Runx2+ niche cells maintain mesenchymal tissue homeostasis through IGF signaling

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Highlights:

1. MSCs are heterogeneous in the adult mouse incisor
2. Runx2+/Gli1+ cells are MSC niche cells, but not MSCs
3. Runx2+/Gli1+ cells coordinate MSC-to-TAC transition and the growth rate of incisor
4. Runx2-mediated IGF signaling controls cell fate of TACs
SUMMARY

Stem cell niches provide a microenvironment to support the self-renewal and multi-lineage differentiation of stem cells. Cell-cell interactions within the niche are essential for maintaining tissue homeostasis. However, the niche cells supporting mesenchymal stem cells (MSCs) are largely unknown. Using single-cell RNA sequencing, we show heterogeneity among Gli1+ MSCs and identify a subpopulation of Runx2+/Gli1+ cells in the adult mouse incisor. These Runx2+/Gli1+ cells are strategically located between MSCs and transit amplifying cells (TACs). They are not stem cells, but help to maintain the MSC niche via IGF signaling to regulate TAC proliferation, differentiation, and incisor growth rate. ATAC-seq and chromatin immunoprecipitation reveal that Runx2 directly binds to Igfbp3 in niche cells. This Runx2-mediated IGF signaling is crucial for regulating the MSC niche and maintaining tissue homeostasis to support continuous growth of the adult mouse incisor, providing a model for analysis of the molecular regulation of the MSC niche.

Key words: Runx2, mesenchymal stem cells, niche, transit amplifying cells
INTRODUCTION

Continuous cell replacement helps to maintain homeostasis in tissues such as the skin and gastrointestinal tract (Blanpain and Fuchs, 2014; Kaukua et al., 2014). Tissue homeostasis is supported by stem cells, which reside within specialized microenvironments, referred to as niches, that in turn provide support and signals to regulate stem cell self-renewal and differentiation (Chacon-Martinez et al., 2018; Rezza et al., 2016; Simons and Clevers, 2011). The complex dynamics of the stem cell niche are orchestrated by the supporting extracellular matrix (ECM), niche cells, and soluble signaling factors that act via autocrine or paracrine mechanisms (Morrison and Spradling, 2008; Scadden, 2014). There are several well-defined niches that harbor stem cells necessary to maintain homeostasis and regenerate tissues after damage. The intestinal epithelium, for example, contains Paneth cells that secrete niche signals such as Wnt3, Egf, and Notch ligand Dll4 to intestinal stem cells (Ganz, 2000; Sato et al., 2011). In the hair follicle epidermis, transit amplifying cells (TACs) crucially help regulate the stem cell niche through producing Sonic hedgehog (Shh) (Hsu et al., 2014). In the mesenchyme, however, niche cells for mesenchymal stem cells (MSCs) have yet to be well defined.

Mammalian teeth harbor MSCs in the dental pulp which contribute to tooth homeostasis and repair. In particular, rodent incisors provide an excellent window into the activities of MSCs and their niches since these teeth continue to grow throughout the animal’s life (Lapthanasupkul et al., 2012; Wang et al., 2007). MSC and TAC populations can be clearly identified in the proximal region of the rodent incisor, residing between the labial and lingual sides of the epithelial cervical loop (Sharpe, 2016; Shi et al., 2019; Zhao et
al., 2014). Recently, using genetic lineage tracing, several markers have been identified as labeling different MSC populations \textit{in vivo} (An et al., 2018b; Feng et al., 2011; Kaukua et al., 2014; Zhao et al., 2014), improving our understanding of the heterogeneity of stem cell populations. Specifically, our previous study has shown that quiescent Gli1+ cells are typical MSCs in the mouse incisor. These stem cells surround the neurovascular bundle in the proximal region of the incisor. This population of MSCs continuously gives rise to TACs, which actively divide and then differentiate into odontoblasts and dental pulp cells to support both homeostasis and injury repair (Zhao et al., 2014). Kaukua and colleagues showed that Plp1/Sox10+ glia-derived MSCs dwell in a niche in the proximal region of the mouse incisor. While Gli1+ MSCs contribute to the entire dental pulp, these multipotent Plp1/Sox10+ Schwann cell precursors (SCPs) and Schwann cells contribute to approximately half of the pulp cells and odontoblasts during development, growth, and regeneration of the incisor (Kaukua et al., 2014). Another study identified an MSC population derived from neuronal glia; they reported a subpopulation of MSCs that express CD90/Thy1 and contribute to 30% of differentiated cell progeny during incisor eruption and injury repair (An et al., 2018b). Collectively, these studies suggest there may be considerable heterogeneity among MSCs in the adult mouse incisor.

\textit{Runx2} encodes a transcription factor that is well known for its important role during bone and tooth development. In humans, \textit{RUNX2} mutations are responsible for an autosomal dominant disorder, cleidocranial dysplasia (CCD), which is associated with bone formation defects (Jaruga et al., 2016; Wang et al., 2013). Disruption of \textit{Runx2} in mice leads to maturational arrest of osteoblasts and therefore a complete lack of
ossification during both endochondral and intramembranous bone formation, while tooth morphogenesis is arrested at the cap stage (D’Souza et al., 1999; Komori et al., 1997; Otto et al., 1997). In the dental mesenchyme, Runx2 regulates mesenchymal odontogenic activity by modulating antagonistic interaction between transcription factors Msx1 and Osr2, and plays an essential role in upregulating mesenchymal Fgf signals during later stages of tooth morphogenesis (Kwon et al., 2015). In the dental epithelium, Runx2 and CCAAT/enhancer binding protein beta (Cebpβ) act synergistically to prevent epithelial-mesenchymal transition (EMT) of odontogenic epithelial stem cells via snail family zinc finger2 (Snai2). Abrogating Cebpβ and Runx2 results in EMT and promotes Sox2 expression and stemness of oral epithelial stem cells, ultimately leading to supernumerary teeth forming around the labial portion of the cervical loop in Cebpβ−/− Runx2+/− mice (Saito et al., 2018). Runx2 is clearly important for early tooth development but its potential function in regulating MSCs in adult tooth homeostasis is unknown.

In this study, we further characterized the Gli1+ cell population in the mouse incisor using single-cell RNA sequencing (scRNA-seq). We revealed that Gli1+ cells constitute a heterogeneous population and identified a subpopulation characterized by expression of Runx2 in the proximal region of the adult incisor. These Runx2+ cells are located in close proximity to both MSCs and TACs, and are thus strategically positioned to support the stem cell niche environment. Furthermore, insulin-like growth factor-binding protein 3 (Igfbp3) secreted by these Runx2+ cells activates insulin-like growth factor 2 (IGF-2) signaling to regulate TAC proliferation and differentiation. We further demonstrated that this subpopulation of Runx2+/Gli1+ niche cells controls the rate of incisor growth in adult mice. This discovery also improves our understanding of the stem cell niche
microenvironment and has broader implications concerning the heterogeneity of Gli1+ cells and their roles in regulating tissue homeostasis.
RESULTS

Runx2 is expressed in a subpopulation of Gli1+ cells in the proximal region of the incisor

MSCs in the mouse incisor have been reported to be labelled by heterogenous markers (An et al., 2018b; Feng et al., 2011; Kaukua et al., 2014; Zhao et al., 2014). To elucidate the heterogeneity of the MSC population in the adult mouse incisor, we performed scRNA-seq analysis on incisors from 1-month-old wild type mice (Figure 1A). Unbiased t-distributed stochastic neighbor embedding (t-SNE) showed Gli1 expression in the dental mesenchyme as well as the epithelium (Figure 1B). Gli1+ cells were selected and re-clustered through t-SNE analysis. Results showed that Gli1+ cells consisted of nine distinct clusters (Figure 1C). We validated and mapped the clusters based on the selected marker gene expression (Figures S1A). We analyzed specific genes in different clusters and identified that Runx2 was highly expressed in a subpopulation located in the proximal region (Figure 1D). To validate the scRNA-seq analysis in vivo, we checked the expression pattern of Runx2 using immunofluorescence staining and confirmed that it is expressed in the proximal region of the incisor mesenchyme, mainly in the lateral portion close to the cervical loop (Figures 1E and 1F). Runx2 expression was also detected in the periodontal ligament and in some odontoblasts (Figure 1E). To visualize the relationship between Runx2+ cells and Gli1+ cells, we analyzed the colocalization of Runx2+ cells with Gli1+ cells using Gli1-LacZ mice. We found that Runx2+ cells overlapped with Gli1+ cells mainly in the region adjacent to the cervical loop (Figures 1G and 1H). To determine whether Runx2+ cells overlapped with TACs, we performed double staining of Runx2 and TAC marker Ki67, which revealed that
Runx2+ cells and TACs were adjacent but mutually exclusive cell populations (Figures 1I and 1J). This expression of Runx2 in Gli1+ cells suggested that it may play a critical role in the mesenchymal tissue homeostasis of the mouse incisor.

**Loss of Runx2 in the Gli1+ lineage impairs the incisor growth rate**

Mouse incisors self-renew throughout the animal’s whole life with the support of Gli1+ MSCs. Since Runx2 is expressed in a subpopulation of Gli1+ cells, we tested whether Runx2 is essential in regulating stem cell fate and therefore incisor homeostasis. We generated Gli1-CreER\textsuperscript{T2};Runx2\textsuperscript{fl/fl} mice, in which Runx2 was inactivated in the Gli1+ lineage after induction with tamoxifen at one month of age. Immunofluorescence staining confirmed that Runx2 was efficiently deleted in the incisor mesenchyme (Figure S1B). We observed that the incisors of these mice had decreased in length 1 month after deletion of Runx2 (Figures 2A and 2B), which was confirmed by micro-computed tomography (micro-CT) (Figures 2C and 2D). Three months later, we noticed more significant shortening of incisors in Runx2 mutant mice (Figures 2E-2I). To observe the incisor growth rate dynamically, we made a notch in the incisor enamel close to the junction with the gingiva one day after induction and measured the growth of the incisor as revealed by the movement of the notch 3 days and 6 days later. The notch movement was significantly slower in Runx2 mutant mice after 6 days (Figures S2Aa-S2Ah). This is consistent with our finding that the ability to repair the incisor after clipping was also compromised in Runx2 mutant mice (Figures S2Ba-S2Bg).

These data indicate that loss of Runx2 affected tissue homeostasis and eventually retarded the growth rate of incisors in Gli1-Cre\textsuperscript{ERT2};Runx2\textsuperscript{fl/fl} mice. Histological analysis revealed abnormal dentin formation and disorganized epithelium near the cervical loop
(Figures 2J-2M) one month after induction. The expression of odontoblast differentiation marker dentin sialophosphoprotein (Dspp) was closer to the proximal end of the incisor in the Runx2 mutants compared to control mice (Figures 2N-2Q), suggesting that Runx2 plays an essential role in regulating odontoblast differentiation.

Since Gli1+ cells contribute to the periodontal ligament in the adult mouse incisor (Figure 4Ba and 4Bc), Runx2 was also deleted in the periodontal ligament in Gli1-CreERT2;Runx2fl/fl mice. We found that there were defects in the periodontal ligament and alveolar bone in Gli1-CreERT2;Runx2fl/fl mice (Fig. S2C). These data indicated that Runx2+ cells also play an important role in the homeostasis of the periodontium.

It has been reported that Gli1+ cells contribute to both mesenchymal and epithelial cell lineages (Seidel et al., 2010; Zhao et al., 2014) and that Runx2 is expressed in mature ameloblasts (Figure S3B). To rule out the possibility that the changes we observed in the mesenchyme after deletion of Runx2 were secondary to changes in the epithelium, we generated Sox2-CreERT2;Runx2fl/fl mice with inducible deletion of Runx2 in the Sox2+ cells, which exclusively contribute to the epithelium (Figure S3A) (Juuri et al., 2012). We induced these mice with tamoxifen at one month of age. Four weeks after induction, Runx2 was lost only in the epithelium in Sox2-CreERT2;Runx2fl/fl mice (Figure S3D). Dentin formation was unaffected in the incisors, based on micro-CT analysis and HE staining (Figure S3F-3J). These data suggested that loss of Runx2 in the ameloblasts had no effect on the proximal dental mesenchyme.

**Runx2+ cells are niche cells that maintain tissue homeostasis in the mouse incisor**
Since Runx2+ cells colocalized with Gli1+ cells, we sought to determine whether Runx2+/Gli1+ cells are a subpopulation of MSCs. We generated Runx2-rtTA;tetO-Cre;tdTomato mice to perform lineage tracing of Runx2+ cells in the adult mouse incisor. One week after induction at one month of age, Runx2+ cells were present in the proximal region of the mesenchyme (Figures 3A and 3B). Analysis at one month and three months after induction showed that Runx2+ cells remained in the proximal region of the incisor and did not differentiate into odontoblasts or dental pulp cells, suggesting that Runx2+ cells do not contribute to the dental mesenchyme during incisor growth (Figures 3C-3F). To assess whether Runx2+ cells contribute to injury repair, we clipped one incisor to approximately half of its length (Figure 3H). Three days after clipping, the injured side was almost repaired such that its length was comparable to that of the uninjured contralateral incisor (Figure 3K). However, Runx2+ cells still did not move away from the proximal region of the incisor or differentiate into odontoblasts during injury repair (Figures 3I and 3L). We also quantified the percentage of Runx2+ cells at different stages. The statistical analysis showed that there was no significant difference in the percentage of Runx2+ cells during growth or injury repair (Figures 3G and 3N).

To further evaluate the relationship between Runx2+ cells and label-retaining cells (LRCs), which are considered to be a population of quiescent stem cells, we injected EdU daily into pups for 4 weeks beginning at postnatal day 5 and traced EdU incorporation for another 8 weeks. The EdU staining showed that LRCs did not overlap with Runx2+ cells (Figure S4). Collectively, based on these data, we concluded that Runx2+/Gli1+ cells are not MSCs. Nevertheless, they reside in the MSC niche and play an important role in regulating growth and tissue homeostasis of adult mouse incisors.
Runx2+ cells maintain the incisor MSC niche through regulating TAC proliferation and differentiation

Although Runx2+/Gli1+ cells are not MSCs, Gli1-Cre$^{ERT2};$Runx2$^{fl/fl}$ mice showed a reduced incisor growth rate. To elucidate how Runx2+ cells control growth and tissue homeostasis via regulating the incisor MSC niche, we first quantified the Gli1+ MSC population in Gli1-Cre$^{ERT2};$Runx2$^{fl/fl};$Gli1-LacZ mice. The number of Gli1+ cells in Gli1-Cre$^{ERT2};$Runx2$^{fl/fl};$Gli1-LacZ mice remained the same as in Gli1-LacZ mice one week after induction (Figures 4Aa and 4Ac), but significantly decreased two weeks after induction (Figures 4Ae and 4Ag). To further investigate the effect of Runx2 loss on the differentiation of Gli1+ MSCs, we assessed the contribution of MSCs to their progeny, comparing Gli1-Cre$^{ERT2};$tdTomato and Gli1-Cre$^{ERT2};$Runx2$^{fl/fl};$tdTomato mice. We measured the length of dental pulp that was positive for tdTomato signal, representing the Gli1+ cells’ progeny in the incisor; we then computed this length as a percentage of the length of the whole dental pulp (Figure 4Be). One week after induction, the percentage of Gli1+ cells’ progeny measured in this manner was unchanged (Figures 4Ba, 4Bb and 4Bf), but it significantly decreased 2 weeks after induction in Runx2 mutant mice (Figures 4Bc, 4Bd, and 4Bg), suggesting that the differentiation rate had slowed.

We also checked the number and differentiation of TACs. Importantly, the number of TACs decreased significantly one week after induction in Gli1-Cre$^{ERT2};$Runx2$^{fl/fl}$ mice, as detected by Ki67 immunofluorescence staining (Figures 4Ca, 4Cc, and 4Ci); there was no concomitant increase in apoptosis detected by TUNEL assay (Figures S5A).
Next we assessed whether there was a change in the TAC differentiation rate in Runx2 mutant incisors. We first identified that the number of TACs was comparable in Runx2 mutant and control mice 5 days after induction (Figure S5B). Then we injected EdU 5 days after induction and assessed the TAC differentiation rate upon euthanizing the mice 48 hours later. Since TACs retain EdU during differentiation in this short time frame, the length of overlap between Dspp+ odontoblasts and EdU+ cells reflected the number of TACs that underwent odontogenic differentiation in this period. Strikingly, there were much fewer double-positive cells in Runx2 mutant incisors compared to the controls (Figures 4Cf, 4Ch, and 4Cj), showing that differentiation of TACs was perturbed in Runx2 mutant mice one week after induction. Clearly, loss of Runx2 in the Gli1+ lineage led to compromised TAC proliferation and differentiation first, then affected the MSC population, which suggests that Runx2+ cells maintain the incisor MSC niche through regulating TAC proliferation and differentiation.

**Runx2-regulated IGF-2 signaling is crucial for incisor tissue homeostasis**

To identify downstream components of the molecular mechanism by which Runx2 regulates the MSC niche, we analyzed gene expression in the proximal region of the incisor by performing RNA-seq on adult Runx2Δfl/fl and Gli1-CreERT2;Runx2Δfl/fl mice one week after induction. Hierarchical clustering showed that gene expression profiles of Runx2 mutant and control mice were well separated (Figure 5A). Five hundred and eleven differentially expressed genes were identified (>2-fold, p<0.05), of which 299 were upregulated and 212 were downregulated (Figure 5B). Analysis of these genes using Ingenuity Pathways Analysis (IPA, QIAGEN) revealed that several signaling pathways related to cell cycle regulation were highly involved, such as p53 signaling,
cyclins and cell cycle regulation, IGF signaling, and Wnt/β-catenin signaling (Figure 5C). We focused on IGF signaling, which is known to play an important role in the MSC niche (Youssef et al., 2017; Ziegler et al., 2019). Specifically, we confirmed that Igf2 protein was downregulated in the Runx2+ and TAC regions of Runx2 mutant incisors (Figure 5Dc) compared to controls (Figure 5Da). IGF1 receptor (Igf1r) was detected in the TAC region by RNAscope both in control and Runx2 mutant mice (Figure S6A). Igf1r could be phosphorylated in control mice (Figure 5De), but failed to be phosphorylated in mesenchymal TACs in Runx2 mutant mice (Figures 5Dg). The expression of phosphorylated insulin receptor substrate 1 (p-Irs1) was also decreased in Runx2 mutant mice (Figures 5Di and 5Dk). Phosphorylated Akt (p-Akt), a downstream target of IGF signaling, was downregulated (Figures 5Dm and 5Do). These results were confirmed by Western blot (Figure 5E).

Igfbp3 secreted by Runx2+ cells is indispensable for maintaining IGF2 signaling

To further explore how Runx2+ cells regulate Igf2, we first checked the mRNA expression pattern of Igf2. Igf2 was highly expressed in the MSC region in both control and Runx2 mutant incisors (Figures S6Ba and S6Bc). Analysis following real-time PCR showed that there was no significant difference in Igf2 mRNA expression levels between control and Runx2 mutant groups (Figure S6Be). The activity of the IGF ligands is regulated by a family of six IGF-binding proteins (IGFBPs) in vertebrates. Therefore, we performed RNAscope to visualize the mRNA expression of each of the IGFBPs (Figure S6C). We then narrowed our focus to Igfbp3, which was specifically downregulated in Runx2+ cell region following the loss of Runx2. We detected the expression pattern of Igfbp3 at the mRNA level using RNAscope. In control mice, Runx2
proteins and *Igfbp3* mRNA were colocalized in the same cells (Figure 5Fa). After deleting *Runx2*, the expression of *Igfbp3* was undetectable specifically in the apical region where Runx2+ cells would have been located (Figure 5Fc). We further confirmed that the expression level of *Igfbp3* was downregulated in the *Runx2* mutant incisor using real-time PCR (Figure 5Fe). However, the expression pattern of *Igfbp3* in the periodontal ligament was still comparable between the *Runx2* mutant (Figure 5Fa) and control incisors (Figure 5Fc), suggesting that Runx2 regulates the periodontium independently, through other mechanisms. To test the function of Igfbp3 in the mouse incisor, we cultured MSCs from control and *Runx2* mutant incisors with serum-free media with or without Igfbp3. The concentration of Igf2 in the culture supernatant, detected using ELISA, was rescued in the *Runx2* mutant group with Igfbp3 (Figure 5G).

To determine whether Runx2 can directly regulate *Igfbp3*, we performed ATAC-seq to assess genome-wide chromatin accessibility. We found that there is a Runx2 binding motif located at the promoter of *Igfbp3* (Figure 5H), which is consistent with a previously discovered Runx2 motif associated with genes regulating osteoblast differentiation (Wu et al., 2014). These motifs share a 5'-TGTGGT core sequence with the Runx2 binding consensus sequence (Portales-Casamar et al., 2010). Chromatin Immunoprecipitation (ChIP) coupled with q-PCR provided direct evidence that Runx2 can bind to *Igfbp3* (Figure 5I). These results demonstrate that Igfbp3 secreted by Runx2+ cells is indispensable for IGF2 signaling in the mouse incisor.

**IGF-2 rescues proliferation and odontogenic differentiation of MSCs from Gli1-*Cre*<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> mice in vitro**
Next, we tested the function of Igf2 in regulating MSC proliferation and odontogenic differentiation in vitro. The number of colonies formed by MSCs from Gli1-Cre\textsuperscript{ERT2};Runx2\textsuperscript{fl/fl} mice (Figure 6C) decreased significantly compared to those formed by MSCs from Runx2\textsuperscript{fl/fl} mice (Figure 6A). Adding Igf2 protein to the culture media rescued the colony formation in the Runx2 mutant group (Figure 6D), but had little effect on the control group (Figures 6B and 6E). We then induced MSCs from Runx2 mutant and control incisors to undergo odontogenic differentiation. Seven days after odontogenic induction, we checked the expression of Dspp using RNAseq in situ hybridization. The expression of Dspp in mutants (Figure 6H) was downregulated compared to controls (Figure 6F). Adding Igf2 protein to the odontogenic induction medium upregulated the expression of Dspp in Runx2 mutant MSCs (Figure 6I), but not the control group (Figure 6G). qPCR confirmed that the gene expression level of Dspp significantly increased in the Runx2 mutant group with Igf2 treatment (Figure 6J). We further checked the calcium deposition during odontogenic differentiation by Alizarin red staining (Kaukua et al., 2014; Li et al., 2018). MSCs from the Runx2 mutant (Figure 6M) deposited less calcium than those from the control (Figure 6K) after 3 weeks of odontogenic induction. Adding Igf2 to the odontogenic induction medium enhanced the deposited calcium significantly in the Runx2 mutant group (Figure 6N), but not in the control group (Figure 6L and 6O). Western blotting confirmed that IGF signaling was activated in the Runx2 mutant group with Igf2, but not in the Runx2 mutant group without Igf2 (Figure 6P). These results suggest that Igf2 could rescue proliferation and odontogenic differentiation of MSCs in Runx2 mutant mice in vitro.
DISCUSSION

Genetic cell lineage tracing has identified that the MSCs in the adult mouse incisor are a population labelled by Gli1 and maintained by Shh secreted from a neurovascular bundle niche (Zhao et al., 2014). These MSCs are crucial in supporting the continuous growth of the rodent incisor throughout the animal’s life. In this study, we have uncovered previously unknown heterogeneity of Gli1+ cells in the adult mouse incisor. Importantly, we identified an unexpected subpopulation of Gli1+ cells strategically located in close proximity to MSCs and TACs in the proximal region of the adult mouse incisor. This subpopulation is characterized by expression of Runx2. The Runx2+ cells are niche cells that secrete Igfbp3 and activate IGF2 signaling to regulate TAC proliferation and differentiation to control the incisor growth rate and maintain tissue homeostasis.

Specialized niches support adult stem cells, which reside within them in a quiescent state (van Velthoven and Rando, 2019). In many ectodermally derived organs, such as in lung epithelium (Lee et al., 2017), intestinal epithelium (Ganz, 2000; Sato et al., 2011), and hair follicle (Gonzales and Fuchs, 2017; Yang et al., 2017), the specialized stem cell niches have been well characterized. These studies took advantage of the well-defined anatomical structures where ectodermal stem cells and their niche are present. Stem cells may act upon or generate their niche to control tissue homeostasis (Clevers et al., 2014). Furthermore, niche cells and factors they secrete play a critical role in regulating stem cells in tissue homeostasis and diseases. For example, niche cells produce signals to induce quiescent neural stem cells to activate and renew themselves (Song et al., 2012). In lung adenocarcinomas, niche cells produce the Wnt ligand, which
regulates stem cells and affects tumor progression (Tammela et al., 2017). In contrast to stem cells in the ectoderm, MSCs and their niche environments are still not well understood.

The adult mouse incisor offers a well-defined model to investigate the MSCs and their interaction with neighboring TACs (Shi et al., 2019; Zhao et al., 2014). For example, a recent study has shown that polycomb Ring1 regulates TAC proliferation through inhibiting Cdkn2a and regulating the activity of Wnt/β-catenin signaling. Depletion of Ring1b in TACs causes specific apoptosis of the stem cells, suggesting that TACs can provide positive feedback to MSCs (An et al., 2018a). To date, however, the niche cell populations for MSCs have yet to be defined, and it is unknown how these niche cells may operate. For the first time, we have identified a previously unknown population of Runx2+/Gli1+ cells that act as niche cells to regulate TAC proliferation and differentiation and can control the growth rate of the adult mouse incisor. These results provide new insights into the MSC niche in the adult mouse incisor and its functional significance in regulating tissue homeostasis in this organ.

The stem cell niche involves cell-cell interactions that regulate the fate of MSCs. We discovered that loss of Runx2 in niche cells led to compromised TAC proliferation and differentiation one week after induction. However, we also noted abnormal dentin formation and increased thickness of dentin one month after induction. The function of Runx2 is cell type-specific and depends upon the stage of cell differentiation. For example, Runx2 activates Dspp expression in preodontoblasts but represses this gene later in odontoblast differentiation (Chen et al., 2005; Miyazaki et al., 2008). Here we found that deleting Runx2 in Gli1+ cells first affected transit amplifying cell (TAC)
proliferation and differentiation. Notch movement and injury repair assays also showed that odontogenesis was compromised. These results suggest that Runx2 regulates odontogenesis by promoting odontogenic lineage commitment early in the differentiation process. At a later stage, we observed increased dentin thickness. This was likely due to loss of Runx2 in the progeny of Gli1+ cells, such as odontoblasts. In odontoblasts, Runx2 inhibits Dspp expression (Chen et al., 2005). Loss of Runx2 in odontoblasts leads to premature Dspp expression and thicker dentin. Another probable reason for the increased dentin thickness is that the migration of Gli1+ cell progeny is slower in Runx2 mutant incisors, which could also cause increased accumulation of dentin matrix.

We further found that Runx2 regulates Igf signaling to control odontoblast differentiation and the growth rate of the adult mouse incisor. The IGF signaling axis is critical in regulating stem cell self-renewal and differentiation. Upon binding the IGF ligands, IGF-1 and IGF-2, Igf1r is activated through auto-phosphorylation, and in turn activates its downstream targets through the PI3K/AKT or Ras/MAPK signaling pathway (Hakuno and Takahashi, 2018; Youssef et al., 2017). It has been shown that IGF-2 is required to maintain human embryonic stem cell self-renewal and pluripotency via IGF-1R signaling (Bendall et al., 2007). During bone remodeling, IGF-1 is released from the bone matrix, where it recruits MSCs to undergo osteoblastic differentiation by activating mammalian target of rapamycin (mTOR); IGFBP3 facilitates this process by inducing IGF-1 to deposit in the bone matrix (Xian et al., 2012). In human dental pulp MSCs (hDSCs), IGF-1R is correlated with retaining pluripotency and self-renewal capacity, and can induce neurite regeneration and neuroplasticity after hDSC transplantation in a stroke model (Lee et al., 2016).
In this study, we have uncovered a Runx2-IGF signaling network in the MSC niche of the adult mouse incisor. *Igf2* mRNA was barely detected in the TAC region, but Igf2 protein could be detected in the TAC region in control mice, suggesting that Igf2 may regulate TAC proliferation and differentiation in a paracrine manner. Loss of Runx2 led to downregulation of Igf2 and failure of Igf1r phosphorylation in the adult mouse incisor. Moreover, the Igf downstream targets p-Irs1 and p-Akt were significantly downregulated in *Runx2* mutant mice. Significantly, exogenous Igf2 could rescue MSC proliferation and odontoblast differentiation defects in incisors of adult *Runx2* mutant mice, whereas Igf2 did not enhance proliferation and differentiation of MSCs from control (*Runx2*/*fl/fl*) incisors. These data suggest that Igf2 is necessary and sufficient to sustain a Runx2-Igf signaling cascade within the MSC niche.

It is well known that the IGF ligands in the circulation and throughout the extracellular space bind with high affinity to IGFBPs. The IGFBPs have several functions, which include prolonging the half-lives of IGFs, localizing IGFs to particular types of cells, and modulating interactions between IGFs and their receptors (Clemmons, 1993, 2016; Firth and Baxter, 2002; Jones and Clemmons, 1995). Our study has shown that Igfbp3 is specifically required for Igf2 signaling as part of the MSC niche signaling network in the adult mouse incisor. IGFBP3 is the most abundant member of the IGFBP family (Allard and Duan, 2018; Clemmons, 2018). In the extracellular environment, most IGFs bind with IGFBP3 to protect ligands from degradation and facilitate delivery to specific tissues (Duan and Xu, 2005; Ranke, 2015). Through ATAC-seq and ChIP-qPCR, we have shown that Runx2 directly regulates *lgfbp3* gene expression. Collectively, these
data suggest that Igfbp3 secreted by Runx2+ cells is essential for IGF2 signaling in regulating tissue homeostasis in the adult mouse incisor.

In conclusion, we have uncovered heterogeneity among Gli1+ cells in the adult mouse incisor that reflects complex functions of MSCs in maintaining tissue homeostasis and repair. We have identified a previously unknown population of Runx2+ cells in the MSC region, which are niche cells but not themselves MSCs. We showed that these Runx2+ niche cells regulate TAC proliferation and differentiation via IGF signaling. Igfbp3 secreted by Runx2+ cells is critical for IGF signaling in the mouse incisor. Our study provides insights into the mechanisms of how stem cell niches work as a local ecosystem to maintain tissue homeostasis, which may also have important implications for tissue regeneration.
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AUTHOR CONTRIBUTIONS

DECLARATION OF INTERESTS
The authors declare no competing interests.
FIGURE LEGENDS

Figure 1. Runx2 is expressed in a subpopulation of Gli1+ cells in the proximal region of the incisor.

(A) Unbiased t-distributed stochastic neighbor embedding (t-SNE) plots of cell clusters in the incisor from 1-month-old wild type mice. Schematic shows the location from which the tissue was harvested. Red dotted line marks dental mesenchyme and blue dotted line marks dental epithelium.

(B) t-SNE plot showing the expression of Gli1 in different clusters of the mouse incisor.

(C) Subpopulations of Gli1+ cells re-clustered by t-SNE analysis.

(D) t-SNE plot showing expression of Runx2 in Gli1+ sub-clusters.

(E and F) Runx2 immunostaining of 1-month-old wild type (WT) mouse. (F) shows high-magnification image of inset in (E). Runx2 expression in odontoblasts is shown in red box in (E).

(G and H) Runx2 and β-gal double immunostaining of incisor from 1-month-old Gli1-LacZ mouse. (H) represents high-magnification image of inset in (G). Arrows show colocalization of Runx2+ cells and Gli1+ cells.

(I and J) Runx2 and Ki67 double immunostaining of incisor from 1-month-old wild type mouse. (J) represents high-magnification image of inset in (I).

White dotted line in (E-J) shows cervical loop. Scale bars, 100 μm.

Figure 2. Loss of Runx2 in the Gli1+ lineage impairs the incisor growth rate.
(A and B) Gross appearance of incisors from Runx2fl/fl (A) and Gli1-CreERT2:Runx2fl/fl mice (B) 1 month after tamoxifen induction (1mpt) at 1 month of age. Arrows point to the lower incisors.

(C and D) Longitudinal micro-CT images from 1-month-old Runx2fl/fl (C) and Gli1-CreERT2:Runx2fl/fl mice (D) 1 month after tamoxifen induction (1mpt).

(E and F) Gross appearance of incisors from Runx2fl/fl (E) and Gli1-CreERT2:Runx2fl/fl mice (F) 3 months after tamoxifen induction (3mpt) at 1 month of age. Arrows point to the lower incisors.

(G and H) Longitudinal micro-CT images from 1-month-old Runx2fl/fl (G) and Gli1-CreERT2:Runx2fl/fl mice (H) 3 month after tamoxifen induction (3mpt).

(I) Comparison of the incisor lengths of Runx2fl/fl (control) and Gli1-CreERT2:Runx2fl/fl (mutant) mice, 1 and 3 months after induction at 1 month of age. n=5 mice, *p<0.05, **p<0.01.

(J-M) Histological analysis of incisors from Runx2fl/fl (J and K) and Gli1-CreERT2:Runx2fl/fl mice (L and M) 1 month after tamoxifen induction (1mpt) at 1 month of age. (K) and (M) represent high-magnification images of insets in (J) and (L), respectively. Arrowhead in (M) indicates abnormal dentin formation.

(N-Q) Dspp RNAscope of incisors from Runx2fl/fl and Gli1-CreERT2:Runx2fl/fl mice 1 month after tamoxifen induction (1mpt) at 1 month of age. (O) and (Q) represent high-magnification images of insets in (N) and (P), respectively. White dotted line shows cervical loop.
Schematic at the bottom indicates induction protocol. Data are represented as mean ± SEM. TMX, tamoxifen. Scale bars, (A-H) 2mm, (J-Q), 100 μm.

Figure 3. Runx2+ cells are niche cells that maintain tissue homeostasis in the mouse incisor.

(A and B) tdTomato immunostaining of incisors from Runx2-rtTA;tetO-Cre;tdTomato mice 1 week after doxycycline induction (1wpd) at one month of age. (B) represents high-magnification image of inset in (A).

(C and D) tdTomato immunostaining of incisors from Runx2-rtTA;tetO-Cre;tdTomato mice 1 month after doxycycline induction (1mpd) at one month of age. (D) represents high-magnification image of inset in (C).

(E and F) tdTomato immunostaining of incisors from Runx2-rtTA;tetO-Cre;tdTomato mice 3 months after doxycycline induction (3mpd) at one month of age. (F) represents high-magnification image of inset in (E).

(G) Quantification analysis of the percentage of Runx2+ cells per high magnification section (B, D and F) 1 week, 1 month and 3 months after induction of Runx2-rtTA;tetO-Cre;tdTomato incisor mesenchyme. n=3 mice/group, NS, no significant difference.

(H) Gross appearance of incisors from 1-month old Runx2-rtTA;tetO-Cre;tdTomato mouse on day 0 after clipping (D0), which took place 1 week after doxycycline induction (1wpd) at one month of age.

(I and J) tdTomato immunostaining of incisors from Runx2-rtTA;tetO-Cre;tdTomato mice D0 after clipping. (J) represents high-magnification image of inset in (I).
(K) Gross appearance of incisors from 1-month old Runx2-rtTA;tetO-Cre;tdTomato mouse on day 3 after clipping (D3). The mice were served doxycycline-free food after clipping.

(L and M) tdTomato immunostaining of incisors from Runx2-rtTA;tetO-Cre;tdTomato mice D3 after clipping. (M) represents high-magnification image of inset in (L).

(N) Quantification analysis of the percentage of Runx2+ cells per high magnification section (J and M) D0 and D3 after clipping of Runx2-rtTA;tetO-Cre;tdTomato incisor mesenchyme. n=3 mice/group, NS, no significant difference.

Schematic at the bottom indicates induction protocol. White dotted line in (A-F, I, J, L and M) shows cervical loop. Dox, doxycycline. Arrows shows tdTomato signaling in the proximal region. All data are represented as mean ± SEM. Scale bars, 100 μm.

Figure 4. Runx2+ cells maintain the incisor MSC niche through regulating TAC proliferation and differentiation.

(A) β-gal staining of incisor from Gli1-LacZ and Gli1-CreERT2;Runx2fl/fl;Gli1-LacZ mice one week (a, c) and two weeks (e, g) after induction. (b, d, f and h) represent high-magnification images of insets in (a, c, e and g), respectively. (i and j) Quantification of the percentage of Gli1+ cells per high magnification section (b, d, f and h) one week (i) and two weeks (j) after induction of Gli1-LacZ and Gli1-CreERT2;Runx2fl/fl;Gli1-LacZ incisor mesenchyme. n=3 mice/group, NS, no significant difference. **p<0.01.

(B) Differentiation rate of Gli1+ MSCs in Gli1-CreERT2;tdTomato and Gli1-CreERT2;Runx2fl/fl;tdTomato mice one week (a, b) and two weeks (c, d) after induction. (e) Schematic showing the method of measuring the length of tdTomato signal and dental
pulp. (f and g) Quantification of the percentage of tdTomato signal one week (f) and two weeks (g) after induction of \textit{Gli1-Cre}^{ERT2}; tdTomato and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl}; tdTomato mice. \(n=3\) mice/group, NS, no significant difference. *\(p<0.05\).

(C) Ki67 immunostaining of incisors from 1-month old \textit{Runx2}^{fl/fl} (a) and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} mice (c) one week after induction. (b, d) represent high-magnification images of insets in (a, c), respectively. (e, g) RNAscope of \textit{Dspp} and EdU staining in \textit{Runx2}^{fl/fl} (e) and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} mice (g) one week after induction. (f, h) represent high-magnification images of insets in (e, g), respectively. (i) Quantification analysis of the percentage of Ki67+ cells per high magnification section (b and d) one week after induction of \textit{Runx2}^{fl/fl} and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} incisor mesenchyme. (j) Quantification analysis of the length of overlap between \textit{Dspp}+ and EdU+ cells (f and h) one week after induction of \textit{Runx2}^{fl/fl} and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} incisor. \(n=3\) mice/group, *\(p<0.05\), **\(p<0.01\).

Schematics at the bottom show tamoxifen induction and EdU injection protocols. White dotted line shows cervical loop. All data are represented as mean ± SEM. Scale bars, (A and C) 100 \(\mu\)m, (B) 500 \(\mu\)m.

**Figure 5.** IGF-2 signaling is downregulated in \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} mice.

(A) Heatmap hierarchical clustering showing the gene expression profiles of \textit{Runx2}^{fl/fl} (control) and \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} (mutant) mice one week after induction at one month of age.

(B) Volcano plot revealing that 299 genes were upregulated and 212 were downregulated (\(>2\)-fold, \(p<0.05\)) in \textit{Gli1-Cre}^{ERT2}; \textit{Runx2}^{fl/fl} mice.
(C) Ingenuity Pathway Analysis (IPA) based on RNA-seq data.

(D) Immunostaining of Igf2 (a, c), p-Igf1r (e and g), p-Lrs1 (i and k), and p-Akt (m and o) in incisors from Runx2<sup>fl/fl</sup> (a, e, i, and m) and Gli1-Cre<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> mice (c, g, k, and o) 1 week after induction at 1 month of age. (b, d, f, h, j, l, n and p) represent high-magnification images of insets in (a, c, e, g, i, k, m and o), respectively. Arrows indicate positive signal and asterisks indicate absence of signal.

(E) Western blot of Igf2, p-Igf1r, Igf1r, p-Lrs1, Lrs1, p-Akt and Akt in the incisor mesenchyme from Runx2<sup>fl/fl</sup> (control) and Gli1-Cre<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> (mutant) mice one week after induction.

(F) Igfbp3 RNAscope and Runx2 immunostaining of incisor from Runx2<sup>fl/fl</sup> (a) and Gli1-Cre<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> (c) mice 1 week after induction at 1 month of age. (b, d,) represent high-magnification images of insets in (a, c,), respectively. (e) Real-time PCR analysis of Igfbp3 in incisor mesenchyme from Runx2<sup>fl/fl</sup> and Gli1-Cre<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> mice 1 week after induction at 1 month of age. n=3/group, *p<0.05. Arrows indicate coexpression of the Igfbp3 mRNA and Runx2 protein, and asterisks indicate absence of signal.

(G) ELISA showing the secreted Igf2 in the culture medium supernatant from the MSCs of Runx2<sup>fl/fl</sup> (control) and Gli1-Cre<sup>ERT2</sup>;Runx2<sup>fl/fl</sup> (mutant) mice with or without Igfbp3 protein. n=3, ***p<0.001.

(H). ATAC-seq analysis of incisor mesenchyme from 1-month old wild type mice. Black box indicates the Runx2 binding motif located at the promoter of Igfbp3.
(l) ChIP with Runx2 antibody (or IgG), followed by q-PCR to compare levels of Runx2 near transcription start site of *Igfbp3*, in incisor mesenchyme from 1-month old wild type mice. n=4, **p<0.01.

Schematics at the bottom show tamoxifen induction protocols. White dotted line in (D and F) shows cervical loop. All data are represented as mean ± SEM. Scale bars, (D) 50 μm, (F) 100 μm.

**Figure 6. Igf2 rescues proliferation and odontogenic differentiation of MSCs from *Gli1-CreERT2;Runx2fl/fl* mice in vitro.**

(A-D) Colony formation of MSCs from *Runx2fl/fl* (A, B) and *Gli1-CreERT2;Runx2fl/fl* (C, D) incisors with (B, D) or without (A, C) Igf2. Arrows indicate colony formation.

(E) Quantification of the colony formation of MSCs from *Runx2fl/fl* and *Gli1-CreERT2;Runx2fl/fl* incisors. n=3, *p<0.05, **p<0.01.

(F-I) *Dspp* RNAscope of MSCs from *Runx2fl/fl* (F, G) and *Gli1-CreERT2;Runx2fl/fl* (H, I) incisors 1 week after odontogenic induction (Odont. Ind.) with (G, I) or without (F, H) Igf2 protein.

(J) Real-time PCR analysis of *Dspp* after odontogenic induction. n=3, *p<0.05, **p<0.01.

(K-N) Alizarin red staining of the MSCs from *Runx2fl/fl* (K, L) and *Gli1-CreERT2;Runx2fl/fl* (M, N) incisors 3 weeks after odontogenic induction with (L, N) or without (K, M) Igf2 protein.
(O) Absorbance analysis of the dissolved Alizarin red contents at 590 nm. n=3, **p<0.01.

(P) Western blot of p-lgf1r, lgf1r, p-lrs1, lrs1, p-Akt and Akt of the MSCs from Runx2fl/fl (control) and Gli1-CreER<T2;Runx2fl/fl (mutant) incisors 1 week after odontogenic induction with or without Igf2 protein.

All data are represented as mean ± SEM. Scale bars, (F-I) 100 μm, (K-N) 500 μm.
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**Experimental Models: Organisms/Strains**

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**RESOURCE AVAILABILITY**

**Lead Contact**

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Yang Chai (ychai@usc.edu).

**Materials Availability**

All unique/stable reagents generated in this study are available from the Lead Contact without restriction.

**Data and Code Availability**

The scRNA-seq data, bulk RNA-seq data and ATAC-seq data of mouse incisors in this publication have been deposited in NCBI’s Gene Expression Omnibus and are accessible through GEO Series accession number GSE154158 ([https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE154158](https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE154158)).

**EXPERIMENTAL MODEL AND SUBJECT DETAILS**

**Animals**

Mice used in this study included *Gli1-CreERT2* knock-in (JAX#007913), *ROSA26*loxP-STOP-loxP conditional reporter (JAX#007905, (Madisen et al., 2010)), *Gli1-LacZ* heterozygotes (JAX#008211, (Bai et al., 2002)), *Sox2-CreERT2* knock-in (JAX#017593, (Li et al., 2015)), *Runx2-rtTA* (gift from Fanxin Long, Washington University School of...
Medicine; (Chen et al., 2014), *tetO-Cre* (JAX#006234), *C57BL/6J* (JAX#000664), and *Runx2<sup>flox/flox</sup>* (gift from Dr. Takeshi Takarada, Okayama University, Japan; (Takarada et al., 2013). Mice were housed in pathogen-free conditions and analyzed in a mixed background. All mice were used for analysis without consideration of sex. All mice were induced at one month of age and euthanized at specific stage as described in figure legend. Genotyping was performed from ear biopsies, which were lysed in DirectPCR tail solution (Viagen 102 T) through incubation at 55°C overnight followed by 85°C heat inactivation for 30 min. PCR-based genotyping (GoTaq Green MasterMix, Promega, and C1000Touch Cycler, Bio-rad) was conducted to identify the mouse lines. All mouse experiments were approved by the Institutional Animal Care and Use Committee at the University of Southern California.

**METHOD DETAILS**

**Tamoxifen and doxycycline administration**

Tamoxifen (Sigma, T5648) was dissolved in corn oil (Sigma, C8267) at 20 mg/ml and injected intraperitoneally at a dosage of 1.5mg/10g body weight daily for 3 consecutive days. Doxycycline rodent diet (ENVIGO, TD.08541) was administered every day.

**scRNA Sequencing**

Four-week-old wildtype *C57BL/6J* mice were used for single-cell transcriptomics experiments. Mandibles were carefully dissected under a stereomicroscope. The surrounding jaw bones were removed by scalpel and the proximal region was then severed. Dental pulp with dental epithelium was isolated, cut into pieces, collected in cold PBS, and digested with 2mg/ml collagenase type I (Worthington, LS004194)
dissolved in α-MEM (Gibco, 12571-048) for 30 min at 37 °C. After incubation, the suspension was homogenized by pipetting and digestion was terminated by adding 10% FBS. The digested tissues were centrifuged at 300g for 5 min and resuspended in 10% FBS. Twenty thousand cells were loaded into the 10X Chromium system with targeted cell recovery of 10,000 cells to be barcoded for scRNA-seq using a Single Cell 3’ Library Kit v3. Sequencing was performed on the Illumina Novaseq System. About 9,318 cells (~63,000 reads per cells) were successfully barcoded and their transcriptomes sequenced. Raw read counts were analyzed using the Seurat R package (Satija et al., 2015).

**EdU incorporation and staining**

For TAC differentiation, EdU (25 µg/g body weight) was intraperitoneally (IP) injected once at 5 days after induction of Gli1-CreERT2;Runx2fl/fl mice and Runx2fl/fl mice. Mice were euthanized and samples were collected 48 hours after Edu injection. For label-retaining cell assay, EdU was IP injected into pups daily beginning at postnatal day 5 for 4 weeks and washed out for another 8 weeks. After euthanasia, the mandible was collected, fixed, and decalcified, followed by cryo-sectioning. Edu was detected using a Click-iT™ Plus EdU Cell Proliferation Kit (Invitrogen, C10637)

**MicroCT analysis**

MicroCT analysis was performed on a SCANCO μCT50 (Scanco V1.28) device at the University of Southern California Molecular Imaging Center. Images were acquired at a resolution of 10 µm with the x-ray source at 90 kVp and 78 µA. Three-dimensional (3D) reconstruction was completed with AVIZO 7.1 (Visualization Sciences Group).
**Immunofluorescence staining**

For immunofluorescence analysis, the dissected mouse mandibles were fixed in 4% paraformaldehyde (PFA) overnight, and then decalcified with 10% EDTA for four weeks. Then, the tissues were dehydrated in 15% sucrose/PBS solution for two hours, then in 30% sucrose/PBS for two hours, and 30% sucrose/OCT (Sakura, Tissue-Tek, 4583) at 4°C overnight followed by embedding in OCT. Sagittal cryosections 8 μm thick were used for immunofluorescence staining following standard protocols. The primary antibodies are listed in Table S1. Alexa Fluor 488 and Alexa Fluor 568 (1:200, Invitrogen) were used as secondary antibodies. DAPI (Invitrogen, 62248) was used for nuclear staining. All images were captured using a Keyence microscope (Carl Zeiss).

For p-Igf1r, p-Irs1, p-Akt and Igf2, Alexa Fluor™ 488/594 Tyramide SuperBoost™ kits (Invitrogen, B40922/40925) were used.

**TUNEL assays**

Apoptosis was detected using a TUNEL assay (Click-iT™ Plus TUNEL Assay for In Situ Apoptosis Detection, Thermo Fisher, C10617) according to the recommended protocol.

**RNAscope in situ hybridization (ISH)**

Cryosections were used for ISH. RNAscope® Multiplex Fluorescent v2 (Advanced Cell Diagnostics, 323110) was used following the protocols of the manufacturer. The signal was detected by TSA Plus Cyanine 3 (System Perkin Elmer, NEL744001KT). All probes used in this study were designed and synthesized by Advanced Cell Diagnostics. Probe details are included in the key resource table.
Quantitative Real-time PCR

The RNeasy Plus Micro Kit (Qiagen, 74004) was used for extraction of total RNA from incisor dental mesenchyme of Runx2^{fl/fl} and Gli1^{CreER^{T2};Runx2^{fl/fl}} mice one week after tamoxifen induction at one month of age. cDNA was synthesized using an iScript™ cDNA Synthesis Kit (Bio-Rad, 1708890). Real-time quantitative PCR was then performed using Sso Fast™ Eva Green® Supermix (Bio-Rad, 1725201) and a CFX 96 Real-time System (Bio-Rad). Gapdh expression was used to normalize gene expression. All primers are listed in table S2.

Incisor injury and notch movement experiments

The mice were anesthetized with isoflurane. The incisor was clipped by removing the erupted part aligned with the gingival papilla. To assess notch movement, a notch was made above the gumline using a carbide bur (Brasseler USA®, 018554U0). Measurements were taken using a digital caliper (VWR® Digital Calipers, 62379-531).

Image J image analysis

ImageJ was used to calculate the percentage of positive immunofluorescence signals in the TAC and MSC regions. The length of incisor, the amount of tdTomato signal, and overlap between EdU signal and Dspp were measured in ImageJ as well.

Colony formation assay

MSCs were harvested as previously described (Zhao et al., 2014). In brief, the proximal region of lower incisor mesenchyme was obtained from 1-month old Runx2^{fl/fl} and Gli1-{CreER^{T2};Runx2^{fl/fl}} mice 5 days after induction. The epithelium was dissected and
removed with fine forceps. The pulp tissue was cut into pieces and digested with solution containing 2mg/ml collagenase type I (Worthington, LS004194) in PBS for 30 min at 37°C. A single-cell suspension was harvested through 70μm strainer (Falcon, 352350) and seeded at 2×10^4/well into 24-well culture plate with growth media (α-MEM [Thermo Fisher Scientific, 12571-048] supplemented with 10% fetal bovine serum [FBS], 100 U·mL^-1 penicillin, and 100 U·mL^-1 streptomycin) in 5% CO₂ at 37°C. Initial cultures were left undisturbed for 2 days to allow cell adhesion. Then the growth media was changed every other day supplemented with or without 100ng/ml mouse recombinant Igf2 (Sigma-Aldrich, 18904) according different groups (showed in Figure 6). After 7 days, the culture plates were stained with 0.1% toluidine blue together with 2% paraformaldehyde solution. Colonies containing more than 50 cells were counted as a single colony cluster.

**MSC odontogenic differentiation**

The dental mesenchyme was obtained from 1-month old Runx2^fl/fl^ and Gli1^CreERT2;Runx2^fl/fl^ mice 5 days after induction as described above. The pulp tissue was cut into pieces and incubated with growth media in 6-well plate. The culture media was left to rest for 4 days to allow tissue adhesion and cell migration. Then the culture media was changed every other day.

2×10^5 MSCs were plated in a 4-well chamber slide (PEZGS0416, Millipore) or 24-well plate (Nest, 702011) and induced in odontogenic differentiation media containing 1% FBS, β-glycerophosphate (β-GP) (5mM), ascorbic acid (50µg/ml), and dexamethasone (DEX) (10nM). 100 ng/ml mouse recombinant Igf2 was added to odontogenic induce media according different groups (showed in Figure 6F-6I). For Dspp RNAscope in situ
hybridization, cells cultured in a 4-well chamber slide were harvested 7 days after induction and the standard protocols of the manufacturer were then followed. To detect mineralized nodules, cells were induced for 21 days, fixed with 4% paraformaldehyde, and stained with 2% Alizarin red S (pH4.2) (ACROS Organics, 400480250). Alizarin red-S contents were extracted with 10% cetylpyridinium chloride in distilled water and measured at 590 nm on SpectraMax iD3 (Molecular Devices, LLC., San Jose, USA).

**ELISA**

The dental MSCs from Runx2^{fl/fl} and Gli1-Cre^{ERT2};Runx2^{fl/fl} mice was harvested as described above. 5×10^4 MSCs were seeded on 48-well plate (Nest,748011) with growth media. After 80% confluency, the culture plate was washed with Phosphate-buffered saline (PBS) for three times and then added 200 μl serum-free media, i.e. α-MEM with or without 50nM mouse recombinant Igfbp3 protein (R&D Systems, 775-B3). The supernatant was harvested at different timepoint (showed in Figure 5I) and stored at -20 °C. The concentration of Igf2 was detected by Mouse/Rat/Porcine/Canine IGF-II/IGF2 Quantikine ELISA Kit (R&D Systems, MG200). The assay procedure followed the manufacture’s protocol.

**Western blot**

For Western blots, the proximal region of incisor mesenchyme was lysed by RIPA buffer (Cell Signaling, 9806) supplemented with Protease inhibitor (ThermoFisher Scientific, A32959) for 30 min on ice. Protein extracts were loaded in 4%-15% precast polyacrylamide gel (Bio-Rad,456-1084), transferred to 0.45μm PVDF membrane, blocked with 5% milk (Bio-Rad,170-6404) for 1h, and incubated with primary antibody
(Supplementary Table 1) at 4°C overnight. After incubation with HRP-conjugated secondary antibody for 1 h at room temperature, signals were detected using Azure 300 (Azure biosystems) and images were taken with cSeries Capture Software.

**RNA sequencing**

Incisor samples taken one week after induction of one-month-old *Gli1-CreERT2;Runx2fl/fl* and *Runx2fl/fl* mice were dissected. The proximal region was collected for RNA isolation with an RNeasy Micro Kit (QIAGEN). The quality of RNA samples was evaluated using an Agilent 2100 Bioanalyzer and all samples used for sequencing had RNA integrity (RIN) numbers >9.0. cDNA library preparation and sequencing were performed by DNA Link, Inc. Single-end reads with 75 cycles were performed on NextSeq500 for three pairs of samples. Raw reads were trimmed, aligned using STAR (version 2.6.1d) with the mm10 genome, and normalized using Upper quartile. Differential expression was calculated by selecting transcripts that had significant changes of P<0.05.

**ATAC-sequencing**

The proximal dental mesenchyme of mouse incisor was dissected from 4-week-old wild type *C57BL/6J* mice. A cell suspension was prepared as described above for scRNA sequencing. Five thousand cells were obtained, spun down, and washed once with cold PBS. Then the cells were resuspended in cold lysis buffer. The transposition reaction, purification and PCR application followed a previously described protocol (Buenrostro et al., 2015). Transposed DNA libraries were sequenced on NextSeq500 High-Output 150 cycles (75PE). ATAC-seq reads were aligned to the UCSC mm10 reference genome with BWA-MEM(Li, 2013). ATAC-seq peaks were called through MACS2 (Zhang et al.,
Peaks were annotated and known transcription factor binding motifs were further analyzed in the ATAC-seq peaks by HOMER (Heinz et al., 2010).

**ChIP-qPCR**

The proximal mesenchymal tissue was dissected from 4-week-old wildtype *C57BL/6J* mice. For each replicate, 60-80mg tissue was combined as one sample. The sample was prepared following the manufacturer’s protocol (Chromatrap,500191). Briefly, The tissue was cut into small pieces, fixed with 1% formaldehyde at room temperature for 15 minutes and then quenched by 0.65 M glycine solution. The sample was washed twice with PBS, resuspended with Hypotonic Buffer and incubate at 4 °C for 10 minutes to get the pellet (nuclei). The pellet was resuspended in Digestion Buffer and chromatin was sheared to 100-500 bp fragments using Shearing Cocktail. 10 µg chromatin with Runx2 antibody (CST12556, 1:50) or Immunoglobulin G negative control (2ug) was added to Column Conditioning Buffer and made up to the final volume of 1000 µl. the immunoprecipitation (IP) slurry was then mixed well and incubated on an end to end rotor for 1 hour at 4 °C. An equivalent amount of chromatin was set aside as an input. The IP slurry was loaded and flowed completely through the Chromatrap® spin column at room temperature. The column was washed three times with Wash Buffer and then the chromatin was eluted using a specially formulated ChIP-seq elution buffer. The chromatin sample was further incubated at 65 °C overnight to reverse cross-linking, along with the untreated input. After treatment with proteinase K, DNA was purified with Chromatrap® DNA purification column. ChIP eluates, negative control and input were assayed by real-time q-PCR in a 20 µl reaction with the following: 1 µl of each primer (Table S2), 10 µl Eva Green® Supermix (Bio-Rad) using a CFX 96 real-time System
(Bio-Rad). The primers were designed through amplifying Runx2-binding motifs in the *Igfbp3* promoter region (Table S2).

**QUANTIFICATION AND STATISTICAL ANALYSIS**

Statistical analysis was performed using GraphPad Prism. Paired Student’s t-tests and one-way analysis of variance (one-way ANOVA) were used to assess significance. Statistical data are presented as mean ± SEM. *P* < 0.05 was considered statistically significant.
REFERENCE


Figure 1. Runx2 is expressed in a subpopulation of Gli1+ cells in the proximal region of the incisor.
Figure 2. Loss of Runx2 in the Gli1+ lineage impairs the incisor growth rate.
Figure 3. Runx2+ cells are niche cells that maintain tissue homeostasis in the mouse incisor.
Figure 4. Runx2+ cells maintain the incisor MSC niche through regulating TAC proliferation and differentiation.
Figure 5. IGF-2 signaling is downregulated in Gli1-Cre^{ERT2};Runx2^{fl/fl} mice.
Figure 6. Igf2 rescues differentiation and odontogenic differentiation of MSCs from Gli1-Cre\textsuperscript{ERT2};Runx2\textsuperscript{fl/fl} mice \textit{in vitro}.

A, C and E. Growth media, Growth media + Igf2
B, D and E. Numbers of colonies

G, I, J and P. Dspp

K, M and O. Ab sorbance (OD)
L, N and O. Igf1r, p-Irs1, p-Akt, Akt, GAPDH
SUPPLEMENTARY FIGURE LEGENDS

Figure S1A. Correlating specific clusters and their in vivo locations in adult mouse incisor. Related to Fig.1.

(Aa-Ac) t-SNE plot showing the expression of Smoc2 (Aa), Sox9(Ab), and Krt14(Ac) in different cell clusters.

(Ad-Ae) RNAscope of Smoc2 (Ad), and Sox9 (Ae) showing the anatomical location of proximal region and dental pulp cells.

(Af) Immunostaining of Keratin 14 (K14) labeling the epithelium.

Figure S1B. Efficient deletion of Runx2 in Gli1-CreERT2;Runx2fl/fl incisors. Related to Fig.2.

(Ba-Bd) Runx2 immunostaining of sagittal sections of incisors from 1-month-old Runx2fl/fl (Ba) and Gli1-CreERT2;Runx2fl/fl (Bc) mice 5 days post-tamoxifen induction (5dpt). Bb and Bd represent high-magnification images of insets in Ba and Bc, respectively.

Schematic at the bottom indicates induction protocol. White dotted line shows cervical loop. Arrows show positive signaling and asterisks indicate absence of signaling. Scale bars, 100 μm.
Figure S2A-B. Notch movement and injury-repair assay in 1-month old Runx2^fl/fl and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl mice. Related to Fig.2.

(Aa-Af) Notch movement in Runx2^fl/fl (Aa-Ac) and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl (Ad-Af) incisors on Day 0 (D0), Day 3 (D3), and Day 6 (D6) after notch creation, which was performed 1 day after induction. All the notches were made in the right side of the incisor above the gumline; the yellow dotted line on the left shows the level of the notch. Blue line shows the outline of the gumline. Schematic at the bottom indicates induction and notch creation protocol.

(Ag-Ah) Quantification of the notch movement in Runx2^fl/fl and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl incisors at D3 (Ag) and D6 (Ah). n=6, NS, no significant difference, ***p<0.001.

(Ba-Bf) Uninjured mouse incisors (Ba, Bd), incisors immediately after clipping (D0; Bb, Be), and injury repair (D3; Bc, Bf) after clipping of Runx2^fl/fl (Ba-c) and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl (Bd-f) incisors. Schematic at the bottom indicates induction and injury protocol. Arrows point to the injury site.

(Bg) Quantification of the repair of Runx2^fl/fl and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl incisors after clipping. n=3, **p<0.01.

All data are represented as mean ± SEM. Scale bars, 2mm.

Figure S2C. Defects in the periodontal ligament and alveolar bone 1 month after induction of Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl mice. Related to Fig.2.

(Ca and Cd) Micro-CT images from 1-month-old Runx2^fl/fl (Ca) and Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl (Cd) mice 1 month after tamoxifen induction (1mpt). Arrow in Ca and arrowhead in Cd point to alveolar bone.

(Cb and Cc) Histological analysis of incisors from Runx2^fl/fl mice 1 month after tamoxifen induction at 1 month of age; Cc shows high-magnification image of inset in Cb.

(Ce and Cf) Histological analysis of incisors from Gli1-Cre<sup>ERT2</sup>;Runx2^fl/fl mice 1 month after tamoxifen induction at 1 month of age; Cf shows high-magnification image of inset in Ce.

Schematic at the bottom indicates induction protocol. AB, alveolar bone; Epi, epithelium; PDL, periodontal ligament. TMX, tamoxifen. Scale bars: Ca and Cd, 2mm; Cb, Cc, Ce and Cf, 100 μm.
Figure S3. There is no observable incisor phenotype 4 weeks after induction of \( \text{Sox2-Cre}^{\text{ERT2}};\text{Runx2}^{0/0} \) mice. Related to Fig.2.

(A) Lineage tracing of \( \text{Sox2-Cre}^{\text{ERT2}};\text{tdTomato} \) mice for 1 month after tamoxifen induction (1mpt) at 1 month of age. Arrows shows tdTomato signaling in the epithelium. White dotted line shows cervical loop.

(B-E) Immunostaining of Runx2 in \( \text{Runx2}^{0/0} \) (B) and \( \text{Sox2-Cre}^{\text{ERT2}};\text{Runx2}^{0/0} \) (D) mice 1m after tamoxifen induction (1mpt) at 1 month of age. C and E represent high-magnification images of insets in B and D, respectively. Arrows show Runx2 signaling in the ameloblast and asterisks indicate absence of signaling.

(F-G) Micro-CT analysis of incisors from \( \text{Runx2}^{0/0} \) (F) and \( \text{Sox2-Cre}^{\text{ERT2}};\text{Runx2}^{0/0} \) (G) mice 1 month after tamoxifen induction (1mpt) at 1 month of age.

(H) Quantification of the incisor lengths from \( \text{Runx2}^{0/0} \) and \( \text{Sox2-Cre}^{\text{ERT2}};\text{Runx2}^{0/0} \) mice 1 month post-tamoxifen induction (1mpt) at one month of age. n=3, NS, no significant difference.

(I-J) Histological analysis of \( \text{Runx2}^{0/0} \) (I) and \( \text{Sox2-Cre}^{\text{ERT2}};\text{Runx2}^{0/0} \) (J) incisors 1 month after tamoxifen induction (1mpt) at one month of age.

Schematic at the bottom indicates induction protocol. All data are represented as mean ± SEM. Scale bars: A, F and G, 500 μm; B-E, I, and J, 100 μm.
Figure S4. There is no overlap between LRCs and Runx2+ cells. Related to Fig. 3.

(A and B) Runx2 immunostaining and EdU staining 8 weeks after 4 weeks of injection of EdU starting from postnatal day 5. (B) represents high-magnification image of inset in (A).

Schematic at the bottom indicates EdU injection and tracing protocol. White dotted line shows cervical loop. Green arrows in (B) show EdU+ cells and red arrows show Runx2+ cells. Scale bars, 100 μm.
Figure S5A. There are no observed apoptotic cells in Runx2^fl/fl or Gli1-Cre^{ERT2};Runx2^fl/fl mice 7 days after induction. Related to Fig.4.

(Aa-Ad) Terminal deoxynucleotidyl transferase dUTP nick end labeling (TUNEL) staining of sagittal sections of mandibular incisors from Runx2^fl/fl (Aa) and Gli1-Cre^{ERT2};Runx2^fl/fl (Ac) mice 1 week after tamoxifen induction (1wpt) at 1 month of age. Ab and Ad represent high-magnification images of insets in Aa and Ac, respectively.

Figure S5B. The number of TACs is comparable in Runx2^fl/fl and Gli1-Cre^{ERT2};Runx2^fl/fl mice 5 days after induction. Related to Fig.4.

(Ba-Bd) Ki67 immunostaining of incisors from Runx2^fl/fl (Ba) and Gli1-Cre^{ERT2};Runx2^fl/fl mice (Bc) 5 days after induction (5dpt) at 1 month of age. Bb and Bd represent high-magnification images of insets in Ba and Bc, respectively.

(Be) Quantification of Ki67+ cells in incisor mesenchyme from Runx2^fl/fl and Gli1-Cre^{ERT2};Runx2^fl/fl mice 5 days post-tamoxifen induction (5dpt) at one month of age corresponding to Bb, Bd. n=3, NS, no significant difference.

Schematic at the bottom indicates induction protocol. White dotted line shows cervical loop. Data are represented as mean ± SEM. Scale bars, 100 μm.
Figure S6A. *Igf1r* is detected in TAC region in *Runx2<sup>fl/fl</sup>* and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* mice 1 week after induction. Related to Fig.5.

(Aa-Ad) RNAscope of *Igf1r* in *Runx2<sup>fl/fl</sup>* (Aa) and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* (Ac) mice 1 week after tamoxifen induction (1wpt) at 1 month of age. Ab and Ad represent high-magnification images of insets in Aa and Ac, respectively. White dotted lines in Aa and Ac indicate cervical loop. Scale bars, 50 μm.

Figure S6B. *Igf2* mRNA levels are comparable in *Runx2<sup>fl/fl</sup>* and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* mice 1 week after induction. Related to Fig.5.

(Ba-Bd) RNAscope of *Igf2* in *Runx2<sup>fl/fl</sup>* (Ba) and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* (Bc) mice 1 week after induction (1wpt) at 1 month of age. Bb and Bd represent high-magnification images of insets in Ba and Bc, respectively. Arrows indicate the expression of *Igf2* in the MSC region.

(Be) Real-time PCR analysis of *Igf2* in *Runx2<sup>fl/fl</sup>* and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* mice 1 week after induction (1wpt) at 1 month of age. n=3, NS, no significant difference.

Schematic at the bottom indicates induction protocol. White dotted lines indicate cervical loop. Data are represented as mean ± SEM. Scale bars, 100 μm.

Figure S6C. IGFBP expression in *Runx2<sup>fl/fl</sup>* and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* mice 1 week after induction. Related to Fig.5.

(Ca-Ct) RNAscope of *Igfbp1* (Ca and Cc), *Igfbp2* (Ce and Cg), *Igfbp4* (Ci and Ck), *Igfbp5* (Cm and Co) and *Igfbp6* (Cq and Cs) in incisors from *Runx2<sup>fl/fl</sup>* (Ca, Ce, Ci, Cm and Cq) and *Gli1-Cre<sup>ERT2;Runx2<sup>fl/fl</sup></sup>* mice (Cc, Cg, Ck, Co and Cs) 1 week after induction at 1 month of age. Cb, Cd, Cf, Ch, Cj, Cl, Cn, Cp, Cr and Ct represent high-magnification images of insets in Ca, Cc, Ce, Cg, Ci, Ck, Cm, Co, Cq and Cs, respectively. Arrows indicate positive signal and asterisks indicate absence of signal. White dotted lines indicate cervical loop. Scale bars, 100 μm.
**Table S1. Antibody sources and concentrations. Related to STAR Methods.**

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**Western Blot**

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**Table S2. List of PCR primers. Related to STAR Methods.**

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