Sox2 and Lef-1 interact with Pitx2 to regulate incisor development and stem cell renewal

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ABSTRACT

Sox2 marks dental epithelial stem cells (DESCs) in both mammals and reptiles, and in this article we demonstrate several Sox2 transcriptional mechanisms that regulate dental stem cell fate and incisor growth. Conditional Sox2 deletion in the oral and dental epithelium results in severe craniofacial defects, including impaired dental stem cell proliferation, arrested incisor development and abnormal molar development. The murine incisor develops initially but is absorbed independently of apoptosis owing to a lack of progenitor cell proliferation and differentiation. Tamoxifen-induced inactivation of Sox2 demonstrates the requirement of Sox2 for maintenance of the DESCs in adult mice. Conditional overexpression of Lef-1 in mice increases DESC proliferation and creates a new labial cervical loop stem cell compartment, which produces rapidly growing long tusk-like incisors, and Lef-1 epithelial overexpression partially rescues the tooth arrest in Sox2 conditional knockout mice. Mechanistically, Pitx2 and Sox2 interact physically and regulate Lef-1 transcriptional expression during development. Thus, we have uncovered a Pitx2-Sox2-Lef-1 transcriptional mechanism that regulates DESC homeostasis and dental development.

KEY WORDS: Cleft palate, Lef-1, Periderm, Pitx2, Sox2, Stem cells

INTRODUCTION

Regenerative organs, such as peripheral blood, hair follicles, intestine and certain types of teeth, house stem cells that reside in a microenvironment known as the niche. This structure acts as a signaling center to control stem cell fate (Clavel et al., 2012; Lane et al., 2014; Spradling et al., 2001). The precise and timely regulation of stem cell renewal and differentiation is essential for tissue formation, growth and homeostasis over the course of a lifetime (Moore et al., 2006), but the molecular mechanisms underpinning this regulation are variable and dependent on tissue-specific signaling and transcription factors.

The continuous growth of rodent incisors occurs via the renewal and differentiation of stem cells in both the epithelial and mesenchymal stem cell niches. During mouse incisor development, both dental epithelial and mesenchymal cells are replenished within one month (Smith and Warshasky, 1975). The labial cervical loop (LaCL), which is located at the proximal end of labial side of the incisor, is the stem cell niche for the dental epithelial stem cells (DESCs) (Fig. 1A) (Biehs et al., 2013; Juuri et al., 2012; Theleff and Tummers, 2009). The neurovascular bundle (NVB) provides a niche in which dental mesenchymal stem cells generate pulp cells and odontoblasts (Kaukua et al., 2014; Zhao et al., 2014). The dental epithelial and mesenchymal components produce signaling factors that promote the differentiation and developmental processes of adjacent tissues.

The transcription factor Sox2 is essential for stem cells and progenitor cells to maintain pluripotency (Boyer et al., 2005; Takahashi and Yamanaka, 2006), and ablation of Sox2 in mice leads to early mortality after implantation (Avilion et al., 2003). Sox2 has important roles in the development of several endodermal tissues, such as the trachea (Xie et al., 2014) stomach and gut (Que et al., 2007), as well as in ectodermal tissues including the anterior pituitary (Jayakody et al., 2012), lens epithelium (Taranova et al., 2006), tongue epithelium (Arnold et al., 2011) and hair follicles (Clavel et al., 2012). Sox2 was recently identified as a marker for DESCs. Sox2+ cells are located in the LaCL and molar cervical loop regions and give rise to the highly proliferative transient-amplifying (TA) cells, which can differentiate into enamel-secreting ameloblasts (Juuri et al., 2012; Li et al., 2015). Conditional inactivation of Sox2 expression using ShhCre revealed aberrant epithelial morphology in the posterior molars (Juuri et al., 2013). In this study, we identified several molecular mechanisms of Sox2 in DESC maintenance and proliferation during tooth initiation and growth.

Previous studies have shown the lymphoid enhancer binding factor 1 (Lef1; also known as Lef1) is regulated by fibroblast growth factor signaling and is required for early tooth development, in which it plays roles in mediating epithelial-mesenchymal interactions (Kratochwil et al., 1996, 2002; Sasaki et al., 2005). Lef-1 deficiency results in arrested tooth morphogenesis at the late bud stage (van Gendern et al., 1994). Epithelial and mesenchymal tissue recombination assays showed that Lef-1 is required only transiently in the dental epithelium (Kratochwil et al., 1996). The majority of Lef-1 expression is shifted to mesenchymal cells/tissues surrounding the epithelium at the bud stage, although Lef-1 expression persists in the basal cells of the epithelium immediately adjacent to the mesenchyme (Kratochwil et al., 1996;
Both Sox2 and Lef-1 are markers of early craniofacial development and are expressed in the oral and dental epithelium (Juuri et al., 2013, 2012; Sasaki et al., 2005; Zhang et al., 2012), but potential Sox2-Lef-1 genetic interactions remain unexplored. A role for Sox2 in DESC maintenance and proliferation during tooth formation has been proposed by conditionally ablating Sox2 in the oral and dental epithelium using the Pitx2Cre system. Conditional inactivation of Sox2 expression in craniofacial tissues leads to severe craniofacial defects, including cleft palate, and arrested incisor development. We report that the Pitx2Cre/Sox2F/F (Sox2cKO) dental defects are due to impaired stem cell proliferation and defective dental epithelial cell differentiation. Because Lef-1 is also required for tooth development and potentially stem cell proliferation, we generated a Lef-1 conditional overexpression mouse and used Pitx2Cre to overexpress Lef-1 in the oral and dental epithelium. We hypothesized that Lef-1 could act as a stem cell factor to induce progenitor cell proliferation and incisor self-renewal. In fact, Lef-1 overexpression formed a new DESC compartment. Furthermore, Lef-1 overexpression partially rescued the incisor phenotype in Sox2cKO mice. Based on our previous reports and new in vitro data, the interaction of Pitx2 and Sox2 regulates Lef-1, Pitx2 and Sox2 expression. In this article, we will provide evidence suggesting a Pitx2-Sox2-Lef-1 regulatory mechanism for DESC maintenance and proliferation.

**RESULTS**

**Specific ablation of Sox2 in the oral and dental epithelium** Consistent with previous reports (Avalion et al., 2003; Ellis et al., 2004), we found that Sox2 is expressed in the lateral ventricle and epithelial tissues in craniofacial regions of embryonic day (E)18.5 wild-type embryos, including the nasal epithelium, oral epithelium,
tongue epithelium and dental epithelium (Fig. S1A,B). As it was previously shown (Juuri et al., 2012), we also detected specific expression of Sox2 in the labial cervical loop (LaCL), where the DESCs reside (Fig. S1C).

To investigate the function of Sox2 in the oral and dental epithelium, we generated Pitx2Cre-Sox2F/F mice, hereafter referred to as Sox2cKO mice. We have previously shown that Pitx2 is expressed in the oral ectoderm at E10.5 and later stages and that Pitx2Cre mice have normal craniofacial and early tooth development (Cao et al., 2010; Li et al., 2013). Pitx2Cre has robust and specific expression in the dental, oral and tongue epithelium at E11.5 and E14.5 (Fig. S1D,E). Immunofluorescence staining demonstrates that Sox2 was efficiently ablated in the lower incisor LaCL and oral epithelium but not in the lateral ventricle of Sox2cKO mice (Fig. S1F-M). These data demonstrate the specificity of the Pitx2Cre, which is not expressed in the lateral ventricle.

**Inactivation of Sox2 leads to lower incisor arrest at E16.5 and abnormalities in upper incisor and molar development**

The first step of mouse tooth development is a thickening of ectoderm-derived oral epithelium at E11.5, after which the thickened epithelium invaginates into the underlying cranial neural crest-derived mesenchyme to form a tooth bud at E12.5. At the bud stage, Sox2cKO tooth germs were detectable but displayed a slightly delayed invagination compared with those of littermate control embryos (Fig. 1B,C). At E14.5, the tooth epithelium further invaginates to envelop the mesenchymal dental papilla to form a cap stage incisor. The cap stage incisors are longitudinally oriented and associated with the oral epithelium compared with control embryos (Fig. 1D,E). At E16.5, the Sox2cKO incisors were smaller, invagination was hindered and the LaCL was severely underdeveloped and lacking structure, compared with Sox2F/F littermates (Fig. 1F,G). At E17.5 and E18.5, lower incisor development regressed in Sox2cKO embryos (Fig. 1H-M), until it was no longer detectable at postnatal day (P)0 (Fig. 1N-P).

Sox2 is also expressed in upper incisors and molars and ShhCre-Sox2F/F mice exhibit molar defects (Juuri et al., 2013). We found that the upper incisors and molars in Sox2cKO embryos were smaller and associated with delayed invagination at E14.5 (Fig. S2A,B). At E16.5, Sox2cKO molars also exhibited an abnormal shape and upper incisors showed a delay in proliferation (Fig. S2C). At P0, Sox2cKO molars lacked cusps (Fig. S2D). These data indicate a role for Sox2 in dental epithelial cell proliferation and tooth growth.

Sox2 was conditionally deleted using the Krt14Cre but we found no obvious incisor defects, although Krt14Cre-Sox2F/F mice exhibited a mild molar defect (Fig. S3). This defect included an expanded dental lamina starting at E13.5 (Fig. S3B,E,H,K,N,Q) and absence of the third molar (data not shown). Interestingly, the pattern of Shh and Fgf4 expression was slightly expanded in E14.5 Krt14Cre-Sox2F/F molars (Fig. S3T,V), suggesting that Sox2 might repress Shh and Fgf4 expression.

**Sox2 regulates incisor growth in adult mice**

Sox2cKO mice die at birth, similar to other Sox2 conditional knockout mice (Juuri et al., 2013; Zhang et al., 2012). To determine whether Sox2 plays a role in adult incisor growth, Sox2F/F mice were crossed with Rosa26CreERT-Sox2F/F mice in which Cre expression can be induced by tamoxifen. After treatment with tamoxifen, we cut the left lower incisors of control and Rosa26CreERT-Sox2F/F mice (Fig. 2A,B). Five days after injury, incisors of tamoxifen-treated control mice grew to a length comparable to the uninjured right lower incisor. By contrast, incisors of tamoxifen-treated Rosa26CreERT-Sox2F/F mice exhibited severely reduced growth, an approximate 50% decrease compared with control mice (Fig. 2B,C). We confirmed that Sox2 expression was ablated in tamoxifen-treated mice by immunofluorescence staining (Fig. 2B).

**Sox2 ablation leads to reduced stem cell proliferation**

Because the loss of Sox2 expression caused embryonic incisor developmental arrest and reduced growth of the adult lower incisor, we next examined proliferation of cells in the LaCL. Immunofluorescence staining of Ki67 (also known as Mki67) in E16.5 Sox2cKO embryonic incisors showed a smaller LaCL and decreased stem cell proliferation in the LaCL compared with control embryos (Sox2F/F) (Fig. 3A-B’). Quantitative analysis indicated that the percentage of Ki67-positive cells was decreased by 40% in Sox2cKO LaCLs (Fig. 3C), suggesting that progenitor cell proliferation was inhibited by loss of Sox2. However, no change in proliferation was detected in the Ki67 of the Sox2cKO embryos compared with controls (Fig. 3A’,B’,C). As a comparison, we detected no change in cell proliferation in Pitx2Cre/Sox2F/F mice (Fig. S4A-C), indicating that the defect is not due to the Pitx2Cre allele.

To determine whether altered progenitor cell proliferation could contribute to reduced incisor growth in Sox2cKO embryos, we performed thymidine analog double labeling in control and Sox2cKO mouse mandibles. In this experiment, highly proliferative cells sequentially incorporate two different thymidine analogues, 5-chloro-2′-deoxyuridine (CldU) and 5-iodo-2′-deoxyuridine (IdU), which allow us to observe and quantify two successive rounds of cell division and potential migration. There were relatively fewer IdU+ cells observed in Sox2cKO LaCL compared with control embryos 1 hour after IdU injection (Fig. 3D,E,G). At 24 h after injection of CldU, the dental epithelial cells in both the proximal region and distal region of control embryos (Sox2F/F) are labeled with CldU (Fig. 3D,D’,red), but there were fewer CldU+ cells in the distal tip of Sox2cKO incisor, suggesting that DESC/progenitor cell migration was affected by loss of Sox2 (Fig. 3E,E,F).

It is possible that reduced growth in the Sox2cKO lower incisor was caused by increased cell death. However, TUNEL staining and immunohistochemistry staining of an early cell death marker, cleaved caspase-3, revealed no obvious cell apoptosis in either Sox2F/F or Sox2cKO incisors (Fig. S4D-K). Therefore, these data suggest that Sox2 primarily regulates progenitor cell proliferation in the LaCL, but the loss of Sox2 in DESCs does not affect the rate of cell death.

**Sox2 and Lef-1 epithelial expression domains are juxtaposed in the mouse oral epithelium and dental placode**

In the Sox2cKO embryos, tooth development is halted at the late bud stage and, interestingly, in Lef-1 null mice dental development is arrested at the late bud stage. To determine whether Sox2 and Lef-1 interact, we analyzed Sox2 and Lef-1 protein expression in E11.5 wild-type (WT), Sox2F/F and Sox2cKO incisors at the dental placode stage (Fig. 4A). Sox2 and Lef-1 were both expressed in the oral epithelium and dental placode of both lower and upper incisors of E11.5 WT embryos (Fig. 4B,C). However, Lef-1 expression was detectable in the anterior regions of the upper and lower incisors,
whereas Sox2 expression was detectable in the posterior region of the incisors (Fig. 4D,E). At E12.5, the pattern of Sox2 and Lef-1 expression were similar to E11.5 as the dental epithelium invaginates into the surrounding mesenchyme (Fig. 4F). As expected, E11.5 Sox2F/F embryos were indistinguishable from WT (Fig. 4E,H-J). Although Sox2 expression was undetectable in Sox2cKO embryos at E11.5, Lef-1 expression was not affected (Fig. 4L-N). Notably, the incisor placodes in Sox2cKO E11.5 embryos also showed delayed epithelial thickening at this stage (Fig. 4K).

To understand further the anterior/posterior expression patterns, coronal sections of E11.5 WT embryos were analyzed for Lef-1 and Sox2 protein expression (Fig. S5A, schematic). Sox2 was expressed in the posterior domain of the lower incisor and Lef-1 was expressed in the anterior region (Fig. S5B, arrowheads showing incisor placodes). Sox2 expression in the molar was localized to the posterior regions and Lef-1 expression was observed in the anterior region on the mandible (Fig. S5B). These results suggest that Sox2 and Lef-1 may act independently of each other to regulate incisor development.

**Conditional overexpression of Lef-1 creates a new LaCL stem cell niche and abnormal 'tusk-like' incisors**

To determine the effect of continuous Lef-1 expression during incisor development, we generated a Lef-1 conditional overexpression mouse. A Lef-1 full-length isoform construct was preceded by a loxP-flanked 'STOP' and inserted into the Rosa26 locus, to make a Cre-responsive Lef-1 conditional knock-in mouse (Lef-1cKI) (Fig. 5A). Lef-1cKI mice were crossed with Pitx2Cre mice to drive the overexpression of Lef-1 in the dental and oral epithelium (Fig. 5A). Lef-1 immunostaining confirmed the overexpression of Lef-1 in the dental epithelium of the conditional overexpression Pitx2Cre-Lef-1cKI embryos (hereafter termed COEL) (Fig. S6C). The COEL mice developed long, thick tusk-like incisors compared with Lef-1cKI mice (control) (Fig. 5B,C). Microcomputed tomography (μCT) analysis of 3-month-old mice revealed that both upper and lower incisors in COEL mice underwent rapid growth compared with Lef-1cKI mice (Fig. 5D,E). The LaCL in the lower incisors of E16.5 COEL embryos were larger than those of control embryos and included a new cell compartment forming on the labial side (Fig. S6A). At P0, the sizes of control and COEL lower incisors were comparable, but an extra branch of the LaCL was detectable in COEL embryos (Fig. S6B).

To determine whether the cells in the branched LaCL of COEL mice are dental epithelial stem cells, we analyzed Sox2 expression in P1 control and COEL LaCL regions. The LaCL and the branched region both contained Sox2-positive stem cells (Fig. 5F,G), suggesting that overexpression of Lef-1 resulted in a new cluster of stem cells. Three-dimensional reconstruction shows the structure of the expanded LaCL with multiple layers and a branching stem cell niche (Fig. 5I-K). Previous studies on tusk-like incisors in Spry2−/−; Spry2−/− mice (Klein et al., 2008) revealed that overgrowth of the lower incisor could be due to ectopic deposition of lingual enamel. To test whether Lef-1 overexpression produced ectopic enamel formation, we performed amelogenin immunostaining in E18.5 embryos and found elevated amelogenin expression in the labial side of COEL LIs, but no ectopic amelogenin expression was detected in the lingual side of COEL incisors (Fig. S6D).

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**Fig. 2. Deletion of Sox2 in adult mice inhibits incisor regeneration.** (A) Tamoxifen treatment, tooth length reduction and histological analysis timeline in Sox2F/F control and Rosa26Cre-ERT/Sox2F/F mice. (B) Images of P29 and P34 mouse incisors after tamoxifen treatment and cutting of the left lower incisor. First column: mouse incisors after cutting half of the left lower incisor. Second column: mouse incisors 5 days after shortening. Third column: microcomputed tomography (μCT) analysis of shortened incisors after 5 days of recovery. Fourth column: Sox2 expression visualized by immunofluorescence (IF) in tamoxifen-treated Rosa26Cre-ERT/Sox2F/F and control mice. (C) Quantification data (mean±s.e.m.) of the relative growth rate of the shortened incisor in Sox2F/F and Rosa26Cre-ERT/Sox2F/F mice after treatment with tamoxifen. Scale bars: 5 mm (μCT images); 100 μm (IF images).
We next investigated whether increased stem cell proliferation in the LaCL could contribute to the increased growth of incisors in COEL mice. BrdU (5-bromo-2'-deoxyuridine) labeling of cells in the E18.5 COEL LaCL showed a 15% increase in progenitor cell proliferation compared with the control LaCL (Fig. 5L,M). However, at P1, proliferation in the LaCL regions was similar to that in the COEL LaCL (Fig. 5O). Most of the cells in the COEL branched LaCL region were not labeled with BrdU, suggesting that these cells were quiescent, i.e. not undergoing proliferation (Fig. 5N). These data point to a model in which overexpression of Lef-1 in the incisor results in increased cell proliferation at embryonic stages and formation of a new compartment of stem cells in the LaCL, which facilitates incisor growth and the formation of tusk-like incisors.

**Lef-1 overexpression rescues tooth arrest in Sox2<sup>cKO</sup> embryos**

Because both Sox2 and Lef-1 appear to control dental epithelial stem cell renewal and maintenance, we next investigated whether Lef-1 overexpression could rescue the tooth arrest in Sox2<sup>cKO</sup> embryos. To test our hypothesis, we crossed Sox2<sup>cKO</sup> mice with COEL mice to produce Pitx2<sup>cCre</sup>/Sox2<sup>F/F</sup>/Lef-1<sup>cKI</sup> (rescue) mice. At E18.5, the Sox2<sup>F/F</sup>/Lef-1<sup>cKI</sup> (control) embryos developed well-formed late bell stage incisors (Fig. 6A). The E18.5 Sox2<sup>cKO</sup> embryos had a remnant of the LI at this stage (Fig. 1K,L). In rescue mice, the LIs are detectable, but the LI was positioned at the anterior region of the mandible and was smaller in size (Fig. 6B). The forward positioning of the LI might be due to oral adhesions that remain. The LaCL in rescue mice was smaller than in control embryos (Fig. 6B). In the labial side of control embryos, the lower incisors develop three layers: odontoblasts, ameloblasts and the stratum intermedium. However, there was only one layer of cells in rescue embryos, suggesting that differentiation was blocked (Fig. 6A,B, blue boxes). Interestingly, the LaCL was partially restored in the rescue embryos (Fig. 6D,D′). Lef-1 is highly expressed in the labial side (Fig. 6C,C′). However, amelogenin was ectopically expressed on the lingual side of the lower incisor in rescue embryos (Fig. 6D,D′). Lef-1 is highly expressed in the lingual cervical loop at E18.5 due to Pitx2<sup>cCre</sup> activity in these mice (Fig. 6E,F). Thus, we speculate that the interplay between Sox2 and Lef-1 with other factors specifies asymmetric amelogenin expression.

**Fig. 3. Sox2 regulates dental epithelial stem cell proliferation and differentiation.** (A−B′) Immunofluorescence staining of the proliferation marker Ki67 in sagittal sections of E16.5 Sox2<sup>F/F</sup> and Sox2<sup>cKO</sup> mouse incisors. (A′,B′) High magnification view of red boxed regions in A and B to show the proliferation in the LaCL (outlined). (A′′,B′′) High magnification view of white boxed regions in A and B to show the proliferation in the LiCL (outlined). (C) Quantification of the ratio of Ki67-positive cells to total cells in the cervical loops. Mean±s.e.m., n=3. (D−F) Progenitor cell differentiation measured using two different labels (CldU and IdU), which were injected and measured after 24 h and 1 h, respectively. The red label-retaining cells (CldU) mark differentiated cells and the green label-retaining cells (IdU) mark recently mitotic cells. The arrows indicate the region of neural vascular bundles. The LaCLs are highlighted by yellow dashed boxes. (D) Quantification of CldU<sup>+</sup> cells in the epithelial tissue of the white boxed region shown in D′ and D″. Mean±s.e.m., n=3. Scale bars: 100 μm.
To determine whether progenitor cell proliferation was rescued and contributes to the development of the LI in rescue mice, we analyzed proliferation at E16.5. Proliferation was dramatically reduced in the LI LaCL region in Sox2cKO mice, but it was restored in rescue embryos (Fig. S8A; H). Thus, overexpression Lef-1 in Sox2-ablated incisors partially rescued the tooth arrest by promoting stem cell maintenance and cell proliferation.

We next investigated whether Lef-1 overexpression affected Sox2 expression in the COEL and rescue E11.5 embryos. Lef-1 expression was not changed in the Pitx2Cv/Sox2CvEF embryos and Sox2 expression was unchanged in the COEL embryos; however, Lef-1 expression was expanded posteriorly in the rescue embryos (Fig. S8A). We also asked whether Pitx2 expression was affected in the Pitx2Cv/Sox2CvEF embryos. Pitx2 expression was detected by in situ hybridization and in the Pitx2Cv/Sox2CvEF E11.5 embryos Pitx2 expression was slightly increased compared with Sox2CvEF embryos owing to the reduced expression of Sox2 (Fig. S8B); we show in later experiments that Sox2 interacts with Pitx2 to inhibit transcriptional activation of Pitx2 expression, thus decreased Sox2 expression would increase Pitx2 expression. Interestingly, because Pitx2CvEF embryos have only one functional allele of Pitx2, the lack of a decrease in Pitx2 expression indicates that the loss of a Pitx2 allele in the Pitx2CvEF mouse does not contribute to the defects in the Sox2KO embryos.

Additionally, Sox2 expression was expanded in the LaCL of COEL E18.5 embryos and specifically in the new stem cell niche compartment (Fig. S8D, arrowhead). The new stem cell compartment showed less Lef-1 expression compared with the complete LaCL (Fig. S8D, merge). Thus, Lef-1 overexpression created a new stem cell compartment but the compartment contained Sox2-positive cells that were not proliferating (Fig. S5).

**Sox2 attenuates Pitx2 transcriptional activation of Lef-1, Sox2 and Pitx2 through direct protein interactions**

To determine a molecular mechanism for the Sox2-Lef-1 effects on incisor development, we focused on the transcriptional activities of these factors in concert with Pitx2. Pitx2 is the first transcriptional marker of tooth development and Pitx2 null mice have tooth development arrest at E12.5 (Liu et al., 2003; Lu et al., 1999). We have previously shown that Pitx2 regulates Lef-1 expression during odontogenesis (Amen et al., 2007; Vadlamudi et al., 2005). RNA-sequencing data showed that Sox2 expression was upregulated in the mandibles of Pitx2 overexpression mice and downregulated in the mandibles of Pitx2 null mice (B.A. and H. Cao, unpublished data), indicating that Pitx2 regulates Sox2. Sequence analyses of the Sox2 promoter identified one Pitx2-binding element located in the 5′UTR and another in a distal element 845 bp upstream of the transcription start site (TSS) (Fig. S9A). Chromatin-immunoprecipitation (ChIP)
showed Pitx2 binding to both elements (Fig. S9B,C). We also identified a putative Sox2-binding element 1972 bp upstream of the Sox2 TSS and ChIP assay showed that Sox2 binds to this element (Fig. S9D-F).

The Sox2 promoter (4.0 kb) was cloned into a luciferase vector and transfected into LS-8 oral epithelial cells to test for regulation by Pitx2 and Sox2. Pitx2 activated the Sox2 promoter 15-fold compared with empty vector and Sox2 activated its own promoter threefold (Fig. S9G). To confirm this regulation, we measured endogenous levels of Sox2, Lef-1 and Pitx2 in LS-8 cells transfected with empty vector (pcDNA3.1), Pitx2 or Sox2. Cells transfected with Pitx2 showed significantly increased levels of Sox2 and Lef-1 transcripts (Fig. S9H), whereas the cells transfected with Sox2 showed no significant difference in the levels of Lef-1 or Pitx2 (Fig. S9H).

Finally, we show, using immunoprecipitation (IP) assays, that Pitx2 and Sox2 interact endogenously (Fig. S10A). We further conclude that the HMG domain and the C terminus in Sox2 protein mediate the Pitx2 binding to Sox2 based on results from a glutathione S-transferase (GST) pull-down assay (Fig. S10B-D).

Taken together, our results show that Sox2 protein and Pitx2 interact endogenously (Fig. S10A). We further conclude that the HMG domain and the C terminus in Sox2 protein mediate the Pitx2 binding to Sox2 based on results from a glutathione S-transferase (GST) pull-down assay (Fig. S10B-D).

Taken together, our results show that Sox2 protein and Pitx2 protein interact to repress Pitx2 transcriptional activity. These findings provide a new mechanism to establish the juxtaposed expression domains of Sox2 and Lef-1 during tooth development. Pitx2 is expressed throughout the oral epithelium and dental placode. In the posterior region of the dental placode, Pitx2 activates Sox2 and the Pitx2-Sox2 complex inhibits Lef-1 expression. In the anterior region of the dental placode, the absence of Sox2 is in this region allows Pitx2 activation of Lef-1. A working model of this new transcriptional regulation and expression of Sox2 and Lef-1 is presented in Fig. 7. At later stages of incisor development in the LaCL, Lef-1 is not expressed in the dental epithelium but shifts to the adjacent mesenchyme. We demonstrate that a Pitx2-Sox2-Lef-1
regulatory mechanism plays a major role in maintaining the stem cell niche and promoting stem cell proliferation (Fig. 7).

**DISCUSSION**

Previous studies have shown an early role for Sox2 in the specification of DESCs, and Sox2+ cells mark DESCs (Juuri et al., 2012; Li et al., 2015). Furthermore, conditional deletion of Sox2 using ShhCre results in abnormal epithelial growth in mouse molars (Juuri et al., 2013), consistent with what we observed in K14Cre;Sox2F/F embryos. However, by using the earliest dental epithelium marker, Pitx2Cre, to ablate Sox2 in the dental and oral epithelium, we found that the loss of Sox2 leads to incisor developmental arrest at E16.5 with a complete disintegration at P0 and abnormal molar growth. We propose that this is mainly due to the failure to maintain the DESC niche at an early stage resulting in a lack of proliferative cells and gradual loss of the incisor tooth germ. These data correlate well with the role of Sox2 in the specification of the stem cell niche (Juuri et al., 2012). Furthermore, loss of Sox2 during adult lower incisor growth resulted in a reduction of incisor regeneration, demonstrating an essential role for Sox2 in maintaining the adult DESC niche. Therefore, these studies show that incisor arrest at E16.5 and abnormal molar formation is due to depletion of the epithelial stem cells in the LaCL, which is regulated by Sox2.

Lef-1 controls stem cell self-renewal and establishes stem and progenitor cell compartments in mouse epidermis and hair follicles (Huang and Qin, 2010; Lowry et al., 2005; Petersson et al., 2011). In our study, Lef-1 overexpression enhanced DESC production and promoted stem cell proliferation but also produced a new compartment of mitotically inactive stem cells in the LaCL leading to dramatically increased growth of the incisor. Thus, Lef-1 activity contributes to the establishment of stem and progenitor cell compartments in the mouse incisor. Sox2 and Lef-1 expression domains define the epithelial component of the initial dental placode, demonstrating distinct roles for these two factors. It appears that Sox2 and Lef-1 control different cell subpopulations in the developing tooth germ. In support of this, Lef-1 overexpression increased the number of cells in the LaCL, but, interestingly, the branched ‘new’ stem cell compartment contained predominantly Sox2+ cells that were not BrdU labeled, suggesting that these cells were quiescent cells. A possible explanation is that the proliferating cells expressing Lef-1 in the lower incisor LaCL are an expanded
group of progenitor cells that contribute to the rapid growth of the COEL incisors. Thus, the quiescent stem cells are partitioned to a new compartment where they give rise to new progenitor cells.

The upper incisor in Sox2-KO embryos also failed to develop normally and at P0 only a remnant remained of the tooth germ. The growth and eruption rate of the upper incisor is slower than that of the lower incisor, which might be due to fewer progenitor cells in the smaller tooth germ of the upper incisor. We speculate that the less severe phenotype of the upper incisor in the Sox2-KO embryos might be due to the reduced number of Sox2+ cells regulating its growth. Interestingly, Lef-1 overexpression greatly increased the growth of the upper incisor.

We found that Lef-1 overexpression rescues tooth arrest in Sox2-KO embryos by enhancing DESC self-renewal and maintenance, further verifying the role of Lef-1 in stem cell maintenance. In these rescue mice, we found amelogenin aberrantly expressed in the lingual epithelial cell layer. Normally, epithelial stem cells differentiate into ameloblast cells only on the labial side, where they express amelogenin and secrete the organic matrices of enamel (Thesleff and Tummers, 2009). This complete switch of amelogenin expression to the lingual epithelial cells is similar to other mouse models. Misregulation of BMP signal regulators can cause ameloblast differentiation defects. For example, overexpression of noggin or follistatin using the K14 (Krt14) promoter disrupts ameloblast differentiation on the labial side of the incisor whereas lack of follistatin causes both sides of the incisor to develop functional ameloblasts that secrete enamel (Plikus et al., 2005; Wang et al., 2007, 2004). Ectopic fibroblast growth factor expression in the lingual side of incisors resulting from ablation of sprouty genes leads to ectopic deposition of enamel on the lingual side (Klein et al., 2008, 2007, 2004). Although COEL embryos do not display this effect, the lack of Sox2 expression in the incisor tooth germ appears to regulate other factors that might interact with Lef-1 to regulate amelogenin expression.

Sox2 can have both inductive and repressive transcriptional effects on Lef-1 promoter activities dependent on other factors to specify
progenitor cell populations during early and late submucosal gland development (Xie et al., 2014). In tooth development, we have identified that the juxtaposed expression of Sox2 and Lef-1 in the dental placode may be coordinated by Pitx2 expression. We have identified a molecular mechanism whereby Pitx2 activates Pitx2, Sox2 and Lef-1 expression in the dental epithelial stem cells and these activations can be abolished by the Pitx2-Sox2 protein complex. Sox2 interacts with Pitx2 and represses Pitx2 transcriptional activity. The identification of Sox2 protein interactions with Pitx2, resulting in the repression of Pitx2 transcriptional activation of many target genes, provides a model for the role of Sox2 in maintaining the dental stem cells and inhibiting differentiation of these cells. Collectively, our study reveals a Pitx2-Sox2-Lef-1 pathway in regulating DESC maintenance and proliferation and this finding may provide novel molecular approaches for tooth regeneration.

MATERIALS AND METHODS

Mouse lines and embryonic staging
The Program of Animal Resources at the University of Iowa housed mice. Each procedure complied with the guidelines set by the University of Iowa Institutional Animal Care and Use Committee. Sox2 conditional knockout mice (Sox2Flox/Flox) have been previously described (Taranova et al., 2006), and the ROSA-CreERT2 [B6.129-Gt(ROSA)26Sorcre/ERT2]JyiJ] mice originated from the Jackson Laboratory (stock number 008463). Each of these strains was a generous gift from John Engelhardt (University of Iowa). The Lef-1 conditional overexpression (COEL) mouse line was generated by inserting Lef-1 downstream of a CAAG promoter and a floxed transcription stop signal. The Pitx2Cre mouse has been described previously (Liu et al., 2003). Each mouse line was derived from a C57BL/6 background. The genotyping primers for all the mouse lines are listed in Table S1.

Cloning, transient transfection and luciferase assay

The Lef-1 2700 bp (Lef-1 2.7) promoter luciferase vector was constructed as previously described (Amen et al., 2007). Sox2 2.0 luciferase reporter was constructed by inserting a ~2.0 kb Sox2 DNA fragment located in the upstream region of Sox2 and containing Pitx2-binding sites into the pTK-luc vector. Similarly, ~5.0 kb upstream of the Pitx2 gene was ligated to pTK-luc to generate the Pitx2 5.0 luciferase reporter. Standard transient transfection by electroporation and luciferase assay were carried out in LS-8 cells (oral epithelial-like cells) according to a previous report (Cao et al., 2013).

Immunohistochemistry, immunofluorescence and histology
The following primary antibodies were used in our study: Sox2 (goat; R&D Systems, AF2018, 1:200; rabbit: Abcam, ab97959, 1:200), GFP (Abcam, ab290, 1:500), Ki67 (Abcam, ab15580, 1:200), Lef-1 (Cell Signaling, #2230, 1:200), cleaved caspase-3 (Cell Signaling, #9661, 1:200) and amelogenin (Santa Cruz, L0506, 1:200). Detailed protocols are provided in the supplementary Materials and Methods.

Quantitative real time PCR gene expression analysis

Total RNAs were extracted from LS-8 cells overexpressing pcDNA 3.1 (empty vector), Pitx2 or Sox2 using an RNasy Mini Kit from Qiagen. Reverse transcription was performed according to the manufacturer’s instructions (BIO-RAD Script Select cDNA Synthesis Kit) using oligo (dT) primers. cDNAs were then adjusted to equal levels by PCR amplification with primers to β-actin. Fold change was calculated based on the 2^(-ΔΔCT) method. All real-time PCR primer sequences are listed in Table S2.

Brdu labeling and IdU/CldU labeling assay

Two hours prior to sacrifice, pregnant mice were injected with BrdU (10 μg/g body weight; Invitrogen, 00-1030); rat monoclonal anti-BrdU antibody (Abcam, ab6326, 1:250) was used in this experiment. The IdU/ CldU labeling assay was performed according to a previous report with modifications (Tuttle et al., 2010). Detailed protocols are provided in the supplementary Materials and Methods.

Incisor injury and recovery assay

Starting from P21, experimental mice (Sox2F/F; Sox2CreERT) and control mice (Sox2F/F) were fed with 130 μg/g bodyweight tamoxifen (Sigma) daily for a week using a gavage needle. After 8 days of tamoxifen treatment (P29), the left lower incisor of the mouse was clipped and its length was recorded using a caliper. Tamoxifen was administered daily for another three doses (P31, P32 and P34), and the animals were sacrificed at P34. The growth rate was analyzed by daily length increase of the injured incisor [growth rate=(lengthP34−lengthP31)/(days−1)]. The relative growth rate was calculated by normalizing the growth rate of injured incisor of experimental mice to control mice.

Chromatin immunoprecipitation assay (ChIP)
The procedure for the ChIP assay has been described previously (Wang et al., 2013). Briefly, the ChIP Assay Kit (Zymo Research, ZymoSpin ChIP Kit, D5210) was used with a modified protocol. LS-8 cells were seeded in T-75 flasks in DMEM supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (Life Technology) and fed 24 h prior to the experiment. On the day of the experiment, the adherent cells were harvested and collected in a 1.5 ml tube. The cells were washed twice in cold PBS solution and crosslinked (1% formaldehyde, room temp, 7 min). After crosslinking, cells were subjected to three rounds of sonication (6 s duration, 25% of maximum amplitude), causing lysis and the shearing of genomic DNA in fragments of approximately 200-1000 bp. DNA/protein complexes were immunoprecipitated with 5 μg Pitx2 antibody (Pitx2 antibody, Capra Sciences, PA-1023) or Sox2 antibody (R&D Systems, AF2018). The same amount of normal rabbit IgG was used to replace the specific antibody to assess the nonspecific immunoprecipitation of the chromatin. All the primer sequences used in this assay are list in Table S2. Three parallel pQCRs were performed using ChIP products. Relative enrichment was calculated using the 2^(-ΔΔCT) method. All the PCR products were visualized on a 1.5% agarose gel to check the size and their identities were confirmed by sequencing.

GST pull-down assays

GST pull-down assays were carried out as previously described (Wang et al., 2013). Briefly, GST-Sox2 full-length and truncated fusion proteins were isolated, purified and suspended in binding buffer (20 mM HEPES buffer, pH 7.5, 5% glycerol, 50 mM NaCl, 1 mM EDTA, 1 mM DTT; with 1% milk and 400 μg/ml ethidium bromide). Bacterially overexpressed and purified Pitx2A protein (2 μg) was added to 10 μg immobilized GST fusion protein in a total volume of 100 μl and incubated for 30 min at 4°C. The beads were pelleted and washed five times with binding buffer. The bound proteins were boiled in SDS loading buffer for 5 min to elute protein from beads. The boiled samples were run on a 12% SDS-PAGE gel. Samples were transferred to a PVDF membrane, immunoblotted and visualized using Pitx2 antibody (Capra Sciences, PA-1023; 1:1000) and ECL reagents (GE HealthCare).

Immunoprecipitation assay

ET16 cells (a gift from Dr Malcolm Snead, University of Southern California) were fed 24 h before the experiment and grown to 90% confluence in two T-175 flasks. Cells were collected and washed twice in ice-cold PBS, and lysed using 5% lysis buffer (Promega) in the presence of EDTA, DTT and 1% Triton X-100. After crosslinking, the cells were subjected to three rounds of sonication (6 s duration, 25% of maximum amplitude), causing lysis and the shearing of genomic DNA in fragments of approximately 200-1000 bp. DNA/protein complexes were immunoprecipitated with 5 μg Pitx2 antibody (Pitx2 antibody, Capra Sciences, PA-1023) or Sox2 antibody (R&D Systems, AF2018). The same amount of normal rabbit IgG was used to replace the specific antibody to assess the nonspecific immunoprecipitation of the chromatin. All the primer sequences used in this assay are list in Table S2. Three parallel pQCRs were performed using ChIP products. Relative enrichment was calculated using the 2^(-ΔΔCT) method. All the PCR products were visualized on a 1.5% agarose gel to check the size and their identities were confirmed by sequencing.
In situ hybridization

Formalin-fixed paraffin-embedded tissue sections were used for in situ hybridization. Tissue samples were prepared following a typical paraffin-embedding process. Frontal sections were cut into segments of 8 µm, and subsequently prepared according to the standard in situ hybridization method described in Gregorieff’s protocol (Gregorieff and Clevers, 2015). The digoxigenin-labeled probe was made using a DIG RNA Labeling Kit (Roche # 1175025910). Primers used for the Pitx2 probe were: Pitx2c-F: ACCAACCTTACGGAACCCGAGT; Pitx2c-T7-R: TAATAGCTACTATAGCTGCAATGCGAAGCATACTCA.

TUNEL assay

Paraffin sections were cut (7 mm) and rehydrated with sequential concentrations of alcohol. The TUNEL assay was carried out using the DeadEnd Fluorometric TUNEL System (Promega, G3250) according to the manufacturer’s protocol.

Imaging and microcomputed tomography (µCT)

Mouse skulls from three experimental and control animals were scanned with a Siemens Inveon Micro-CT/PET scanner using 60 kVp and 500 mA with a voxel size of 30 µm. Reconstructed images were imported using Osirx DICOM software.

3D reconstruction of the labial cervical loops

Three-dimensional (3D) reconstructions of the labial cervical loop (LaCL) in P2 Lef-1cKO and COEL mice were made from serial sagittal sections (7.0 µm). The labial epithelial tissues were manually traced on consecutive sections and automatically aligned using the StackReg plugin for ImageJ. The final 3D reconstructions were rendered using Imaris software from Bitplane AG.


