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Defects and rescue of the minor salivary glands in Eda pathway mutants

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ABSTRACT
Despite their importance to oral health, the mechanisms of minor salivary gland (SG) development are largely unexplored. Here we present in vivo and in vitro analyses of developing minor SGs in wild type and mutant mice. Eda, Shh and Fgf signalling pathway genes are expressed in these glands from an early stage of development. Developing minor SGs are absent in Eda pathway mutant embryos, and these mice exhibit a dysplastic circumvallate papilla with disrupted Shh expression. Supplementation of Eda pathway mutant minor SG explants with recombinant EDA rescues minor SG induction. Supplementation with Fgf8 or Shh, previously reported targets of Eda signalling, leads to induction of gland like structures in a few cases, but these fail to develop into minor SGs.

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Introduction

Salivary glands (SGs) have an important role in providing lubrication for digestion and protection of the oral tissues. In addition to the major SGs (reviewed in Tucker (2007)), the mammalian oral cavity also contains many minor SGs. These small glands provide ongoing protection to the oral tissues by secreting saliva continuously (Hand et al., 1999). Furthermore, study of developing minor SGs may reveal new information about the development of related epithelial structures such as the hair follicles, teeth or other glands. Despite their importance to oral health and potential interest to developmental biologists, the mechanisms of minor salivary gland (SG) development are largely unexplored.

The minor SGs are located in the submucosa of the tongue, cheeks and palate and secrete mostly mucus saliva. These glands are simpler in structure than the major SGs, lacking a complex branched ductal system and existing continuously within the surrounding connective tissue, rather than within a mesenchyme capsule (Hand et al., 1999). The development of the murine submandibular gland (SMG), the largest major SG, has been clearly characterized and develops from a thickening of the oral epithelium at E11.5, subsequently undergoing bud formation, branching morphogenesis and terminal differentiation. This process involves an array of signalling pathways including Sonic Hedgehog (Shh), Fibroblast Growth Factor (Fgf) and Ectodysplasin A (Eda) (Jaskoll and Melnick, 1999; Hoffman et al., 2002; Jaskoll et al., 2004a,b; Wells et al., 2010). By contrast, information on the genes involved in minor SG development is lacking, although it has been shown that the homeobox transcription factor Nkx3.1 is expressed during mouse minor SG development and plays a role in duct morphogenesis (Schneider et al., 2000).

The Eda signalling pathway is required for ectodermal organ development. Mutations in Eda pathway genes cause hypohidrotic ectodermal dysplasia (HED), characterized by defective development of the hair, teeth and exocrine glands (Clarke et al., 1987). Eda encodes the tumour necrosis factor-like ligand EDA A1 (Srivastava et al., 1997). EDA A1 signals through its receptor EDAR (Srivastava et al., 1997; Monreal et al., 1999; Headon et al., 2001) and instigates downstream activation of Np63 (Kumar et al., 2001). Recessive mutations in EDA are responsible for X-linked HED, the most common form of HED (Kere et al., 1996), while dominant and recessive mutations in EDAR and EDARADD have been found in families carrying autosomal HED (Monreal et al., 1999; Headon et al., 2001). The spontaneous mouse mutants EdaTa/Ta, EdarAdd−/− and EdaradΔ8/8Ct (Srivastava et al., 1997; Monreal et al., 1999; Headon et al., 2001) exhibit a similar phenotype to human HED in that the development of the hair, teeth and exocrine glands is impaired (Falconer et al., 1951; Grüneberg, 1965; Claxton, 1967; Grüneberg, 1971; Blecher et al., 1983). Analysis of Eda pathway mutant mice has revealed that Eda signalling plays a role in SMG branching morphogenesis (Jaskoll et al., 2003; Wells et al., 2010), but the role of Eda signalling in minor SG development has not been examined thoroughly. The classical study of gland development in EdaTa/Ta states that lingual and palatal minor SGs are absent in EdaTa/Ta embryos (Grüneberg, 1971), although it is unclear whether this represents developmental delay or a failure of initiation. As well as the minor SG defect, Grüneberg (1971) also reported that EdaTa/Ta embryos exhibit a...
developing minor SGs by I). The structures examined in the WT were consistent in all the embryos we examined, indicating that the stage at which minor SGs develop, and their positioning within the oral cavity, is highly regulated. The sequential appearance of minor SGs in different locations on the tongue and palate was consistent in all the embryos we examined, and we also noticed that glands simultaneously arose in identical regions on the left and right sides of the embryo (Fig. 1A). This indicates that the stage at which minor SGs develop, and their positioning within the oral cavity, is highly regulated.

Mucous minor SGs are absent in Eda pathway mutant adults

To confirm whether the embryonic Eda pathway mutant minor SG defects persist into adulthood, we compared sections of adult Eda pathway mutant and WT oral cavities (Fig. 2). In the WT, a large number of mucous glands are present on the palate and tongue. A number of serous glands are also observed in association with the CVP (Von Ebner’s glands) anterior to the lingual mucous glands (Fig. 2A). In EdaTa/Ta, EdarTa/Ta and EdardlJ/dlJ embryos of the same stage, histological indications of developing minor SGs are absent (Fig. 1B–C, E, EdaraddCR/CR not shown).

In the E17.5 WT, some of the developing lingual glands have formed distinct ducal and acinar structures, with hollowed out ducts forming well defined lumina. There is evidence of mucus production at E17.5 and E18.5, as indicated by Alcian blue staining within the ducts and end buds. In addition, a number of glands are now visible on the palate (Fig. 1F,H,K). In Eda pathway mutant embryos of the same stage, histological signs of developing minor SGs are absent (Fig. 1G, I). The structures examined in the WT were confirmed to be developing minor SGs by in situ hybridisation of Nkx3.1 (Schneider et al., 2000) (Fig. 1J).

The sequential appearance of minor SGs in different locations on the tongue and palate was consistent in all the embryos we examined, and we also noticed that glands simultaneously arose in identical locations on the left and right sides of the embryo (Fig. 1A). This indicates that the stage at which minor SGs develop, and their positioning within the oral cavity, is highly regulated.

EdaTa/Ta mice exhibit a dysplastic CVP with disrupted Shh expression

While characterizing the minor SG phenotype in Eda pathway mutants, we also examined the CVP. In agreement with the observations of Grüneberg (1971), we confirmed that the embryonic CVP is dysplastic in EdaTa/Ta, EdaraddCR/CR and EdardlJ/dlJ (Fig. 3A and B, EdaTa/Ta and EdardlJ/dlJ not shown), appearing as a downward fissure rather than a raised dome. During WT early tongue development, Shh is expressed in the developing epithelial dome of the CVP where it is thought to regulate proliferation and epithelial invagination leading to the structure’s characteristic morphology (Lee et al., 2006; Kim et al., 2009) (Fig. 3C). In EdaTa/Ta, Shh expression was restricted to one side of the developing CVP and was absent from the opposite wall of the dome where no epithelial trench had formed (Fig. 3D). Therefore, in the absence of Eda, CVP Shh expression appears disrupted, resulting in loss of the trench on one side.

Eda, Shh and Fgf pathway genes are expressed from the earliest stages of minor SG development

To shed light on the mechanisms regulating the induction and early development of the minor SGs, we studied the expression of a selection of genes during early minor SG development. Because minor SGs fail to initiate in Eda pathway mutant mice, we first chose to examine Eda pathway activity. In addition, we examined the expression of Shh and Fgf pathway genes, because these pathways are possible targets of Eda signalling (Pummillia et al., 2007; Melnick et al., 2009). To study Eda pathway activity, we examined the expression of Edaradd, since the expression of this gene likely reflects the location where the pathway is acting. At E15.5, Edaradd was expressed in the budding minor SGs and throughout the oral epithelium (Fig. 3E and F). At the same stage, Shh mRNA was weakly detected in the budding glands but not throughout the oral epithelium (except in the developing rugae) (Fig. 3G and H). Ptc1, the Shh signalling receptor and target, was expressed in the budding glands, particularly at the distal portion of the bud (Fig. 3I). To examine Fgf signalling activity, we studied the expression of Erm, an Ets-family transcription factor target of Fgf signalling (Wasylyk et al., 1998). Erm was detected strongly in the budding glands at an early stage of development. Erm expression was confined to the developing glands, and was not detected in the oral epithelium (Fig. 3J).

Minor SGs fail to develop in EdaTa/Ta tongue explants

We developed a novel minor SG culture system allowing us to follow the development of lingual minor SGs in tongue explants. After development of E13.5 WT whole tongues for 48 hours in vitro, developing minor SG buds were visible at the posterior lateral area of the tongue (Fig. 4A). Minor SG buds were absent in EdaTa/Ta tongues at this stage (Fig. 4C). After 72 hours in culture, more buds were visible on the lateral WT tongue, and further buds appeared closer to the midline (Fig. 4B), in agreement with our histological data. Developing lingual glands remained absent in EdaTa/Ta tongues at this stage (Fig. 4D).

To quantify these observations, the tongue explants were sectioned and subjected to histology staining and in situ hybridisation of an Nkx3.1 probe. Developing minor SGs, as defined by Nkx3.1 expressing epithelial thickenings, were counted over all sections from each explant, and the number of developing glands in WT, EdaTa/+, and EdaTa/Ta explants compared. While no Nkx3.1 expressing regions were present in EdaTa/Ta tongues (Fig. 4F, H, I), a mean of ~6 Nkx3.1 positive developing lingual glands were present in WT tongues (Fig. 4E, G, I). Nkx3.1 positive lingual glands were present in EdaTa/+, but appeared reduced in number in comparison with WTs (Fig. 4I).
Fig. 1. Minor SGs are absent in Eda pathway mutant embryos. Frontal sections. (A) E15.5 WT oral cavity showing epithelial buds and downgrowths (arrows). (B) E15.5 Eda^{Ta/Ta} (n = 6) oral cavity stage matched to (A). Developing minor SGs are absent. (C) E15.5 Eda^{Ta/Ta} (n = 5) oral cavity stage matched to (A) showing similar absence of developing minor SGs. (D) High magnification of E15.5 WT oral cavity showing downgrowth of the posterior lateral tongue epithelium (arrow), and additional buds towards the midline. (E) High magnification of Eda^{Ta/Ta} tongue epithelium. Developing minor SGs are absent. (F) E17.5 WT oral cavity. A number of developing lingual and palatal minor SGs are seen (arrows). (G) E17.5 Eda^{Ta/Ta} (n = 3) oral cavity stage matched to (F). Developing minor SGs remain absent. (H) High magnification of E17.5 WT lingual gland. Distinct ductal and acinar structures have formed, and the duct exhibits a well-defined lumen. Alcian blue staining indicates mucus production. (I) High magnification of E17.5 Eda^{Ta/Ta} oral cavity showing absence of developing minor SGs. (J) E17.5 oral cavity. Nkx3.1 is expressed in developing minor SGs (arrows). (K) WT E18.5 oral cavity. Alcian blue staining indicates differentiated glands on the tongue and a number of palatine minor SGs are present (arrows). nc, nasal cavity; oc, oral cavity; t, tongue; p, palate. Scale bar in A (for A–C, J) = 200 μm. Scale bar in D (for D, E) = 100 μm. Scale bar in F (for F, G, K) = 500 μm. Scale bar in H (for H, I) = 100 μm.
Exogenous EDA A1 rescues minor gland induction in EdaTa/Ta

We investigated whether minor SG induction can be rescued by recombinant EDA A1 supplementation in vitro. E13.5 EdaTa/Ta and EdaTa/+ tongues were cultured with 500 ng/mL EDA A1, and control tongues were cultured in the absence of EDA A1. After 4 days in culture, tongue explants were sectioned and subjected to histology staining and in situ hybridisation of an Nkx3.1 probe. Developing minor SGs, as defined by Nkx3.1 expressing epithelial thickenings, were counted over all sections from each explant, and the mean number of developing glands in treated and control explants compared. While no Nkx3.1 expressing regions were present in control EdaTa/Ta tongues (Fig. 5A, C, E), a mean of ~4 Nkx3.1 positive developing lingual glands were present in EDA A1 treated EdaTa/Ta tongues (Fig. 5B, D, E). A trend towards increased minor gland number was also observed in WT and EdaTa/+ tongues treated with EDA A1 in comparison with untreated WT tongues (Fig. 5E).

Exogenous Shh and Fgf8 do not fully rescue minor gland induction in Eda+/+]

We tested whether application of exogenous Shh or Fgf8, potential targets of EDA signalling, would result in rescue of the minor SGs in Eda pathway mutant tongues. For these experiments, we moved to Eda+/+ explants. These mice lack functional Edar, and we considered them the best system for a downstream rescue since the possibility of activating signalling via Edar is abolished. E13.5 Eda+/+ tongues were cultured with either 500 ng/mL Fgf8b or 2.5 μg/mL Shh–N peptide, and control tongues were cultured in the absence of recombinant protein. These proteins were also tested simultaneously on SMG explants to confirm that they were functional (Wells et al., 2010). After 4 days in culture, tongue explants were sectioned and subjected to histology staining and in situ hybridisation of an Nkx3.1 probe. No Nkx3.1 expression was detected in control Eda+/+ explants. In 3/19 Fgf8b-treated tongues, weak Nkx3.1 expression was evident in 1 or 2 gland-like structures, indicating possible rescue of minor SGs in a limited number of explants (Fig. 6A–D). No Nkx3.1 expression was detected in Shh-treated Eda+/+ explants, although Nkx3.1-negative gland like structures were noted. In location and morphology, these structures were similar to minor SGs, suggesting that Shh causes the induction of a small number of glands which then do not develop further (Fig. 6E–H, J). Expression of Nkx3.1 was detected in developing glands in Eda+/+ tongues as expected (Fig. 6I).

Discussion

Minor SGs develop by epithelial downgrowth and are highly regulated

Our data represents, to our knowledge, the first thorough description of minor SG development in the mouse. We show that the minor SGs develop by epithelial thickening and budding, and subsequent downgrowth and differentiation. However, unlike the SMGs, the minor SGs lack a mesenchyme capsule (Hand et al., 1999). This raises the question of where the signals instructing the positioning and development of the glands reside. Recombination experiments have shown that major SG branching is driven by the surrounding mesenchyme (Grobsstein, 1953), but it has been speculated that the initiation signals may come from the oral epithelium as in the developing tooth (Tucker, 2007). Our data showing that the minor glands are able to initiate development without signals from a mesenchyme capsule certainly suggests that the major SGs may be able to do the same, only requiring mesenchymal signals to instruct later branching morphogenesis. It is tempting to speculate that the minor SGs do not branch extensively because they do not have access to such stimulatory signals as those secreted by the major SG mesenchyme.

To date the only known marker of developing minor SGs was Nkx3.1 (Schneider et al., 2000). Here we show that Edaradd, Shh, Ptc1 and Erm also mark the minor SGs from the earliest stages of their development. Shh is a known mitogen (Ingham and McMahon, 2001) and it seems likely that its function in the developing minor SG is to promote proliferation and epithelial downgrowth, as in the developing hair follicle (Millar, 2002). In addition, our data showing expression of both Ptc1 and Shh in the epithelium, rather than in separate tissue compartments, indicates that Shh signalling regulates minor SG development in an autocrine manner. Fgf signalling is required for major SG development (reviewed in Tucker (2007)), and our finding of strong Erm expression in the developing minor SGs is in agreement with this.
**Eda signalling is required for minor SG initiation**

Our data showing Eda pathway gene expression in the developing minor SGs and our analyses of minor SG development in Eda pathway mutant mice indicate a requirement for Eda signalling in minor SG initiation. The observation that Eda°/° embryos exhibit a mild phenotype with respect to their minor SGs indicates that levels of Eda signalling are important in minor SG development. This idea fits with
data showing that human female carriers of XL-HED exhibit reduced saliva flow (Lexner et al., 2007). No information is yet available on the signalling mechanisms involved in initiating development of major or minor SGs; our work indicates an involvement for Eda signalling. The literature also lacks information on genes involved in determining the type of SG that will develop. The specific requirement for Eda in mucous minor SG initiation contrasts with the case of the SMGs (Melnick et al., 2009) and serous minor SGs, which do not require Eda signalling for initiation, and evokes the different requirements for Eda in the distinct types of hair follicles. In Eda<sup>Ta/Ta</sup>, secondary and tertiary hair follicles initiate normally, but primary hair follicles fail to initiate (Laurikkala et al., 2002).

**Fig. 4.** Minor SGs fail to develop in Eda<sup>Ta/Ta</sup> tongue explants. Tongue explants in culture (A–D) and sectioned (E–H). Insets in A–D show high magnification of dashed boxes. (A) E13.5 WT tongue explants after 48 hrs in culture. Lingual epithelial buds are visible (outlined). (B) Explant shown in (A) after 72 h in culture. More epithelial buds are visible on lateral tongue and towards the midline (outlined). (C) E13.5 Eda<sup>Ta/Ta</sup>-/- tongue explant after 48 h in culture. Budding minor SGs are absent. (D) Explant shown in (C) after 72 hrs in culture. Developing minor SGs remain absent. (E) E13.5 + 72 h WT posterior tongue section (trichrome stained). Developing lingual glands are apparent (arrows). (F) E13.5 + 72 hrs Eda<sup>Ta/Ta</sup> posterior tongue section. Developing lingual glands are absent. (G) Serial section to (E), showing Nkx3.1 expression in developing lingual glands (arrows). (H) Serial section to (F). Nkx3.1 expression is absent. (I) Chart representing mean lingual gland number counted per genotype group. Number of explants per group: Eda<sup>Ta/Ta</sup> (n = 7), Eda<sup>Ta/+</sup> (n = 3), WT (n = 6). Error bars represent one standard error±mean. Scale bar in A (for A–D) = 1000 µm. Scale bar in E (for E–H) = 200 µm. * indicates hyoid cartilage.
Eda pathway mutant minor SGs can be rescued with recombinant EDA A1 in vitro

Using our minor SG culture system, we show that supplementation of E13.5 EdaTa/Ta tongues with EDA A1 results in rescue of gland development. This agrees with data showing that exogenous EDA A1 rescues primary hair follicle development in EdaTa/Ta skin explants (Laurikkala et al., 2002). EDA A1 injection has been shown to rescue most aspects of the EdaTa/Ta phenotype (Gaide and Schneider, 2003) and as a result recombinant EDA A1 is promising a cure for sufferers of HED. HED patients demonstrate reduced whole saliva flow (Nordgarden et al., 2001) leading to xerostomia (dry mouth), a reduced quality of life and further damage to an already compromised dentition. However, the ability of this protein to rescue minor SG development in EdaTa/Ta had not been studied. Our findings are encouraging for future attempts to correct SG defects in HED patients. Although our histological studies showed an absence of minor SGs in Eda pathway mutant embryos, the fact that these glands are rescued with EDA A1, and that they develop in the expected position, implies that a group of cells able to respond to the signal are in fact present in Eda pathway mutants.

Exogenous Shh and Fgf8 do not fully rescue minor gland induction in Edar<sup>dl/dl</sup>

QPCR data has indicated that Shh is a potential target of Eda signalling in the SMGs (Melnick et al., 2009), and treatment of embryonic EdaTa/Ta skin cultures with recombinant EDA A1 results in upregulation of Shh (Pummillia et al., 2007). A number of Nkx3.1 expression domains in the developing embryo, such as the prostate gland, are dependent on Shh (Schneider et al., 2000). We were unable to demonstrate rescue of Nkx3.1 expression in Edar<sup>dl/dl</sup> tongue explants by Shh supplementation, although we did observe the presence of gland-like tissue. Shh overexpression is associated with tumour formation in the skin (Oro et al., 1997), and it is possible that the tissue we observe is the result of overproliferation. Our finding that Shh is not sufficient to completely rescue minor SG development in the absence of Eda signalling agrees with data showing that exogenous Shh is unable to rescue primary hair placode induction in EdaTa/Ta skin cultures (Pummillia et al., 2007).

Fgf8 is another potential target of Eda signalling in the SMGs (Melnick et al., 2009). Other studies have shown growth factor mediated rescue of aspects of the EdaTa/Ta phenotype. EGF injection...
administered to EdaTa/Ta pups rescues sweat gland development (Blecher et al., 1990). In embryonic EdaTa/Ta tooth explants, cusp morphogenesis is partially rescued by exogenous Fgf10 (Pispa et al., 1999), although it is unclear whether this is through a mechanism independent of Eda signalling, such as an increase in epithelial proliferation. In our study, 3 out of 19 cultures showed induction of Nkx3.1-positive minor SG structures in response to Fgf8 supplementation, indicating that Fgf8 is not sufficient to rescue reliably. This may
be to the greater importance of alternative Fgf ligands in minor SG development, or a subtle difference in the developmental stage of the tongue explants which did show a rescue. It seems plausible that neither Fgfb nor Shh are able to act alone in minor SG development and may require other factors for normal morphogenesis, or act in concert with each other.

Materials and methods

Animals

All Eda pathway mutant mice were on the FVB/N background. E13.5 WT, Eda\textsuperscript{fl/fl} and Eda\textsuperscript{fl/pt} embryos were obtained from Eda\textsuperscript{+/-} females crossed with Eda\textsuperscript{fl/fl} males. E13.5 Edar\textsuperscript{fl/fl} and Edar\textsuperscript{fl/+} embryos were obtained from Edar\textsuperscript{fl/+} females crossed with Eda\textsuperscript{fl/fl} males. E15.5 and E17.5 Eda\textsuperscript{fl/fl}, Edar\textsuperscript{fl/fl} and Edaradd\textsuperscript{1-1} embryos were obtained from homozygous females crossed with hemi-/homozygous males. In the text, Eda\textsuperscript{fl/fl} refers to Eda\textsuperscript{fl/fl} females and Eda\textsuperscript{fl/pt} males: Edar\textsuperscript{fl/fl} and Edaradd\textsuperscript{1-1} refer to homozygous animals. CD1 mice were bred to obtain stage matched control animals where required. Pregnant females were sacrificed by cervical dislocation and noon on the day of discovery of the vaginal plug was designated day 0.5 of development. Embryos were harvested and desiccated in phosphate buffered saline (PBS) for immediate fixation, or in complete culture medium (Advanced Dulbecco modified Eagle's minimal essential medium F-12 (DMEM-F12) (Gibco, Invitrogen) supplemented with 1% penicillin/streptomycin and 1% Glutamax (Gibco, Invitrogen)) for tongue culture experiments.

Genotyping

DNA was extracted by digestion of tail snap tissue in 0.5 mg/ml proteinase K at 55 °C overnight, followed by phenol chloroform purification and ethanol precipitation. Genotype of E13.5 WT, Eda\textsuperscript{fl/fl} and Eda\textsuperscript{fl/pt} embryos was identified by PCR analysis using primer sets specific for Eda (covering the exon 1 region deleted in Eda\textsuperscript{fl/fl} and therefore failing to generate a product from Eda mutant DNA), Y chromosome and Actin (for positive control). Primer sequences were: EDA: 5′-AGGA-CAGTACTGCGCTGT-3′ (forward), 5′-GCCGCGCCCTCTCCTAGC-3′ (reverse), Y chromosome: 5′-CTGGAGCTCTACAGTGATGA-3′ (forward), 5′-CAGTTACAATCAACACATAC-3′ (reverse), Actin: 5′-GCTTCTGAGATGTGCCTCTCT-3′ (forward), 5′-ACACAGGCTTTGATGTTGC-3′ (reverse). These primers generated 509 bp (Eda), 343 bp (Y chromosome) and 159 bp (Actin) fragments.

The Edar mutant animals used in this study were of the down\textsuperscript{Jackson} strain which possess a G to A point mutation within the Edar death domain (Headon and Overbeek, 1999). Genotype of E13.5 Edar\textsuperscript{fl/fl} and Edar\textsuperscript{fl/+} embryos was determined by PCR analysis using Edar specific primers, the forward primer containing a one nucleotide mismatch from the template DNA. The mismatch enabled the generation of a TaqI restriction site unique to the WT sequence. Primer sequences were 5′-TGAAAAACATGGGCCACCTTGCTC-3′ (forward, mismatch underlined), 5′-TCACCTACACGCTGCCTGTGCTG-3′ (reverse). These primers generated a 309 bp product. Overnight digestion of Edar\textsuperscript{fl/fl} product with TaqI (Sigma) at 65 °C resulted in 142 bp and 167 bp fragments (due to a natural TaqI site within the PCR product), whereas restriction of Edar\textsuperscript{fl/+} product resulted in fragments of 167 bp, 142 bp, 120 bp and 22 bp. Fragments were visualised on a 3% agarose gel. The mismatch primer was designed using dCAPS Finder 2.0 online software.

PCR cycling conditions were as follows: 94 °C 2 min 30 s, 94 °C 30 s, 54 °C 30 s, 72 °C 1 min for 36 cycles.

Tissue processing and sectioning

Tissues were fixed in 4% paraformaldehyde (PFA) at 4 °C overnight and washed in PBS before dehydration in a methanol and isopropylol series, and clearing in 1,2,3,4-tetrahydroxyphenalene. Adult heads were additionally subjected to decalciication in 1% PFA and 25% 0.5 M EDTA in PBS for 2 weeks prior to dehydration. Cleared samples were incubated in paraffin wax at 65 °C before embedding in moulds. Sections were cut to a thickness of 8 μm, mounted on glass slides (Superfrost Plus™, VWR International) and dried on a 42 °C hotblock overnight.

In situ hybridisation

Radioactive in situ hybridisation of 35S-UTP-labelled Edaradd probe was performed as described in Tucker et al. (1999). Edaradd was linearized with SpeI and transcribed with T3. Sections were counterstained with methyl green and photographed under darkfield. In situ hybridisation of dioxygenin-labelled Shh, Ptc1, Erm and Nkx3.1 probes was performed according to modified Wilkinson procedures (Wilkinson, 1995) and sections were counterstained with eosin. Shh was linearized with EcoRI and transcribed with T7. Nkx3.1 was linearized with EcoRV and transcribed with T7. Ptc1 was linearized with BamHI and transcribed with T3. Erm was linearized with HindIII and transcribed with T7.

Histology staining

Sections were cleared with Histoclear™, rehydrated through an ethanol series and washed in dH2O. Sections were stained with haematoxylin and eosin (H&E) and differentiated in acid alcohol, or alternatively were stained with Sirius red in picric acid, Alcian blue and haematoxylin (trichrome) where appropriate. After staining, sections were washed in dH2O, dehydrated through an ethanol series, cleared in xylene and coverslipped with DPX mounting medium.

Organ culture

Tongues were dissected whole in complete culture medium and care was taken to remove all SMG tissue. Explants were mounted on membranes (BD Falcon cell culture inserts) and floated over culture medium in glass bottom dishes (MatTek Corporation). Medium for experimental explants was supplemented with recombinant Fc-EDA A1 (Gaide and Schneider, 2003) Fgfb, or Shh-N peptide (R&D Systems). Explants were cultured in a 37 °C, 5% CO2 incubator, photographed and the medium changed daily.

Analysis

Unpaired t-tests were performed for statistical comparison of groups of data and p values are shown in the figures. Data were analysed and converted to charts using Microsoft Office Excel 2007. The level of statistical significance was taken as p<0.05.

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Conflict of interest statement

The authors declare no conflicts of interest.

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References


Falconer, D.S., Fraser, A.S., King, J.W.B., 1951. The genetics and development of Crinkled, a new mutant in the house mouse. J. Genet. 50, 324.


