fold) after suppression of SOX2 or TP63, in KYSE70 cells. See Supplemental Table 5 for the 93 genes at the intersection. (C) Correlation of expression of the 93 genes co-occupied by SOX2 and p63 and downregulated upon SOX2 and TP63 suppression with SOX2 mRNA expression from the lung SCC TCGA. Of these 93 genes within TCGA lung SCC samples with the top quartile of SOX2 expression, 5 genes were on the list of Cancer Gene Census (green circles). (D) ETV4 mRNA, determined by quantitative RT-PCR, before and after induction of shSOX2 or shTP63 in KYSE70 cells (the stable cell lines used in Figure 4). Mean ratio ± SD of triplicates is shown. *\( P < 0.05 \), 2-way ANOVA with Bonferroni post-test.
Identification of SOX2-p63 collaboration in SCC may further explain why SOX2 amplifications are so enriched in SCCs; given that TP63 is located approximately 7 Mb from the SOX2 locus, these genes were often coamplified. The squamous-specific joint actions of SOX2 and p63, each of which helps maintain the immature precursor population of squamous epithelia, may thus be frequently co-opted during the process of squamous carcinogenesis. However, it remains to be determined what differences may exist between SOX2 function in SCC and in squamous epithelial precursor cells. As SOX2 expression increases in the process of amplification/overexpression and new chromatin sites become accessible during transformation to cancer, it is likely that new transcriptional targets emerge. The extent to which SOX2 binding to these predicted novel sites contributes to its oncogenic function, and the relative importance of p63 SOX2 interactors. See Supplemental Methods for details.

Methods

Further information can be found in Supplemental Methods.

Cell lines. SCC cells were maintained in RPMI 1640 (HCC95 and KYSE70) or DMEM (TT) with 10% FBS. H9 ES cells were provided by T. Schlaeger (Boston Children’s Hospital, Boston, Massachusetts, USA).

TAP. TAP of FLAG-HA-SOX2 with nuclear pellets prepared from SCC cells was performed as recently described (48). Briefly, chromatin pellet separated from solubilized nuclear fraction (NE) was digested with Micrococcal nuclease. The chromatin extract (CE) was incubated with anti-FLAG-agarose (Sigma-Aldrich). The eluate was filtered and further incubated with anti-HA-agarose conjugate (Santa Cruz) followed by elution with HA peptide (4 mg/ml). The final HA eluate from CE fractions was processed for LC-MS/MS sequencing and data analysis.

Protein digestion, LC-MS/MS data acquisition, and database searching. Purified tryptic peptides of CE fractions were analyzed on an LTQ-Orbitrap-XL mass spectrometer equipped with a Digital PicoView electrospray source platform, modified from a recently described method (49–52). MS spectra were searched against 3 appended databases and processed to remove peptide spectral matches (PSMs) to the forward database with FDR > 1.0%. Protein abundance was estimated by calculating the sum of the extracted ion chromatograms area of the 3 most intense peptides (53). Proteins identified in >1% of 108 negative TAP controls were removed from the sets of SOX2 interactors. See Supplemental Methods for details.

Immunofluorescence. TT cells stably expressing FLAG-HA-SOX2 and parental TT cells were seeded on cover slips. Cells were fixed for 20 minutes with 4% paraformaldehyde, permeabilized for 20 minutes with PBS containing 0.02% Triton X-100, and blocked with 10% goat serum in PBS for 3 hours. Cells were then stained with either mouse anti-FLAG or rabbit IgG antibody as control. Expression of endogenous or ectopic SOX2 was detected by Alexa Fluor 594 (red) and p63, each of which helps maintain the immature precursor population of squamous epithelia, may thus be frequently co-opted during the process of squamous carcinogenesis. However, it remains to be determined what differences may exist between SOX2 function in SCC and in squamous epithelial precursor cells. As SOX2 expression increases in the process of amplification/overexpression and new chromatin sites become accessible during transformation to cancer, it is likely that new transcriptional targets emerge. The extent to which SOX2 binding to these predicted novel sites contributes to its oncogenic function, and the relative importance of p63

Figure 7

SOX2 and p63 regulate ETV4 expression that is essential for cell growth in SCCs. (A) ChIP signals of SOX2 or p63 for the indicated cell lines near ETV4. 2 loci near the TSS of ETV4 were co-occupied by SOX2 and p63 in all 3 SCC lines (arrows); the locus upstream of TSS was not enriched for SOX2 ChIP in H8 ES cells (red arrow). (B) ChIP enrichment of SOX2, determined by qPCR, was attenuated after shTP63 induction in KYSE70 cells at the locus 3 kb upstream of ETV4 (2 distinct sets of primers were used [P1 and P2]) and the SOX2 locus. However, other SOX2-occupied regions (CCND1, JUN, HDAC9, and CD55 promoters) were not affected. Percent recovery of input for ChIP was calculated based on 10% non-IP DNA sample for each experiment. Mean ± SD of triplicates are shown. *P < 0.05, t test. (C) Growth of KYSE70 cells after seeding, following infection with 2 independent shETV4s or with shLacZ control. Data are mean ± SD of cell plated in 6 wells. *P < 0.001 vs. shLacZ, sum-of-squares F test of exponential growth model. Immunoblots for ETV4 protein as well as β-actin in the lysates of the respective cells are also shown. (D) Anchorage-independent growth of the same KYSE70 cells as in C. Mean colony numbers ± SD of triplicate wells 3 weeks after seeding are shown. *P < 0.001, t test with Dunnett multiple-comparison test. Representative images are also shown. Original magnification, ×6.3.
Cell growth assays and anchorage-independent growth assays. shRNA viral transfer, induction with Dox, cell growth assays, and anchorage-independent growth assays were performed as previously described (2, 55).

IP and GST pulldown assays. Whole-cell lysate of KYSE70 cells or 293T cells transfected with pcDNA3-ANp63α-FLAG and pcDNA3-SOX2 were incubated with SOX2 antibody or goat IgG antibody and Dynabeads Protein G (Invitrogen) or anti-FLAG-agarose. GST pulldown assay was performed as previously described (56).

ChIP, qPCR, and Illumina sequencing. SOX2, p63 ChiP-seq, and JunD ChIP-qPCR were performed as previously described with modifications (55). See Supplemental Table 8 for primers used for qPCR. DNA libraries for Illumina cluster generation and sequencing with Illumina HiSeq 2000 were performed according to the manufacturer’s protocol.

ChIP-seq data analysis and motif analysis. The binding sites for SOX2 or p63 were detected using MACS (22) after aligning to hg18 and normalization for copy number variation. Correlation matrix of ChiP-seq data sets was constructed from Pearson correlations between peak occurrence profiles. SOX2 and p63 binding peaks present in 2 or more SOX2 ChiP-seq data from SCC cells with and without evidence for significant p63 occupancy from composite p63 ChiP-seq analysis were distinguished, and vice versa for p63 peaks. Target genes were defined as genes whose TSSs were within 50 kb from SOX2 or p63 binding sites. Motifs for SOX2, p63, OCT4, or AP1 consensus binding closest to the center of SOX2 occupancy were profiled to the relative distance from SOX2 motif. See Supplemental Table 9 for details for threshold and number of occurrences along the genome for each motif.

dDNA library construction for RNA-seq. KYSE70 cells expressing Dox-inducible shSOX2 or shTP63 were treated with or without Dox for 4 days. cDNA library prepared from extracted RNA samples were sequenced with HiSeq 2000 (Illumina).

RNA-seq analysis. RNA-seq reads were aligned to hg19 and exon-exon junctions (ensemble v64) with PRADA pipeline (57). Transcriptome was collapsed to gene level using GENCODE version 12. Gene expression was represented by the average expression of each annotated gene. RNA-seq data from SCC cells with and without evidence for significant p63 occupancy were subjected to competitive analysis to determine ONCOGENE status.

Acknowledgments

We thank Ramesh Shviddasani, Myles Brown, and Orit Rozenblatt-Rosen for helpful discussions; Thorsten Schlaeger for providing H9 ES cells; and Fujiko Duke for technical assistance. This work was supported by the National Cancer Institute (K08 CA134931 to A.J. Bass), a Dana-Farber/Harvard Cancer Center Lung Cancer SPORE Developmental Project Award (NIH P50 CA095778 to A.J. Bass and K. Wong), the Lung Cancer Research Foundation (to A.J. Bass), and a Clinical Scientist Development Award from the Doris Duke Charitable Foundation (to A.J. Bass). J. Que is supported by grant R00 DX082650; A.K. Rustgi is supported by grants P01 CA098101, R01 DK060694, R01 DK056645, and P30 DK053066; and M. Meyerson is supported by grants R01 CA109038, P01 CA154303, P20 CA09578, and U24 CA126546.

Received for publication June 13, 2013, and accepted in revised form December 30, 2013.

Address correspondence to: Adam J. Bass, Dana-Farber Cancer Institute, 450 Brookline Ave, Boston, Massachusetts 02215, USA. Phone: 617.632.2477; Fax: 617.582.9830; E-mail: Adam_Bass@dfci.harvard.edu.


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