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Multiple roles for Sox2 in the developing and adult mouse trachea

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The esophagus, trachea and lung develop from the embryonic foregut, yet acquire and maintain distinct tissue phenotypes. Previously, we demonstrated that the transcription factor Sox2 is necessary for foregut morphogenesis and esophagus development. We show that Sox2 is also required for the normal development of the trachea and lung. In both the embryo and adult, Sox2 is exclusively expressed in the epithelium of the trachea and airways. We use an *Nkx2.5-Cre* transgene and a *Sox2* floxed allele to conditionally delete *Sox2* in the ventral epithelial domain of the early anterior foregut, which gives rise to the future trachea and lung buds. All conditional mutants die of respiratory distress at birth, probably due to abnormal differentiation of the laryngeal and tracheal cartilage as a result of defective epithelial-mesenchymal interaction. About 60% of the mutants have a short trachea, suggesting that the primary budding site of the lung shifts anteriorly. In the tracheal epithelium of all conditional mutants there are significantly more mucus-producing cells compared with wild type, and fewer basal stem cells, ciliated and Clara cells. Differentiation of the epithelium lining the conducting airways in the lung is abnormal, suggesting that Sox2 also plays a role in the differentiation of embryonic airway progenitors into specific lineages. Conditional deletion of *Sox2* was then used to test its role in adult epithelium maintenance. We found that epithelial cells, including basal stem cells, lacking *Sox2* show a reduced capacity to proliferate in culture and to repair after injury in vivo. Taken together, these results define multiple roles for Sox2 in the developing and adult trachea.

KEY WORDS: Sox2, Foregut development, Trachea, Epithelial-mesenchymal interaction, Epithelial differentiation, Injury-repair, Mouse

INTRODUCTION

The anterior foregut of the mammalian embryo initially consists of a simple epithelial tube surrounded by mesoderm. Through a well-orchestrated series of developmental processes this simple tube gives rise to the esophagus, trachea and lungs, each containing epithelial and mesenchymal cells with a characteristic organization and phenotype. A major challenge is to define the genetic and cellular mechanisms underlying the patterning, morphogenesis and differentiation of these different foregut-derived organ systems. Work over the past few years has uncovered important roles for signaling pathways and downstream transcription factors that mediate the reciprocal interactions between the epithelium and mesenchyme (Cardoso and Lu, 2006; Miller et al., 2004; Shannon and Hyatt, 2004). Previous studies from our lab provided evidence that the transcription factor Sox2 plays a key role in the early dorsoventral patterning of the foregut and in the subsequent development of the esophagus (Que et al., 2007). We now extend these studies to identify crucial roles for Sox2 in the development of the tracheal epithelium and, indirectly, in the differentiation of the surrounding mesenchyme.

Sox2 belongs to a family of evolutionarily conserved transcription factors containing a Sry-related high mobility group (HMG) box. In the early mouse embryo and in human and mouse embryonic stem (ES) cells, Sox2 synergizes with its partners to regulate the transcription of many other transcription factors, including Nanog and Oct4 (Pou5f1 – Mouse Genome Informatics) that function within a network to maintain self-renewal and pluripotency (Chen et al., 2008b). Later in development, *Sox2* is expressed in the endodermal epithelium of the tongue, esophagus, trachea and lung, and plays crucial roles in the differentiation and morphogenesis of these organ systems (Gontan et al., 2008; Ishii et al., 1998; Okubo et al., 2006; Que et al., 2007). In the case of foregut development, *Sox2* is initially expressed at highest levels in the dorsal epithelium of the undivided tube that will give rise to the esophagus. It is expressed at relatively lower levels in the ventral region that will give rise to the trachea and lung buds (Que et al., 2007). We have shown a dose-dependent role for Sox2 in the separation of the foregut into the esophagus and trachea. Sixty percent of $Sox2^{EGFP/COND}$ hypomorphic mutants with barely detectable levels of Sox2 protein have a defect known as esophageal atresia and tracheal-esophageal fistula (EA/TEF) (Que et al., 2006; Que et al., 2007). In the remaining 40% of hypomorphic mutants with ~17% of wild-type Sox2 levels, the foregut does separate into esophagus and trachea. However, the esophagus has an abnormal phenotype resembling a condition in humans known as mucus metaplasia (Que et al., 2006). Consistent with an important role of Sox2 in the differentiation of the mucus-producing cells, reduced levels of SOX2 have been found in regions of intestinal metaplasia in both the esophagus and antral mucosa of human patients with Barrett's esophagus (Chen et al., 2008a; Tsukamoto et al., 2004).

At birth, the trachea is surrounded by a segmental array of C-ring cartilages along the ventral side and by smooth muscle dorsally. The tracheal lumen is lined by a pseudostratified epithelium composed of three major cell populations [basal, ciliated, and secretory (Clara-like) cells] and two minor ones (neuroendocrine and mucus-producing cells). Several signaling pathways and downstream transcription factors play crucial roles in specifying these different cell lineages during development. Perturbation of these signaling molecules and transcription factors inevitably affects the development of the trachea (Metzger et al., 2008; Mucenski et al., 2005). For example, loss of the transcription factor p63 (Tcp1 –

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Mouse Genome Informatics) results in the depletion of basal cells in the trachea and the development of an epithelium composed mainly of ciliated cells (Daniely et al., 2004). By contrast, when *Sox2* is overexpressed in the lung epithelium, p63-positive cells are ectopically present in the peripheral airways, accompanied by an increased number of neuroendocrine cells and reduced branching (Gontan et al., 2008). Although the emerging evidence suggests that Sox2 plays important roles in the development of the respiratory system, the exact role of this transcription factor in the trachea remains unclear.

To address this problem we have employed an *Nkx2.5-Cre* transgene that is expressed in the early ventral foregut to delete *Sox2*. In the majority of conditional mutants, separation of the foregut into esophagus and trachea and branching morphogenesis of the lung proceeds normally. However, the trachea is shorter than normal, with abnormal differentiation of mesenchymal and epithelial cells. With a temporally controllable CreER system, we further show that Sox2 is required for maintenance of the tracheal epithelium in the adult mouse. Loss of *Sox2* impairs the ability of epithelial cells to repopulate the denuded trachea after injury.

MATERIALS AND METHODS

Mice

The mouse line with a $Sox2^{COND}$ allele in which the only exon of *Sox2* is flanked by *loxP* sites was derived by Taranova et al. (Taranova et al., 2006) and maintained on a mixed (129/SvEv × C57Bl/6) genetic background. No abnormal phenotype was observed in unrecombined homozygotes at any stage. The *Nkx2.5-Cre* mouse line was generated by Dr Robert Schwartz (Moses et al., 2001). $Gt(ROSA)26Sor^{tm1Sor}$ (referred to as *R26R*) and *Tg(CMV-cre/ESR1)1Ipc* (referred to as *CMV-CreER*) lines were obtained from the Jackson Laboratory. To activate Cre recombinase, Tamoxifen (Tmx, 0.2 mg/g body weight, dissolved in corn oil) was administered intraperitoneally (Rawlins et al., 2007). Airway injury was initiated by exposing adult male mice to 500 ppm SO_2 in air for 3 hours (Rawlins et al., 2007).

Tissue preparation and immunostaining

The trachea and lungs were dissected in phosphate buffered saline (PBS) and fixed in 4% paraformaldehyde in PBS for 3-4 hours at 4°C. After dehydration they were embedded in paraffin for sectioning and immunohistochemistry using the following antibodies: anti-p63 (1:500, mouse monoclonal, Santa Cruz clone 4A4), anti-Sox2 (1:500, rabbit polyclonal, Chemicon AB5603), anti-BrdU (1:500, mouse monoclonal, Sigma clone BU-33), anti-keratin 5 [1:1000, chicken polyclonal, kindly provided by Dr Terry Lechler, Duke University Medical Center (DUMC), Durham, NC, USA], anti-T1α (1:500, hamster monoclonal, University of Iowa Hybridoma Bank clone 8.1.1), anti-Ki67 (1:500, mouse monoclonal, Vector Labs, Burlingame, CA, USA), anti-CC10/Scgb1a1 (1:2000, rabbit polyclonal, kindly provided by Dr Barry Stripp, DUMC, Durham, NC, USA), anti-acetylated α-tubulin (1:1000, mouse monoclonal, Sigma), anti-CGRP (1:1000, rabbit polyclonal, Peninsula Laboratories), anti-Foxa2 [1:200, rabbit polyclonal, Sasaki and Hogan (Sasaki and Hogan, 1994)], anti-Shh (1:50, goat polyclonal, R&D Systems), chicken anti-Muc5ac (kindly provided by Dr Samuel Ho, University of Minnesota, Minneapolis, MN, USA), anti-smooth muscle actin (SMA; 1:500, mouse monoclonal, Sigma A2547), anti-phosphorylated Histone H3 (1:500, rat monoclonal, Sigma HTA28), anti-cleaved caspase 3 (1:200, rabbit polyclonal, Cell Signaling 9661) and anti-Sox9 (1:500, rabbit polyclonal, Santa Cruz SC-20095). For whole-mount X-gal staining followed by paraffin embedding and sectioning see Que et al. (Que et al., 2006).

Periodic acid-Schiff (PAS) and alcian blue staining

For Periodic acid-Schiff staining, sections were treated with or without amylase (α-amylase from *Aspergillus oryzae*, Fluka 10065: 0.5% in distilled water at 37°C for 15 minutes), then stained in Schiff's reagent (Sigma, S-5133). For alcian blue staining, sections were treated with 3% acetic acid solution for 3 minutes, stained in alcian blue for 30 minutes and counterstained with eosin. For whole-mount staining of cartilage, dissected tracheas were fixed in 95% ethanol for 18 hours followed by overnight staining with 0.03% alcian blue dissolved in 80% ethanol and 20% acetic acid.

Culture of tracheal epithelial cells

Epithelial cells were isolated from tracheas of adult *CMV-CreER* mice after three Tmx injections over a period of 5 days (one injection every other day). For isolation, the trachea was washed and then treated with 20 U/ml Dispase (BD Biosciences, Bedford, MA, USA) in PBS for 22 minutes at room temperature. Then the epithelial layer was peeled off with fine forceps and incubated in 0.1% trypsin with 0.04% EDTA (diluted with PBS from 0.5% trypsin with 0.2% EDTA stock solution, GIBCO) for 18 minutes at 37°C to dissociate it into single cells. The cells were filtered through a cell strainer (pore size 40 μm, BD Biosciences) and cultured in 35 mm culture dishes coated with 120 μl 1.75 mg/ml rat tail type I collagen (R&D Systems) at 37°C in 5% CO_2. The cell density was 8×10^4 cells/dish. The medium contained DMEM/F-12 (1:1, GIBCO), Insulin-Transferrin-Selenium-A Supplement (1:100 diluted from stock solution, Invitrogen 51300-044), 100 U/ml penicillin G, 100 μg/ml streptomycin, 4 mM L-glutamine (GIBCO), 10 ng/ml heparin (Sigma) and 30 μg/ml bovine pituitary extract (Invitrogen) with 20 ng/ml Fgf2 and 25 ng/ml Egf (R&D Systems). Medium was refreshed every three days. For each experiment, cultures were repeated at least three times. After culture, cells were stained with Wright blue or fixed with 4% PFA for 10 minutes at 4°C and then stained with antibodies.

BrdU labeling

For embryonic (E) day 18.5 embryos, BrdU (Amersham Bioscience, UK) was injected intraperitoneally into pregnant females at a dose of 10 μl/g bodyweight. For postnatal (P) day 0 newborns and adults the same dose of BrdU was injected intraperitoneally. After 2 hours, tissues were collected and fixed in 4% PFA in PBS (pH 7.4). For immunohistochemistry, anti-BrdU antibody (1:500, mouse monoclonal, Sigma clone BU33) was used, in combination with a MOM Kit (Vector Labs).

Quantitative analysis

For calculating the proportion of proliferating (BrdU positive or Ki67 positive), basal (p63 positive), Clara (Scgb1a1 positive), ciliated (acetylated α-tubulin positive) and mucus-producing (alcian blue positive) cells in the total epithelium, longitudinal sections (ten sections per trachea) through the same level of each trachea were selected for measurement. Tissue images were obtained using an Axiophot light microscope (Carl Zeiss, Germany) or a Leica ASMDW laser scanning confocal microscope. Cells were manually counted on a *z*-series of optical sections, and multiple optical sections were examined to distinguish cell boundaries.

RT-PCR

Total RNA was extracted from each tissue by RNeasy (Qiagen) and cDNA was synthesized from 500 ng total RNA by SuperScript (Invitrogen). Semi-quantitative PCR for specific genes was performed using the following primer sets (5′-3′): *Hoxa5*, AGCAGCAGAGAGGGGGTTGG, GCGGGTCAGGTAGCGGTTGA; *Raldh2*, ATCCACGGCACTTCA-ATCCC, GCAGGTGAGCGGTGTCTGTT; *Shh*, GTCCCTTGTCCT-GCGTTTCA, GTGGCGGTTACAAAGCAAAT; *Ptc1*, CCTGGCTCT-GATGACCGTTG, CATTGAGAACCCCCAAGACG; *Sox2*, AACG-GCTCGCCCACCTACAGC, CAGGGGCAGTGTGCCGTATTTGG; *Sox9*, GAGGCCACGGAACAGACTCA, CAGCGCCTTGAAGATAG-CATT; and *ß-actin*, GTCGTACCACAGGCATTGTGATGG, GCAATGC-CTGGGTACATGGTGG.

RESULTS

Expression of Sox2 during trachea and lung development

We have previously reported a dynamic expression of Sox2 in the epithelial cells of the early foregut. At E9.5, before foregut separation, both $Sox2^{EGFP}$ and Sox2 protein are expressed at

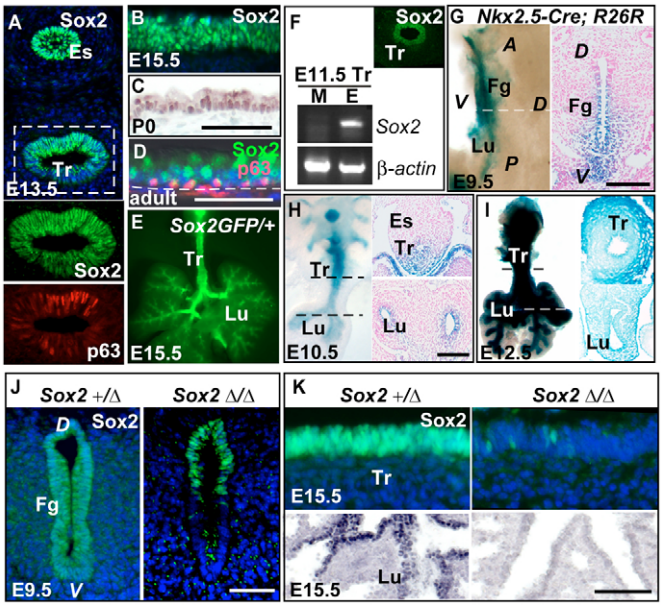

Fig. 1. Expression of Sox2 in the trachea and use of *Nkx2.5-Cre* to delete *Sox2*. (**A-F**) Sox2 expression in the developing and adult trachea. (A) Immunohistochemical localization of Sox2 protein in the esophagus and trachea at E13.5. Lower panels are magnified views of trachea stained with anti-Sox2 and anti-p63 antibodies. (B-D) Immunohistochemical localization of Sox2 in the trachea at E15.5 (B), P0 (C) and adult (D) stages. In D, p63 and Sox2 colocalize in basal cells. (E) Fluorescence microscopy of the trachea and lung at E15.5. (F) RT-PCR shows that *Sox2* is exclusively expressed in the epithelium, and insert shows an E11.5 trachea immunostained with anti-Sox2 antibody. (**G-I**) *Nkx2.5-Cre* expression in the early foregut (stages E9.5-12.5) as detected in *R26R* embryos through X-gal staining. Left and right panels show the whole-mount X-gal staining and a section of these stained samples, respectively. The dashed line delineates where the section is cut. (**J**,**K**) Immunostaining with anti-Sox2 antibody on early foregut and its derivatives in *Nkx2.5-Cre;Sox2*$^{+/COND}$ (*Sox2+/Δ*) controls and *Nkx2.5-Cre;Sox2*$^{COND/COND}$ (*Sox2 Δ/Δ*) mutants. Nuclei are counterstained with DAPI (blue). Es, esophagus; Tr, trachea; Lu, lung; Fg, foregut; A, anterior; P, posterior; D, dorsal; V, ventral; M, mesenchyme; E, epithelium. Scale bars: 100 μm.

higher levels dorsally than ventrally (Que et al., 2007). We now specifically focus on the Sox2 expression pattern in the developing trachea (Fig. 1A-F). At E11.5 and E13.5, following foregut separation, levels remain higher in the esophagus than the trachea (Que et al., 2007) (Fig. 1A). Within the E13.5 trachea, Sox2 is also differentially expressed, with higher levels dorsally in association with more p63-positive cells (Fig. 1A). Between E15.5 and P0, Sox2 is expressed in virtually all of the epithelial cells of the trachea (Fig. 1B,C; see Fig. S1A in the supplementary material). In the adult, although all the epithelial cells express Sox2, some of them maintain high levels (Fig. 1D; see Fig. S1B,C in the supplementary material). For example, 78%±12% of basal cells express high levels of Sox2 (n=3, see Fig. S1C in the supplementary material). Consistent with the finding of Gontan et al. (Gontan et al., 2008), in the developing lung Sox2 is expressed in the epithelium of the proximal airways but is absent from the distal tips and primitive alveoli. This is shown clearly using the *Sox2*^{EGFP} allele (Fig. 1E), as well by immunohistochemistry of sections (Fig. 1K).

Deletion of *Sox2* using *Nkx2.5-Cre* in the early ventral foregut endoderm results in a perinatally lethal phenotype

In the trachea of *Sox2* hypomorphic (*Sox2*$^{EGFP/COND}$) mutants (Que et al., 2007), Sox2 protein can still be detected in the epithelium by immunohistochemistry, even though the level of protein is dramatically decreased compared with wild type (data not shown). To study the effect of complete *Sox2* deletion in the ventral epithelium that gives rise to the trachea and lung, we used the *Nkx2.5-Cre* transgene in combination with the floxed *Sox2*^{COND} allele. *Nkx2.5-Cre* drives recombination in the ventral epithelial cells of the undivided foregut earlier than E9.5. This is shown by *lacZ* expression in *Nkx2.5-Cre;R26R* embryos (Fig. 1G). In addition, recombination of the reporter is also seen in the ventral mesenchyme where *Nkx2.5-Cre* is active (Fig. 1G). At E10.5, E12.5 and E16.5 *lacZ* expression is maintained in the trachea and lung, which are derived from the ventral foregut (Fig. 1H,I; see Fig. S1D in the supplementary material). In both tissues, *lacZ* is expressed in the epithelial and mesenchymal compartments. However, it is important to note that Sox2 expression is confined to the epithelium (see Fig. 1F), so that the *Nkx2.5-Cre* expression in the mesenchyme of *Sox2*$^{COND/COND}$ embryos is functionally irrelevant.

To delete *Sox2* in the ventral epithelium of the foregut, *Sox2*$^{COND/COND}$ mice were mated with *Nkx2.5-Cre;Sox2*$^{COND/+}$ mice. None of the *Nkx2.5-Cre;Sox2*$^{COND/+}$ control embryos examined at any stage has visible defects in foregut and cartilage development, showing that Cre by itself is not toxic. By contrast, at P0 all *Nkx2.5-Cre;Sox2*$^{COND/COND}$ compound mutants gasp for air and die within 3 hours, apparently owing to the abnormal development of laryngeal and tracheal cartilages (see below). As expected, at E9.5 Sox2 protein is undetectable in the ventral foregut epithelium of compound mutants (Fig. 1J), and only very few Sox2-positive cells remain in the trachea and distal airways at E15.5 (Fig. 1K).

Analysis of *Nkx2.5-Cre;Sox2*$^{COND/COND}$ embryos showed that the overall size and shape of conditional mutant lungs, as well as the size and wet weight of individual lobes are similar to *Nkx2.5-Cre;Sox2*$^{COND/+}$ controls (Fig. 2A and data not shown). However, 60% of conditional mutants have a shorter trachea and longer main bronchi than controls (Fig. 2B). Measurement of the individual lengths of the trachea and left main bronchus indicates a significant difference in control versus mutant (1.9 mm versus 1.3 mm for trachea, P<0.01; 1.0 mm versus 1.5 mm for left main bronchus, P<0.01, n=5 for each group; Fig. 2C). Nevertheless, the combined length of the trachea and the left main bronchus is not significantly different (P>0.05).

We previously reported the formation of TEF in 60% of *Sox2*$^{EGFP/COND}$ hypomorphic mutants on the mixed (129/SvEv × C57BL/6) background (Que et al., 2007). In the present study 10% (3/30) of mutants at P0 also have TEF. Significantly, all those mutants were generated by mating the same *Sox2*$^{COND/COND}$ female with three different *Nkx2.5-Cre;Sox2*$^{COND/+}$ males (129/SvEv × C57BL/6; see Fig. S2B in the supplementary material). This suggests that modifier loci in different genetic backgrounds can alter the severity of the phenotype caused by conditional deletion of *Sox2* in the ventral epithelium before foregut separation.

Abnormal cartilage development in tracheal mesenchyme of *Nkx2.5-Cre;Sox2*$^{COND/COND}$ embryos

Skeletal preparations and histological analysis revealed disorganized laryngeal and tracheal cartilages in compound mutants (Fig. 2D and see Fig. S2A,B in the supplementary material). The cricoid and thyroid cartilages are the two major

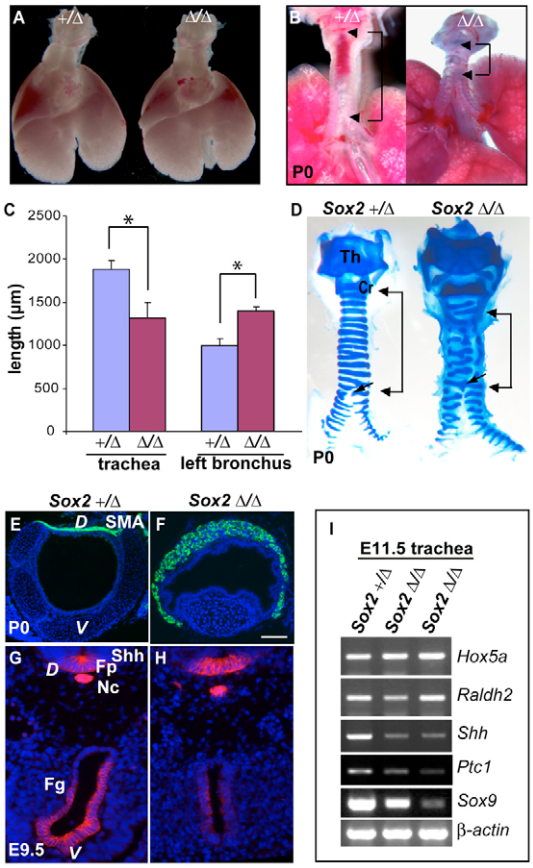

Fig. 2. Abnormal development of larynx and trachea in *Nkx2.5-Cre;Sox2*$^{COND/COND}$ mutants. (**A**) Gross morphology of lung and trachea in control (left) and mutant (right) mice. (**B**,**C**) Short trachea (bracket) and long main bronchus in P0 mutants (n=5; *P<0.01). (**D-F**) Abnormal differentiation of mesenchymal cells in the mutant trachea. (D) Alcian blue staining reveals abnormal laryngeal and tracheal cartilage (bracket). Note the reduced number of incomplete cartilage rings in mutants (arrows). (E,F) Immunostaining with anti-SMA antibody to show ectopic expression of smooth muscle actin in the ventral side of the trachea in mutants. (**G-I**) Downregulated Shh signaling in the early foregut of mutants. (G,H) Immunohistochemical localization of Shh protein in the unseparated foregut. Nuclei are counterstained with DAPI (blue). (I) Semi-quantitative RT-PCR for expression in control and mutant tracheas of several genes involved in the development of laryngeal and tracheal cartilage. Th, thyroid; Cr, cricoid; Fg, foregut; Fp, floor plate; Nc, notochord; D, dorsal; V, ventral. Scale bar: 100 μm.

components of the larynx, with the thyroid cartilage normally being the larger of the two. In all mutants analyzed by whole-mount alcian blue staining at P0 (n=12), the thyroid cartilage was variably abnormal in shape (Fig. 2D and see Fig. S2A,B in the supplementary material). In some mutants, the cricoid cartilage was larger than the thyroid cartilage due to fusion with the first tracheal ring. This defect resembles the cartilage defects in *Hoxa5* null mutants (Aubin et al., 1997). In addition, the tracheal cartilage rings lose their classic C-shape, and in mutants with a short trachea the number of cartilage rings is reduced (10-11 in wild type and 3-8 in mutant; Fig. 2D). In comparison with the reduced size of the cartilage, the dorsal domain of smooth muscle cells extends more ventrally in the mutant trachea at E15.5 and P0 (Fig. 2E,F; see Fig. S2C,D in the supplementary material). Although *Sox2* is also deleted in the major airways of the lung (Fig. 1K), patterning of the smooth muscle in both the airways and blood vessels is not altered (data not shown).

Previous studies have shown that several genes regulate the differentiation of laryngeal and tracheal mesenchymal cells (Aubin et al., 1997; Chisaka and Capecchi, 1991; Mendelsohn et al., 1994; Vermot et al., 2003). Using PCR primers for transcripts of such genes, we were unable to detect any significant change of expression of *Hoxa5* and *Raldh2* (*Aldh1a2* – Mouse Genome Informatics) in E11.5 mutant tracheas by RT-PCR (Fig. 2I). However, the level of *Shh* expression is greatly reduced after *Sox2* ablation. Consistent with reduced Shh signaling, the transcript levels of its downstream targets *Sox9* and *Ptc1* (*Ptch1* – Mouse Genome Informatics) are also downregulated (Fig. 2I). At the protein level, a reduction of Shh is detected as early as E9.5 in the unseparated foregut, whereas the expression of Shh in the floor plate, notochord and primary lung buds is unaffected (Fig. 2G,H and data not shown).

Deletion of *Sox2* in the epithelium leads to abnormal differentiation, including excessive generation of mucus-producing cells

The epithelium of the newborn mouse trachea contains ciliated, secretory (Clara-like) and mucus-producing columnar cells. It also contains a few neuroendocrine cells and a population of p63-positive basal cells making up about 30% of the total epithelium. There is strong evidence that these basal cells are the stem cells of the trachea (Hong et al., 2004; Schacht et al., 2003; Schoch et al., 2004). Previously, we have shown a reduction of p63-positive basal cells in the separated esophagus and forestomach of *Sox2* hypomorphic mutants (Que et al., 2007). We also noted that the proportion of p63-positive basal cells within the total epithelium is reduced in the tracheas of these mutants at E18.5 and P0 (data not shown). In agreement with this, *Nkx2.5-Cre;Sox2*$^{COND/COND}$ mutants have a lower proportion of p63-positive cells than wild type. This difference can be detected as early as E13.5 (Fig. 3A-G). A similar reduction is seen using two other basal cell markers, keratin 5 and T1-α (Schacht et al., 2003; Schoch et al., 2004) (Fig. 3E,F and data not shown).

In addition, the proportions of ciliated (acetylated α-tubulin-positive) and Clara (Scgb1a1-positive) cells are both greatly reduced in P0 mutants (Fig. 4A,B; P<0.01). By contrast, the proportion of alcian blue- and PAS-positive mucus-producing cells is significantly increased (Fig. 4C-F; P<0.01), and these cells are also reactive for Muc5ac staining (Fig. 4G,H). Other studies have implied that the transcription factor Foxa2 represses the expression of the *Muc5ac* gene (Wan et al., 2004). Consistent with this, the proportion of Foxa2-positive cells is reduced in the mutant compared with the wild-type control (Fig. 4I,J and see Fig. S2E,F in the supplementary material). Further colocalization analysis revealed that the alcian blue-positive cells and Foxa2-positive cells are two distinct populations (see Fig. S2G in the supplementary material). In addition, transmission EM analysis of mutant tracheas reveals many epithelial cells containing apically located membrane-bound vesicles, typical of mucus-containing vesicles (see Fig. S2H in the supplementary material) (Evans et al., 2004). When quantitating different cell populations we noted that ~15% cells are not positive for any of the tracheal epithelial markers p63, Scgb1a1, acetylated α-tubulin or calcitonin gene-related peptide (CGRP) (Fig. 4K). Of note, in larger bronchi and mutant lungs in which *Sox2* has been deleted (Fig. 1K) we also observed a significant reduction of p63-positive, ciliated and Clara cells, but no increase in alcian blue-positive cells (see Fig. S2I,J in the supplementary material and data not shown).

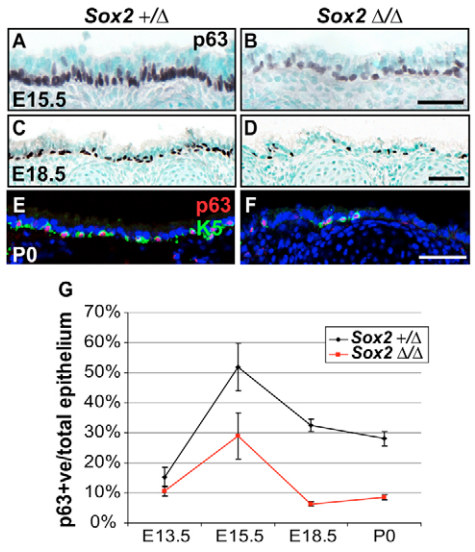

Fig. 3. Decreased number of p63-positive cells in *Nkx2.5-Cre;Sox2$^{COND/COND}$* mutants at different developmental stages. (**A-D**) Immunohistochemical staining with anti-p63 antibody in control (A,C) and mutant (B,D) tracheas at E15.5 (A,B) and E18.5 (C,D). Nuclei are counterstained with methyl green. (**E**,**F**) Immunostaining with anti-keratin 5 (green) and anti-p63 (red) antibodies in the P0 trachea. (**G**) Quantification of p63-positive cells in tracheas at E13.5, E15.5, E18.5 and P0. At each stage, three individual tracheas were included. Scale bars: 50 μm.

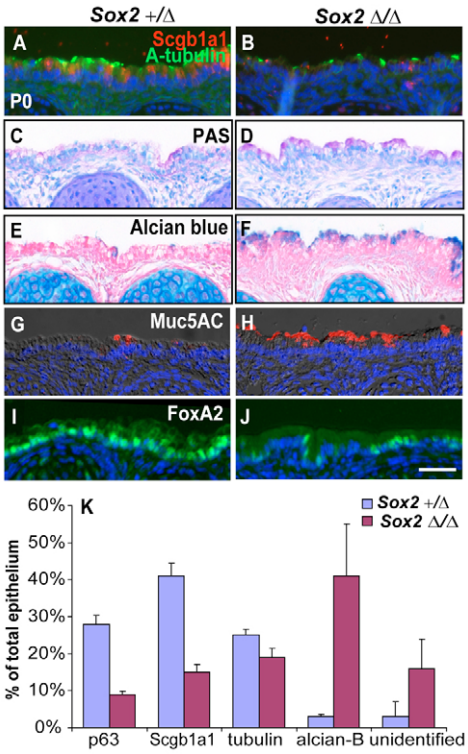

Fig. 4. Abnormal differentiation of tracheal and lung epithelial cells at P0. (**A**,**B**) Decreased number of ciliated (acetylated α-tubulin-positive, green) and Clara (Scgb1a1-positive, red) cells in mutant trachea (B), compared with control (A). (**C-H**) Increased number of mucus-producing cells in mutant tracheas visualized by PAS (C,D), alcian blue (E,F) and anti-Muc5ac (G,H) staining. (**I**,**J**) Immunostaining with anti-Foxa2 antibody. (**K**) Quantification of the percentage of the different cell lineage to total epithelium in the trachea. Numbers are obtained from analyzing ten sections at the same level from each of three individual tracheas from both *Nkx2.5-Cre;Sox2$^{+/COND}$* controls and *Nkx2.5-Cre;Sox2$^{COND/COND}$* mutants. PAS, periodic acid-Schiff. Scale bar: 50 μm.

In spite of these dramatic changes in the cellular composition of the trachea, we detected no significant change in the rate of proliferation of the total epithelium after deleting *Sox2*, as judged by BrdU labeling after a 2-hour pulse at E18.5 and P0 (n=3 for each group; see Fig. S3A-E in the supplementary material).

Sox2 is required for the in vitro proliferation of adult tracheal epithelial cells

Studies have shown the importance of Sox2 in the self-renewal and proliferation of stem/progenitor cells in the adult brain and pituitary gland (Fauquier et al., 2008; Ferri et al., 2004; Suh et al., 2007). We therefore asked whether Sox2 is also crucial for the homeostasis of the adult tracheal epithelium. To address this question, we first established a culture system that allowed us to grow adult tracheal epithelial cells in vitro. Single cells derived from enzymatically isolated epithelium (8×10^4/35 mm plate) were cultured in serum-free medium with Fgf2 and Egf (see Materials and methods). Under these conditions the epithelial cells attached, proliferated and formed small patches. Subsequently, cells in many of the patches flattened and ceased proliferation. By day 10 there were approximately 40 colonies/35 mm dish, predominantly of two types; those containing small basal cells (p63-positive) and those containing flattened Clara cells (Scgb1a1-positive; Fig. 5A). By day 15, only basal cell colonies (4-7 colonies/35 mm plate) survived and propagated. These basal cells expressed high levels of p63 and Sox2 (Fig. 5B).

We then used the ubiquitously expressed *CMV*-driven *CreER* to conditionally delete *Sox2* in the adult following Tamoxifen (Tmx) injection. In this system, after Tmx induction Cre recombinase is translocated into the nucleus to excise the targeted gene. Control experiments show that CreER drives recombination in 80% of tracheal epithelial cells in *CMV-CreER;R26R* mice after three injections over a period of 5 days (see Fig. S4D,E in the supplementary material).

With the same Tmx injection scheme we deleted *Sox2* in the tracheal epithelium of the *CMV-CreER;Sox2$^{COND/COND}$* compound mutants (Fig. 5C-E). At the time of harvesting (2 days after final injection) the number of p63-positive basal cells, Clara and ciliated cells is unchanged compared with wild-type controls (*CMV-CreER* and *CMV-CreER;Sox2$^{COND/+}$*) or *CMV-CreER;Sox2$^{COND/COND}$* mutants without Tmx injection (see Fig. S4F-I in the supplementary material). The tracheal epithelial cells were then isolated from both conditional mutant and wild type, and the same number cultured (8×10^4/35 mm plate). By day 5, in the control group 140±13, 146±21 and 34±10 patches were p63-positive, Scgb1a1-positive and p63-Scgb1a1 double positive, respectively (n=3, see Fig. S4A-C in the supplementary material). Up to 70% of these colonies had a cell number larger than 15 and ~1.6% of the total epithelial cells were positive for the proliferation marker phosphorylated Histone H3 (see Fig. S4H in the supplementary material). By day 15, each 35 mm culture dish contained 4-7 basal cell colonies that were positive for p63 (n=5, Fig. 5K,M). By contrast, loss of *Sox2* led to about a fourfold reduction in the number of cell patches compared with

controls at day 5 (n=3, P<0.01; Fig. 5J). The average size of the colonies was also smaller, and only 42% of patches had a cell number larger than 15. The proliferation index was 0.7%, calculated by staining for phosphorylated Histone H3 (see Fig. S4K in the supplementary material). The number of colonies positive for p63, Scgb1a1, and p63 and Scgb1a1, was 37±13, 50±11 and 9±3, respectively (n=3). When examined at day 10, only very few cells were positive for phosphorylated Histone H3 and, by day 15, all of these colonies disappeared (n=5, Fig. 5L,O).

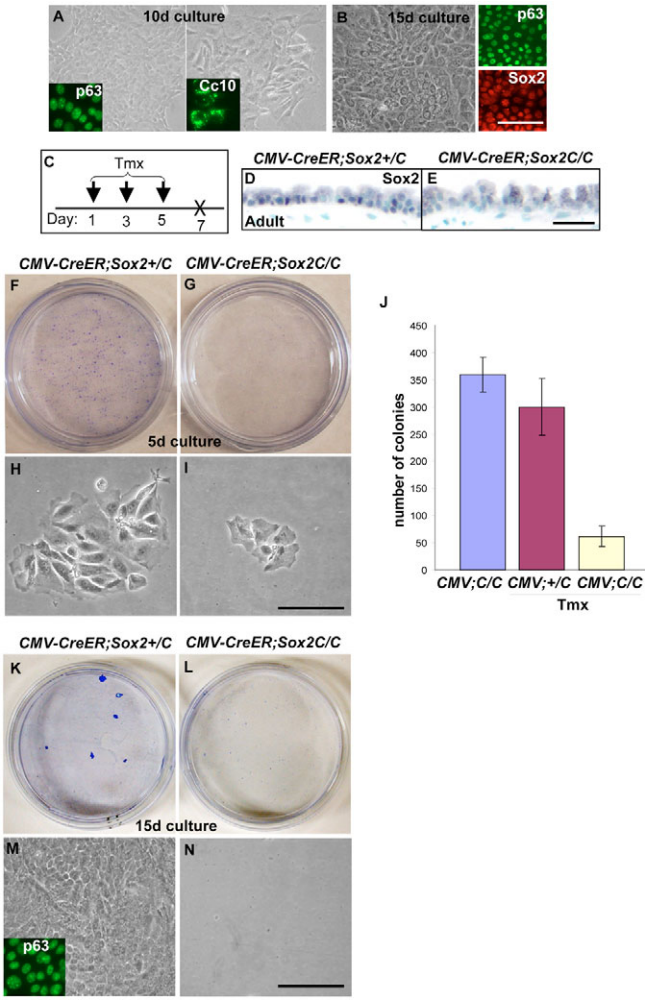

Fig. 5. Sox2 regulates the proliferation of adult tracheal epithelium in culture. (**A**) Representative colonies present on culture day 10 express either p63 or Scgb1a1 (CC10; inserts). (**B**) Representative colony present on day 15 that co-expresses p63 and Sox2. (**C-E**) Efficient deletion of *Sox2* in the adult trachea of *CMV-CreER;Sox2*$^{COND/COND}$ mutants. (C) Timeline of the Tamoxifen (Tmx) treatment protocol. (D,E) Immunohistochemistry of Sox2 in wild-type (D) and mutant (E) tracheas. (**F-J**) *Sox2* deletion reduces proliferation of tracheal epithelium isolated from wild type (F,H) or conditional mutants (G,I) and cultured for 5 days. H and I are representative colonies from F and G, respectively. (J) Number of colonies per 35 mm culture dish. Data are from three independent experiments. (**K-N**) Basal cell colonies present in controls (K), but not in mutants (L), in 15-day cultures. M is a representative colony from K. N is from L, showing no surviving colony in this 35 mm culture dish. Insert in M shows representative colony stained with anti-p63. Colonies in F,G and K are stained with Wright blue. Scale bars: 50 μm.

Sox2 is required for the homeostasis and repair of adult tracheal epithelial cells in vivo

To test the role of Sox2 in long-term maintenance of the adult epithelium, we analyzed the tracheas of *CMV-CreER;Sox2*$^{COND/COND}$ mutants 3 months after Tmx exposure (n=4; Fig. 6A). *CMV-CreER;Sox2*$^{COND/+}$ mice treated with Tmx served as controls. At the time of harvest (90 days after the final injection), Sox2 protein is undetectable in the tracheal epithelium of mutants (Fig. 6B,C). Moreover, the epithelium is composed of flattened cells that are more loosely packed than controls, as judged by morphology and internuclear distance (Fig. 6D-E′). The number of epithelial cells per unit length of trachea (500 μm) is reduced from 160±11 in wild type to 114±5 in mutants (n=4). The proportion of cells in the total epithelium positive for the proliferation marker Ki67 (Mki67 – Mouse Genome Informatics) is decreased by 72% in mutants compared with controls (n=4) (Fig. 6J-L). Consistently, we also observed a decreased rate of BrdU incorporation in mutants after a 2-hour labeling period (see Fig. S4L-O in the supplementary

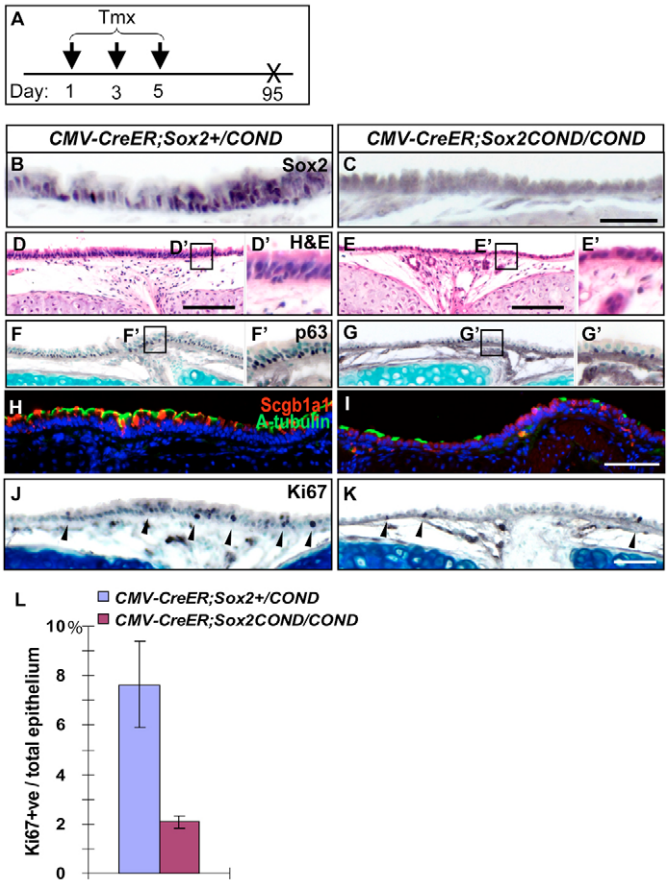

Fig. 6. Sox2 is required for homeostasis of the adult tracheal epithelium. (**A**) Timeline of the Tamoxifen treatment. (**B**,**C**) Immunohistochemistry with anti-Sox2 antibody. (**D-E′**) Hematoxylin and eosin (H&E) staining of adult trachea. D′ and E′ are magnified views of boxed region in D and E, respectively. (**F-G′**) Immunohistochemistry staining with anti-p63 antibody. (**H**,**I**) Immunostaining with anti-Scgb1a1 (red) and anti-acetylated α-tubulin (green) antibodies. (**J-L**) Decreased proliferation of tracheal epithelium after loss of Sox2 protein. (J,K) Immunohistochemistry staining with anti-Ki67 antibody. (L) Ratio of Ki67-positive epithelium along total tracheal epithelium. Four mutant and control tracheas are included. Scale bars: 100 μm.

material). However, there is no significant apoptosis in mutants as detected by cleaved caspase 3 antibody staining (data not shown). *Sox2* depletion in the adult also altered the composition of the tracheal epithelium, and a reduction of the proportion of basal, ciliated and Clara cells was observed in mutants (Fig. 6F-I). The proportion of basal cells in the total epithelium decreases by 24.6% compared with controls. However, unlike the embryonic trachea, no significant increase of alcian blue-positive or mucus-producing cells is noticed after *Sox2* deletion, and approximately 20% of the epithelial cells are not positive for any markers examined, including CGRP.

The ability to repair after injury is an important feature of the tracheal epithelium. To investigate whether loss of *Sox2* affects this property, we used a model in which SO_2 induces damage to the tracheal epithelium. Normally, the epithelium starts to regenerate 24 hours after injury, and is fully recovered by 7-10 days (Rawlins et al., 2007). Two days after the final of three Tmx injections, *CMV-CreER;Sox2*$^{COND/COND}$ (n=3) and *CMV-CreER;Sox2*$^{COND/+}$ (n=3) control male mice were exposed to SO_2, and the tracheas were harvested 15 days later (17 days after final injection; Fig. 7A). As before, Sox2 protein is undetectable in the *CMV-CreER;Sox2*$^{COND/COND}$ compound mutants (data not shown). Strikingly, the repair of the trachea is impaired after *Sox2* deletion (Fig. 7B-C″). Examination of sections shows that in some parts of the trachea the epithelial cells are disorganized and the underlying mesenchyme is actively proliferating (data not shown), and inflammatory cells are still present (Fig. 7C). In wild-type trachea, regenerated epithelial cells lining the airways are tightly packed (Fig. 7B′-B″) and have differentiated normally into basal, ciliated and Clara cells (Fig. 7F,H). By contrast, the tracheal epithelium in mutants is flattened and loosely packed, in particular on the dorsal surface (Fig. 7C′-C″). Proliferation, as indicated by Ki67 expression, is also decreased (Fig. 7D,E). Moreover, *Sox2* deletion affects the differentiation of the regenerated epithelium. The numbers of basal, ciliated and Clara cells are greatly reduced (Fig. 7G,I), and the proportion of p63-positive cells is decreased by 17.2%. However, we were unable to detect significant increase of alcian blue-positive cells after regeneration in mutants compared with wild type (data not shown).

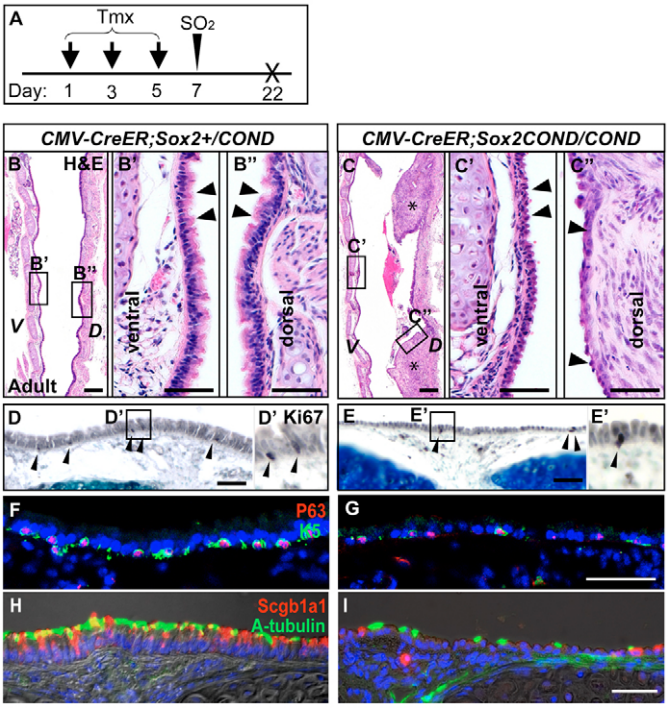

Fig. 7. Sox2 is required for proliferation and differentiation of the regenerating tracheal epithelium in a SO_2-injured mouse model. (**A**) Timeline of the Tamoxifen and SO_2 treatment protocol. (**B-C″**) H&E staining of regenerated trachea. B′ (ventral), B″ (dorsal) and C′ (ventral), C″ (dorsal) are magnified views of the boxed region in B and C, respectively. Arrowheads indicate epithelium. Note that in C there are numerous inflammatory cells within the lumen, asterisks in C indicate smooth muscles bulging into the lumen. (**D-I**) Immunohistochemistry of the regenerated epithelium with antibodies against Ki67 shows more proliferative cells (arrowheads) in control (D) versus mutant (E) tracheas. D′ and E′ are magnified views of the boxed region in D and E, respectively. (F,G) Anti-keratin 5 (green) and anti-p63 (red); (H,I) anti-Scgb1a1 (red) and anti-acetylated α-tubulin (green). D, dorsal; V, ventral. Scale bars: 50 μm.

DISCUSSION

In this article we extend our previous studies on the role of Sox2 in foregut development to show that it also has crucial functions in the developing and adult trachea. Conditionally deleting *Sox2* during embryonic development affects the differentiation of both epithelium and mesenchyme. Loss of *Sox2* in the adult perturbs the homeostasis of the tracheal epithelium and impairs the regeneration process after injury.

Role of Sox2 in laryngeal and tracheal development involves epithelial-mesenchymal interactions

All of the *Nkx2.5-Cre;Sox2*$^{COND/COND}$ mutants die at birth with abnormal laryngeal cartilage. Up to 60% of the mutants also have a shortened trachea and deformed tracheal cartilage. Previously, several genes, including *Shh*, *Hoxa5* and *Raldh2*, have been implicated in regulating the early development of the tracheal and laryngeal cartilages (Chisaka and Capecchi, 1991; Litingtung et al., 1999; Mendelsohn et al., 1994; Pepicelli et al., 1998; Vermot et al., 2003). Neither Hoxa5 nor Raldh2 appears to be affected by the loss of *Sox2*. However, we did observe decreased levels of Shh protein and RNA in the mutant epithelium of the E9.5 foregut and E11.5 trachea. We also observed decreased transcript levels of Shh downstream targets *Ptc1* and *Sox9*, which are expressed in the mesenchyme to regulate its differentiation (Miller et al., 2004; Miller et al., 2001). Given the similar defects in foregut separation and tracheal cartilage in *Shh* and *Sox2* mutants (Litingtung et al., 1999), we suggest that these two molecules fall into the same regulatory pathway. In addition, we noted that the domain of smooth muscle expands into the ventral side of the mutant trachea. It is possible that a threshold level of Shh is required for the differentiation of the mesenchyme towards cartilage versus smooth muscle in the trachea.

Up to 60% of conditional mutants have shortened a trachea and longer main bronchi than controls, although the total length is the same. One explanation for this phenotype is a defect in the positioning of the primary lung buds during foregut development. The retinoic acid signaling pathway has been shown to induce lung budding through inhibiting TGFβ in the ventral foregut (Chen et al., 2007). This inhibition allows for the localized high expression of *Fgf10*, which in turn induces the formation of primary lung buds (Desai et al., 2004). Deletion of *Fgf10* abrogates the lung budding process (Sekine et al., 1999). We and others have shown that Fgf10

negatively regulates *Sox2* expression in the ventral foregut and lung (Nyeng et al., 2008; Que et al., 2007), and we noticed a gradual decrease of *Sox2* expression from anterior to posterior in the ventral foregut (unpublished observations). In addition, at sites where the primary lung buds are formed, *Sox2* expression is lost (Sherwood et al., 2008). We therefore propose that downregulation of *Sox2* by Fgf10 at a specific site within the ventral foregut is necessary to initiate lung budding. Consequently, as noticed in the present study, *Sox2* deletion throughout the ventral foregut leads to an anterior shift in the budding site in some mutants. However, a more complex network must exist that includes other signaling molecules, as truncated tracheas also occur in mutants with a disrupted Wnt signaling pathway (Li et al., 2002; Li et al., 2008). Recent studies by us and others have shown that Wnt signaling, as evidenced by TOP-Gal expression, is active in the ventral foregut endoderm at E9.5 (Li et al., 2008; Okubo and Hogan, 2004; Shu et al., 2005). In light of a recent report that Sox2 forms a complex with β-catenin to regulate transcription of genes such as cyclin D1 (Chen et al., 2008c), it is tempting to speculate that Sox2 could similarly work with Wnt signaling to determine the budding site of the lung. That said, we cannot exclude the possibility that the truncated trachea results from the disorganized patterning of mesenchyme. This might in turn affect the morphogenesis of the epithelium, although we were not able to detect significant differences in proliferation between mutants and wild-type tracheas.

Role of Sox2 in the development of the tracheal epithelium

Sox2 is crucial for the development of several tissues, including brain, retina and tongue (Miyagi et al., 2008; Okubo et al., 2006; Suh et al., 2007; Taranova et al., 2006). Loss of Sox2 function results in cell cycle exit and differentiation of retinal progenitor cells (Taranova et al., 2006). Here, we show that *Sox2* deletion in the early ventral foregut epithelium results in the abnormal differentiation of tracheal epithelium, but it seems to occur without an effect on cell proliferation. This observation is consistent with our previous findings in the embryonic tongue and esophagus (Okubo et al., 2006; Que et al., 2007). Ferri et al. (Ferri et al., 2004) also notice that Sox2 is not required for the proliferation of the embryonic neural epithelium, and they suggest that Sox1 and Sox3, two other members of the SoxB1 family, play compensatory roles (Ferri et al., 2004).

We observed a significant decrease in the proportion of basal, ciliated and Clara cells after deleting *Sox2*. By contrast, more mucus-producing cells (Muc5ac-positive) are present in the mutant trachea. We also observed that up to 15% of the epithelial cells lack expression of any of the lineage specific markers examined. These results emphasize that Sox2 is required for the normal differentiation of the epithelium in the developing trachea. Recently Gontan et al. (Gontan et al., 2008) reported that Sox2 overexpression in embryonic lung epithelium also affects the differentiation, and significantly more neuroendocrine cells and p63-positive cells are present compared with wild type (Gontan et al., 2008). In future studies it will be important to determine the response of tracheal epithelium to increased Sox2 levels.

Role of Sox2 in maintenance of the adult trachea

Although Sox2 is not needed for the proliferation of the embryonic epithelium, it plays crucial roles in the maintenance of adult tracheal epithelium. Our first evidence comes from in vitro culture. We noted that after *Sox2* deletion both the number and size of cell colonies are reduced, and no p63-positive basal cells continue to proliferate or form large colonies of undifferentiated cells. This suggests that Sox2 is needed for the self-renewal of these cells, which have been shown by in vivo lineage tracing to be stem cells (Hong et al., 2004). However, Sox2 does not appear to only affect basal cells, as the survival and proliferation of differentiated lineages, which transiently form colonies of large flattened cells, are also reduced. Since the starting population for the culture is a mixture of different cell types, we are unable to dissect out the contribution of Sox2 to each lineage. In the future studies, one could use *CreER* expressed in specific cell types such as basal or Clara cells to determine the effect of deleting *Sox2* in the adult.

Our injury-repair mouse model has lent further support to the importance of Sox2 for maintaining adult tracheal epithelium. In mice without *Sox2*, the repair after SO_2 injury is severely hampered. Loss of *Sox2* not only decreases proliferation of the epithelium but also affects differentiation. Similar to what we have observed at steady state in mutants without *Sox2*, the numbers of basal, ciliated and Clara cells in mutants also decrease after regeneration. Several lines of evidence have shown that a network of transcription factors important for embryonic development can be reused during injury-repair processes in the respiratory system (Cardoso and Whitsett, 2008). Our data suggest that Sox2 is a potential key player in this network.

In summary, here we present new evidence that Sox2 plays multiple roles in both the developing and adult trachea. In the embryo, Sox2 is required for specifying the lung budding site and the subsequent differentiation of both tracheal mesenchyme and epithelium. Conditionally deleting *Sox2* leads to a reduction in the number of basal, ciliated and Clara cells, whereas the number of mucus-producing cells is increased (Fig. 8). In the adult, Sox2 continues to play important roles and it regulates both the proliferation and differentiation of the epithelium at steady state and following injury (Fig. 8). In future studies it will be important to determine the downstream effectors and target genes of Sox2 in the respiratory system.

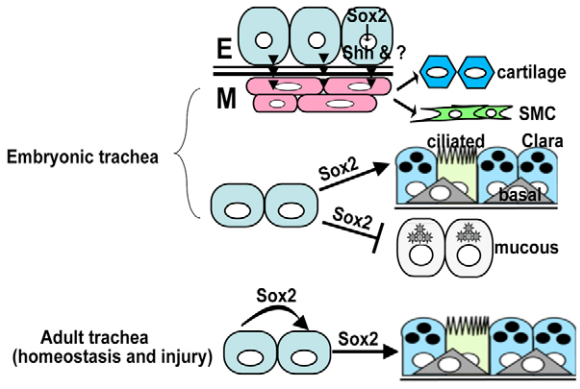

Fig. 8. Model for the roles of Sox2 in developing and adult trachea. At embryonic stage, Sox2 is required for the differentiation of tracheal mesenchyme and epithelium. Conditional deletion of *Sox2* results in a decreased number of basal, Clara and ciliated cells, and more mucus-producing cells in the developing trachea. In the adult, Sox2 regulates both proliferation and differentiation at steady state and following injury. *Sox2* deletion leads to reduced proliferation of tracheal epithelium both in vivo and in vitro. Loss of *Sox2* also impairs the regeneration process of the trachea after inhaled SO_2-induced injury.

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Supplementary material

Supplementary material available online at
http://dev.biologists.org/cgi/content/full/136/11/1899/DC1

References

Aubin, J., Lemieux, M., Tremblay, M., Berard, J. and Jeannotte, L. (1997). Early postnatal lethality in Hoxa-5 mutant mice is attributable to respiratory tract defects. *Dev. Biol.* **192**, 432-445.

Cardoso, W. V. and Lu, J. (2006). Regulation of early lung morphogenesis: questions, facts and controversies. *Development* **133**, 1611-1624.

Cardoso, W. V. and Whitsett, J. A. (2008). Resident cellular components of the lung: developmental aspects. *Proc. Am. Thorac. Soc.* **5**, 767-771.

Chen, F., Desai, T. J., Qian, J., Niederreither, K., Lu, J. and Cardoso, W. V. (2007). Inhibition of Tgf beta signaling by endogenous retinoic acid is essential for primary lung bud induction. *Development* **134**, 2969-2979.

Chen, X., Qin, R., Liu, B., Ma, Y., Su, Y., Yang, C. S., Glickman, J. N., Odze, R. D. and Shaheen, N. J. (2008a). Multilayered epithelium in a rat model and human Barrett's esophagus: expression patterns of transcription factors and differentiation markers. *BMC Gastroenterol.* **8**, 1.

Chen, X., Vega, V. B. and Ng, H. H. (2008b). Transcriptional regulatory networks in embryonic stem cells. *Cold Spring Harb. Symp. Quant. Biol.* (in press).

Chen, Y., Shi, L., Zhang, L., Li, R., Liang, J., Yu, W., Sun, L., Yang, X., Wang, Y., Zhang, Y. et al. (2008c). The molecular mechanism governing the oncogenic potential of SOX2 in breast cancer. *J. Biol. Chem.* **283**, 17969-17978.

Chisaka, O. and Capecchi, M. R. (1991). Regionally restricted developmental defects resulting from targeted disruption of the mouse homeobox gene hox-1.5. *Nature* **350**, 473-479.

Daniely, Y., Liao, G., Dixon, D., Linnoila, R. I., Lori, A., Randell, S. H., Oren, M. and Jetten, A. M. (2004). Critical role of p63 in the development of a normal esophageal and tracheobronchial epithelium. *Am. J. Physiol. Cell Physiol.* **287**, C171-C181.

Desai, T. J., Malpel, S., Flentke, G. R., Smith, S. M. and Cardoso, W. V. (2004). Retinoic acid selectively regulates Fgf10 expression and maintains cell identity in the prospective lung field of the developing foregut. *Dev. Biol.* **273**, 402-415.

Evans, C. M., Williams, O. W., Tuvim, M. J., Nigam, R., Mixides, G. P., Blackburn, M. R., DeMayo, F. J., Burns, A. R., Smith, C., Reynolds, S. D. et al. (2004). Mucin is produced by clara cells in the proximal airways of antigen-challenged mice. *Am. J. Respir. Cell Mol. Biol.* **31**, 382-394.

Fauquier, T., Rizzoti, K., Dattani, M., Lovell-Badge, R. and Robinson, I. C. (2008). SOX2-expressing progenitor cells generate all of the major cell types in the adult mouse pituitary gland. *Proc. Natl. Acad. Sci. USA* **105**, 2907-2912.

Ferri, A. L., Cavallaro, M., Braida, D., Di Cristofano, A., Canta, A., Vezzani, A., Ottolenghi, S., Pandolfi, P. P., Sala, M., DeBiasi, S. et al. (2004). Sox2 deficiency causes neurodegeneration and impaired neurogenesis in the adult mouse brain. *Development* **131**, 3805-3819.

Gontan, C., de Munck, A., Vermeij, M., Grosveld, F., Tibboel, D. and Rottier, R. (2008). Sox2 is important for two crucial processes in lung development: branching morphogenesis and epithelial cell differentiation. *Dev. Biol.* **317**, 296-309.

Hong, K. U., Reynolds, S. D., Watkins, S., Fuchs, E. and Stripp, B. R. (2004). In vivo differentiation potential of tracheal basal cells: evidence for multipotent and unipotent subpopulations. *Am. J. Physiol. Lung Cell Mol. Physiol.* **286**, L643-L649.

Ishii, Y., Rex, M., Scotting, P. J. and Yasugi, S. (1998). Region-specific expression of chicken Sox2 in the developing gut and lung epithelium: regulation by epithelial-mesenchymal interactions. *Dev. Dyn.* **213**, 464-475.

Li, C., Xiao, J., Hormi, K., Borok, Z. and Minoo, P. (2002). Wnt5a participates in distal lung morphogenesis. *Dev. Biol.* **248**, 68-81.

Li, Y., Gordon, J., Manley, N. R., Litingtung, Y. and Chiang, C. (2008). Bmp4 is required for tracheal formation: a novel mouse model for tracheal agenesis. *Dev. Biol.* **322**, 145-155.

Litingtung, Y., Lawler, A. M., Sebald, S. M., Lee, E., Gearhart, J. D., Westphal, H. and Corden, J. L. (1999). Growth retardation and neonatal lethality in mice with a homozygous deletion in the C-terminal domain of RNA polymerase II. *Mol. Gen. Genet.* **261**, 100-105.

Mendelsohn, C., Lohnes, D., Decimo, D., Lufkin, T., LeMeur, M., Chambon, P. and Mark, M. (1994). Function of the retinoic acid receptors (RARs) during development (II). Multiple abnormalities at various stages of organogenesis in RAR double mutants. *Development* **120**, 2749-2771.

Metzger, D. E., Stahlman, M. T. and Shannon, J. M. (2008). Misexpression of ELF5 disrupts lung branching and inhibits epithelial differentiation. *Dev. Biol.* **320**, 149-160.

Miller, L. A., Wert, S. E. and Whitsett, J. A. (2001). Immunolocalization of sonic hedgehog (Shh) in developing mouse lung. *J. Histochem. Cytochem.* **49**, 1593-1604.

Miller, L. A., Wert, S. E., Clark, J. C., Xu, Y., Perl, A. K. and Whitsett, J. A. (2004). Role of Sonic hedgehog in patterning of tracheal-bronchial cartilage and the peripheral lung. *Dev. Dyn.* **231**, 57-71.

Miyagi, S., Masui, S., Niwa, H., Saito, T., Shimazaki, T., Okano, H., Nishimoto, M., Muramatsu, M., Iwama, A. and Okuda, A. (2008). Consequence of the loss of Sox2 in the developing brain of the mouse. *FEBS Lett.* **582**, 2811-2815.

Moses, K. A., DeMayo, F., Braun, R. M., Reecy, J. L. and Schwartz, R. J. (2001). Embryonic expression of an Nkx2-5/Cre gene using ROSA26 reporter mice. *Genesis* **31**, 176-180.

Mucenski, M. L., Nation, J. M., Thitoff, A. R., Besnard, V., Xu, Y., Wert, S. E., Harada, N., Taketo, M. M., Stahlman, M. T. and Whitsett, J. A. (2005). Beta-catenin regulates differentiation of respiratory epithelial cells in vivo. *Am. J. Physiol. Lung Cell Mol. Physiol.* **289**, L971-L979.

Nyeng, P., Norgaard, G. A., Kobberup, S. and Jensen, J. (2008). FGF10 maintains distal lung bud epithelium and excessive signaling leads to progenitor state arrest, distalization, and goblet cell metaplasia. *BMC Dev. Biol.* **8**, 2.

Okubo, T. and Hogan, B. L. (2004). Hyperactive Wnt signaling changes the developmental potential of embryonic lung endoderm. *J. Biol.* **3**, 11.

Okubo, T., Pevny, L. H. and Hogan, B. L. (2006). Sox2 is required for development of taste bud sensory cells. *Genes Dev.* **20**, 2654-2659.

Pepicelli, C. V., Lewis, P. M. and McMahon, A. P. (1998). Sonic hedgehog regulates branching morphogenesis in the mammalian lung. *Curr. Biol.* **8**, 1083-1086.

Que, J., Choi, M., Ziel, J. W., Klingensmith, J. and Hogan, B. L. (2006). Morphogenesis of the trachea and esophagus: current players and new roles for noggin and Bmps. *Differentiation* **74**, 422-437.

Que, J., Okubo, T., Goldenring, J. R., Nam, K. T., Kurotani, R., Morrisey, E. E., Taranova, O., Pevny, L. H. and Hogan, B. L. (2007). Multiple dose-dependent roles for Sox2 in the patterning and differentiation of anterior foregut endoderm. *Development* **134**, 2521-2531.

Rawlins, E. L., Ostrowski, L. E., Randell, S. H. and Hogan, B. L. (2007). Lung development and repair: contribution of the ciliated lineage. *Proc. Natl. Acad. Sci. USA* **104**, 410-417.

Sasaki, H. and Hogan, B. L. (1994). HNF-3 beta as a regulator of floor plate development. *Cell* **76**, 103-115.

Schacht, V., Ramirez, M. I., Hong, Y. K., Hirakawa, S., Feng, D., Harvey, N., Williams, M., Dvorak, A. M., Dvorak, H. F., Oliver, G. et al. (2003). T1alpha/podoplanin deficiency disrupts normal lymphatic vasculature formation and causes lymphedema. *EMBO J.* **22**, 3546-3556.

Schoch, K. G., Lori, A., Burns, K. A., Eldred, T., Olsen, J. C. and Randell, S. H. (2004). A subset of mouse tracheal epithelial basal cells generates large colonies in vitro. *Am. J. Physiol. Lung Cell Mol. Physiol.* **286**, L631-L642.

Sekine, K., Ohuchi, H., Fujiwara, M., Yamasaki, M., Yoshizawa, T., Sato, T., Yagishita, N., Matsui, D., Koga, Y., Itoh, N. et al. (1999). Fgf10 is essential for limb and lung formation. *Nat. Genet.* **21**, 138-141.

Shannon, J. M. and Hyatt, B. A. (2004). Epithelial-mesenchymal interactions in the developing lung. *Annu. Rev. Physiol.* **66**, 625-645.

Sherwood, R. I., Chen, T. Y. and Melton, D. A. (2008). Transcriptional dynamics of endodermal organ formation. *Dev. Dyn.* **238**, 29-42.

Shu, W., Guttentag, S., Wang, Z., Andl, T., Ballard, P., Lu, M. M., Piccolo, S., Birchmeier, W., Whitsett, J. A., Millar, S. E. et al. (2005). Wnt/beta-catenin signaling acts upstream of N-myc, BMP4, and FGF signaling to regulate proximal-distal patterning in the lung. *Dev. Biol.* **283**, 226-239.

Suh, H., Consiglio, A., Ray, J., Sawai, T., D'Amour, K. A. and Gage, F. H. (2007). In vivo fate analysis reveals the multipotent and self-renewal capacities of Sox2+ neural stem cells in the adult hippocampus. *Cell Stem Cell* **1**, 515-528.

Taranova, O. V., Magness, S. T., Fagan, B. M., Wu, Y., Surzenko, N., Hutton, S. R. and Pevny, L. H. (2006). SOX2 is a dose-dependent regulator of retinal neural progenitor competence. *Genes Dev.* **20**, 1187-1202.

Tsukamoto, T., Inada, K., Tanaka, H., Mizoshita, T., Mihara, M., Ushijima, T., Yamamura, Y., Nakamura, S. and Tatematsu, M. (2004). Down-regulation of a gastric transcription factor, Sox2, and ectopic expression of intestinal homeobox genes, Cdx1 and Cdx2: inverse correlation during progression from gastric/intestinal-mixed to complete intestinal metaplasia. *J. Cancer Res. Clin. Oncol.* **130**, 135-145.

Vermot, J., Niederreither, K., Garnier, J. M., Chambon, P. and Dolle, P. (2003). Decreased embryonic retinoic acid synthesis results in a DiGeorge syndrome phenotype in newborn mice. *Proc. Natl. Acad. Sci. USA* **100**, 1763-1768.

Wan, H., Kaestner, K. H., Ang, S. L., Ikegami, M., Finkelman, F. D., Stahlman, M. T., Fulkerson, P. C., Rothenberg, M. E. and Whitsett, J. A. (2004). Foxa2 regulates alveolarization and goblet cell hyperplasia. *Development* **131**, 953-964.