Apical constriction and epithelial invagination are regulated by BMP activity

Vijay K. Jidigam, Raghuraman C. Srinivasan, Cedric Patthey and Lena Gunhaga*

ABSTRACT
Epithelial invagination is a morphological process in which flat cell sheets transform into three-dimensional structures through bending of the tissue. It is accompanied by apical constriction, in which the apical cell surface is reduced in relation to the basal cell surface. Although much is known about the intra-cellular molecular machinery driving apical constriction and epithelial invagination, information of how extra-cellular signals affect these processes remains insufficient. In this study we have established several in vivo assays of placodal invagination to explore whether the external signal BMP regulates processes connected to epithelial invagination. By inhibiting BMP activity in prospective cranial placodes, we provide evidence that BMP signals are required for RhoA and F-actin rearrangements, apical constriction, cell elongation and epithelial invagination. The failure of placode invagination after BMP inhibition appears to be a direct consequence of disrupted apical accumulation of RhoA and F-actin, rather than changes in cell death or proliferation. In addition, our results show that epithelial invagination and acquisition of placode-specific identities are two distinct and separable developmental processes. In summary, our results provide evidence that BMP signals promote epithelial invagination by acting upstream of the intracellular molecular machinery that drives apical constriction and cell elongation.

KEY WORDS: BMP, F-actin, Invagination, RhoA, Apical constriction, Placodes

INTRODUCTION
Epithelial invagination is a morphological process in which flat cell sheets transform into three-dimensional structures, like an epithelial pit/sac/cup or a furrow. The process of invagination is crucial during development as it plays an important role for the formation of the lens, inner ear, nasal cavity, adenohypophysis, trachea and salivary glands – all of which are different pit/sac/cup structures. Processes that involve furrow formation are gastrulation and neural tube bending, as well as the development of the placodes, the olfactory, lens, otic and epibranchial and non-sensory (hypophyseal) components of the peripheral nervous system (PNS) (reviewed in Baker and Bronner-Fraser, 2001; Jidigam and Gunhaga, 2013). Placodal cells derive from the neural plate border region, in which Bone Morphogenetic Protein (BMP) activity play an important role for its specification at late blastula stages (Linker et al., 2009; Patthey et al., 2009). Moreover, BMP signals are also required for the individual specification of placodal cell types at later stages (Brugmann et al., 2004; Glavic et al., 2004; Nguyen et al., 1998; Patthey et al., 2008; Sjodal et al., 2007). In most vertebrate embryos, three sensory placodes, the olfactory, lens and otic, and the non-sensory hypophyseal placode undergo invagination. Invagination is initiated soon after cell elongation and thickening of the epithelium, and involves inwards bending of the epithelium resulting in the formation of a cup-shape structure, often referred to as pit-structures. Whether the initial process of placode invagination is regulated by a common molecular mechanism, or is controlled by unique molecular codes for each individual placode remains to be determined.

In this study we have established in vivo assays of chick olfactory, lens, otic and hypophyseal placode invagination to explore how BMP activity regulates processes connected to epithelial invagination. Our in vivo results provide evidence that RhoA and F-actin rearrangements, apical constriction, cell elongation and...
epithelial invagination are regulated by a common BMP-dependent molecular mechanism. We conclude that the failure of placode invagination in BMP loss-of-function experiments is not caused by alterations in cell death or proliferation, or loss of placodal identity, but rather as a direct result of disrupted apical accumulation of RhoA and F-actin, which leads to lack of apical constriction and reduced cell length. In addition, our results show that epithelial invagination and acquisition of placode-specific identities are two independent developmental processes.

RESULTS

BMP activity is detected in placodal regions around the time of invagination

To study invagination we first characterized the timing of initial invagination in BMP loss-of-function experiments in chick (*Gallus gallus*). Invagination begins around Hamburger and Hamilton (1951) stage 10/11 in the otic placode (Fig. S1A,B), stage 14 in the lens placode (Fig. S1C,D), and stage 17 in the olfactory placode (Fig. S1E,F). BMP signals have been shown to play an important role for the generation of placodes (Brugmann et al., 2004; Glavic et al., 2004; Linker et al., 2009; Nguyen et al., 1998; Patthey et al., 2009, 2008; Sjödal et al., 2007). To address whether BMP activity might play a role in the invagination of placodes, we first examined the expression pattern of *Bmp4* and *Bmp7*, as well as the location of its downstream signaling mediator phosphorylated (p)Smad1/5/8 prior to and around the time of placode invagination. At stages 8-10, *Bmp4* and *Bmp7* expression and pSmad1/5/8 are detected in the otic placode region (Fig. 1A; data not shown). Moreover, at stages 11-14, and stage 14-17, *Bmp4* and *Bmp7* expression and pSmad1/5/8 are observed in the lens and olfactory placodal domains, respectively (Fig. 1B,C; data not shown). Thus, in the olfactory, lens and otic placodal regions *Bmp4*, *Bmp7* expression and pSmad1/5/8, indicative of BMP activity, are detected at the time point for initiation of sensory placode formation and invagination.

BMP signals are required for placode invagination

To examine whether BMP signals are required for the invagination of sensory placodes, we performed *in vivo* experiments in which BMP activity was inhibited. This was accomplished by *in ovo* electroporation of a construct expressing the BMP antagonist Noggin in olfactory and lens placodal regions. A green fluorescent protein (GFP) vector was transferred alone or together with the Noggin-expressing vector in the ectodermal region of interest prior to the onset of invagination. After culture, successfully electroporated embryos with GFP staining within the lens or olfactory regions were analyzed.

All control lens electroporated embryos exhibited normal morphology of the lens epithelium (Fig. 2A; *n*=12/12). In contrast, when Noggin was electroporated in the lens, the invagination was suppressed and no thickened placode formed (Fig. 2B; *n*=15/15). Also control olfactory electroporated embryos exhibited normal morphology of the olfactory epithelium (Fig. 2C; *n*=21/21), whereas all Noggin-electroporated embryos exhibited disturbed invagination of the olfactory epithelium (Fig. 2D; *n*=21/21). On occasion, and depending on the electroporation efficiency, a small invagination in a GFP negative region of the electroporated olfactory placodal domain could be detected (Fig. S2B). The majority of the Noggin-electroporated olfactory regions still possessed a placode (*n*=18/21), as observed by the thickened ectoderm (Fig. 2D, *n*=12/21; Fig. S2A, *n*=5/21; Fig. S2B, *n*=1/21), while a few embryos completely lacked placode formation in the Noggin-electroporated side (Fig. S2C; *n*=3/21). Using a whole embryo three-dimensional (3D)-OPT imaging technique, the disrupted invagination of the olfactory placode and lack of pit formation was clearly visible after BMP inhibition (*n*=4/4), compared to control embryos (*n*=4/4) (Fig. 2E-H; Movies 1, 2).

We next analyzed the invagination process of the otic placode. Electroporating stage 6/7 embryos in the otic region, which lies in the proximity of the heart region, consistently resulted in heart malformation and arrested development (data not shown),

![Fig. 1. BMP expression patterns in otic, lens and olfactory placodes.](image)
At earlier stages, BMP activity has been shown to be important for the specification of placodal progenitors (Brugmann et al., 2004; Glavic et al., 2004; Nguyen et al., 1998; Patthey et al., 2008; Sjödal et al., 2007). Moreover, previous studies have indicated that BMP signals are required for the specification of lens fibre cells from stage 4 until stage 13, in part by regulating the onset of L-Maf (Pandit et al., 2011; Sjödal et al., 2007), which also was verified in this study (Fig. S3). Therefore, we examined if the disrupted invagination in the BMP loss-of-function experiments might be a consequence of disturbed acquisition of placodal cell identity in the olfactory and otic placodes, or whether at this stage BMP activity is required specifically for the invagination process. To address this issue, we examined whether differentiated cell types were generated in placodes of Noggin-treated embryos, using a set of molecular markers that uniquely define specific placodes.

The olfactory placode normally give rise to sensory and respiratory olfactory cells (Maier et al., 2010). The sensory domain includes stem-cell like Hes5+ cells and post-mitotic HuCD+ neurons, whereas cells in the respiratory region express Id3 (Maier et al., 2010). In addition, Id3 is a direct target gene of BMP signaling, and can be used as readout of BMP activity (Hollnagel et al., 1999). All control embryos electroporated in the olfactory placodal region expressed Hes5 and HuC/D in the sensory domain and Id3 in the respiratory region of the invaginated olfactory pit (Fig. 4A; n=3/3). In contrast, inhibition of BMP suppressed the generation of Id3+ respiratory cells, (Fig. 4B; n=4/4) which confirmed the suppression of BMP activity and indicated a loss of respiratory cell types in line with previous results (Maier et al., 2010). However, Hes5 and HuC/D expression were still detected in the flat olfactory epithelium (Fig. 4B; n=4/4). Thus, although BMP signals are required for the specification of olfactory respiratory cells at this stage, the generation of placodal cells with an olfactory sensory identity are not dependent on BMP signals.

In the otic placode, Irxl+ and Lmx1b+ are markers of the posterior non-neurogenic otic epithelium, and consistently control electroporated embryos expressed these markers in the otic placode (Fig. 4C; n=3/3). In the BMP-inhibited flat otic epithelium, Lmx1b+ cells were generated throughout the otic region, whereas Irxl+ cells were detected in the posterior part of the otic region (Fig. 4D; n=3/3). These results indicate that at this stage the specification of otic...
placodal cells occurs independently of BMP activity. Together, these results provide evidence that cells can differentiate beyond the placode stage and mature into differentiated cell types in the absence of invagination. Thus, the acquisition of placode-specific cell types and placode invagination are independent processes.

**Disturbed invagination after BMP inhibition is not due to changes in cell death or proliferation**

We next analyzed whether inhibition of BMP activity caused a reduction of the proliferation rate and/or increased cell death in the prospective placodal epithelium, thereby leading to disrupted invagination of the sensory placodes. For this purpose we examined the expression of the cell proliferation marker phosphorylated HistoneH3 (pHH3) and the cell death marker activated (a) Caspase3 in control and BMP-inhibited embryos (either Noggin-electroporated in the lens and olfactory regions, or Dorsomorphin treated embryos for the otic region). Quantification of aCaspase3+/GFP+ double-positive cells revealed no significant changes in aCaspase3+ cells in the Noggin-electroporated lens or olfactory ectodermal region compared to control embryos (Fig. S4A,B). Moreover, no significant change in aCaspase3+ cells in the otic ectodermal region in Dorsomorphin-treated embryos was observed compared to control embryos (Fig. S4C). Regarding proliferation, there was no significant change in pHH3+/GFP+ double-positive cells in the Noggin-electroporated lens (Fig. S4D), and no significant change in pHH3+ cells in the otic region of Dorsomorphin-treated embryos compared to control embryos (Fig. S4F). On the other hand a significant decrease in pHH3+ cells was observed in the Noggin-electroporated olfactory region compared to control embryos (Fig. S4E). These data suggest that, although reduced cell proliferation in the olfactory placode might affect the invagination process, reduced cell proliferation or increased apoptosis in general cannot explain failure in placode invagination after BMP inhibition.

**BMP inhibition prevents cell shape changes in prospective placodal cells**

Cell elongation and apical constriction facilitates the invagination process. To analyze whether BMP inhibition disrupted cell elongation and/or apical constriction, we measured the cell length,
basal cell width and the apical cell width in control and BMP-inhibited placode regions. The olfactory placode was the optimal tissue to use for these studies, since BMP-inhibition resulted in a lack of invagination, but did not affect placode formation, and GFP-electroporated cells could be readily visualized to examine cell size and shape (Fig. 2D). GFP+ cells from the medial invaginated part of the olfactory pit were analyzed in both control (n=8) and Noggin treated (n=8) embryos, with a total of 74 control cells and 61 Noggin-treated cells (Fig. 5).

BMP inhibition in the olfactory region significantly reduced the cell length from an average of 50 µm in the control to an average of 33 µm in the Noggin-electroporated cells (Fig. 5A-E). In addition, the apical width of the Noggin-electroporated cells was significantly increased (average of ∼2.8 µm) compared to control cells (average of ∼1.2 µm) (Fig. 5D,F), whereas the average basal width was not significantly changed (Noggin ∼5 µm vs control ∼5.5 µm) (Fig. 5D,G). This resulted in an apical/basal ratio of 0.56 for Noggin-electroporated cells compared to 0.22 for control embryos. Thus, in placodal cells deprived of BMP activity cell elongation was reduced and apical constriction was abrogated.

**BMP inhibition disrupts apical accumulation of RhoA and F-actin**

Apical constriction and placode invagination have been shown to be mediated by apical accumulation of RhoA that facilitate apical localization of F-actin, which in turns activates the actin-myosin network (Plageman et al., 2011, 2010; Sai and Ladher, 2008). Using confocal microscopy, we analyzed whether the accumulation of RhoA and the apical restriction of F-actin were disturbed in the BMP inhibited placodal regions. In all three invaginating sensory placodes, the normal apical localization of RhoA and F-actin was lost upon BMP-inhibition (Fig. 6A-D; Fig. 7A,B). In the BMP inhibited embryos, the expression of RhoA was severely reduced or completely lost, and the cellular sub-localization of F-actin, visualized by Phalloidin staining, was changed to the periphery of the ectodermal cells (Fig. 6B,D; Fig. 7B) instead of being apically restricted as seen in control embryos (Fig. 6A,C; Fig. 7A). These results suggest that BMP activity is required for proper accumulation of RhoA and F-actin at the apical side of the cells and for subsequent apical constriction.

To further assess a general requirement for BMP signals during epithelial invagination we also analysed the hypophyseal non-sensory placode, by electroporating the Noggin construct in the hypophyseal region at stage 12 and cultured to approximately stage 15/16. Control embryos showed accumulated expression of F-actin at the apical region of the cells, and an invagination of the hypophyseal epithelium (Fig. S5A; n=4). Inhibition of BMP activity disrupted the apical accumulation of F-actin, and suppressed the invagination of the hypophyseal epithelium (Fig. S5B; n=5). RhoA was not expressed at the examined stages in the hypophyseal epithelium (Fig. S5; n=5). Thus, BMP signals are required for F-actin accumulation and the invagination process in both sensory and non-sensory placodes.

**Blocking ROCK activity mimics BMP inhibition and disrupts placode invagination**

RhoA is known to form a complex together with Trio, Shroom3 and Rock1/2, and inhibition of either RhoA or Rock1/2 activity disrupts apical constriction and placode invagination (Borges et al., 2011; Plageman et al., 2011; Sai et al., 2014). To directly evaluate and compare our BMP-inhibition results with experiments inhibiting ROCK activity, we used the Cornish pasty method to culture whole embryos together with Y27632, a pharmacological ROCK inhibitor. During these conditions the otic, lens and olfactory placodes failed to invaginate (Fig. 7C; Fig. S6B,D), in a similar manner as after BMP inhibition (Fig. 7B; Fig. 6B,D). In addition,
confocal microscopy showed that the expression of RhoA was severely reduced or completely lost, and F-actin was located at the periphery of the ectodermal cells instead of being apically restricted as seen in control embryos (Fig. 7A,C; Fig. S6A-D). Notably, lens placode formation was visible after ROCK inhibition (Fig. S6B, n=5/5; C, n=6/6). (B,D) Inhibition of BMP signaling disturbed the apical accumulation of RhoA and F-actin in both lens and olfactory epithelial cells (B, n=7/7; D, n=7/7). Boxed regions indicate the areas of higher magnification images. Arrows in C and D indicate the apical side. Scale bars: 100 µm (lower magnification); 10 µm (higher magnification). Ap, apical; Ba, basal.

**DISCUSSION**

**BMP is required for epithelial invagination**

By studying three different sensory placodes and one non-sensory placode we have unraveled a common mechanism, in which BMP activity is required for epithelial invagination. Our data in chick show that expression of BMP ligands and pSmad1/5/8 is detected in the placodal regions prior to and around the onset of epithelial invagination. Consistently, in mouse, targeted deletions of different components of the BMP pathway lead to disturbed lens vesicle and olfactory pit formation (Beebe et al., 2004; Furuta and Hogan, 1998; Maier et al., 2010; Wawersik et al., 1999). In addition, our previous results in chick have indicated that defective BMP signaling disrupts lens and olfactory placode invagination (Maier et al., 2010; Pandit et al., 2011). Our present results from studying the lens, olfactory, otic and hypophyseal placodes suggest that neither loss of placodal identity, reduced cell proliferation or increased cell death is causing the disturbed placode invagination after BMP inhibition. In agreement with this, it has previously been shown that disturbed invagination of the mouse otic placode, caused by Gata3 deficiency, is not due to increased apoptosis (Lilleväli et al., 2006). In addition, our results in the olfactory and
Otic placodes indicate that the process of cell elongation, which enables thickening of the ectoderm, is BMP independent. Subsequently, a disturbed placode invagination following attenuation of BMP signaling is not caused by a failure in placode formation.

Though BMP activity plays an important role for epithelial invagination, it is not the only signaling pathway that regulates this complex process. Studies in chick and mouse have shown that FGF activity is required for proper invagination of the olfactory and otic placodes (Maier et al., 2010; Sai and Ladher, 2008; Zelarayan et al., 2007). In addition, using chick otic tissue cultures it has been suggested that FGF activity plays a critical role for the activation of myosin II and reorganization of F-actin, followed by placode invagination (Sai and Ladher, 2008). Knockdown of FGF3 expression using silencing (si) RNA in the developing otic region in chick leads to partially invaginated placodes or failure in otic vesicle formation (Zelarayan et al., 2007). Moreover, Gata3 deficient mouse embryos exhibit a loss of Fgf10 expression in the otic epithelium followed by disrupted otic placode invagination (Lillevåli et al., 2006), and FGF signaling has been shown to be required for apical constriction in the zebrafish lateral line primordium (Zelarayan et al., 2007). Moreover, Gata3 deficient mouse embryos exhibit a loss of Fgf10 expression in the otic epithelium followed by disrupted otic placode invagination (Lillevåli et al., 2006), and FGF signaling has been shown to be required for apical constriction in the zebrafish lateral line primordium (Zelarayan et al., 2007). In addition, many studies have contributed to findings how a complex of RhoA, Rock1/2, Trio and Shroom3 connects to F-actin and myosin to regulate apical constriction (reviewed in Chauhan et al., 2015; Kondo and Hayashi, 2015; Martin and Goldstein, 2014; Sawyer et al., 2010). Consistently, our results show that in vivo inhibition of ROCK activity disrupts RhoA and F-actin accumulation and the subsequent invagination process of sensory placodes. Moreover, our data provide evidence that morphologically the ROCK-depleted otic placodes indicate that the process of cell elongation, which enables thickening of the ectoderm, is BMP independent. Subsequently, a disturbed placode invagination following attenuation of BMP signaling is not caused by a failure in placode formation.

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placodal epithelia were indistinguishable from the BMP-inhibited flat placodal domain, indicating that BMP activity acts up-stream of the ROCK-regulatory molecular machinery to regulate epithelial invagination.

Our results also show that suppressed BMP activity in placodal cells diminishes cell elongation. Consistently, the onset of Decapentaplegic (Dpp) signaling, the fly homolog of the vertebrate BMP signaling molecules, correlates with the cell elongation process in the developing Drosophila wing discs (Shen and Dahmann, 2005; Widmann and Dahmann, 2009). Moreover, Dahmann and colleagues have shown that Dpp signaling is both required and sufficient to regulate an elongated columnar cell shape by controlling the sub-cellular localization of activated Rho1 and Myosin II (Widmann and Dahmann, 2009). Interestingly, Drosophila mutations in wolknauel resulted in reduced Dpp signaling and impaired mesoderm invagination (Haecker et al., 2008). The existence of a general mechanism whereby BMP activity regulates morphogenesis is further supported by results in cell lines, in which both BMP2 and BMP7 induces actin reorganization in pluripotent C2C12 cells and fibroblast, respectively (Gamell et al., 2008; Konstantinidis et al., 2011). Taken together, BMP signals appear to activate a common regulatory pathway for actin rearrangement connected to cell and tissue morphogenesis, including epithelial invagination.

**Invagination and acquisition of placodal cell identity are independent developmental processes**

BMP signals are known to be required for the specification of placodal cell types at early stages (Linker et al., 2009; Patthey et al., 2009). Our results now show that lack of invagination in BMP loss-of-function experiments is not a mere consequence of the loss of placodal cell identity, as shown by the fact that the flat otic and olfactory epithelia are still thickened, and cells within it still express individual placode-specific markers. Thus, at these stages, any changes in gene regulatory networks caused by the loss of BMP activity clearly do not act at the level of the placode versus non-placode cell type decision. This indicates that acquisition of placodal cell identity and epithelial invagination are two independent developmental processes that can be experimentally separated. In agreement with this, it has been shown that failure in epithelial apico basal polarity and F-actin rearrangements during neural tube closure does not affect ventral or dorsal cell specification or cell differentiation (Eom et al., 2011, 2012). However, in the lens, our present and previous results provide evidence that BMP signals are required for the specification of lens fiber cells from stage 4 until stage 13, in part by regulating the onset of L-Maf (Pandit et al., 2011; Sjödal et al., 2007). Thus, in the lens, the two BMP-dependent processes of lens cell specification and invagination overlap in time, explaining why both lens identity and invagination are lost upon BMP inhibition. On the other hand, our data show that in ROCK loss-of-function experiments the lens ectoderm fails to invaginate, but still forms an L-Maf-positive placode, supporting our findings that acquisition of placodal cell identity and epithelial invagination can be separated. Whether BMP signaling promotes expression of effector genes related to apical constriction and morphogenetic movements, or whether its effects are mediated by post-translational modifications resulting into cytoskeletal rearrangements remains to be elucidated.

In summary, we have established in vivo assays of epithelial invagination in chick enabling morphological and genetic observations of the invagination process in four different placodes. Our results provide evidence that BMP signals promote epithelial invagination by acting upstream of the intracellular molecular machinery that drives apical accumulation of RhoA and F-actin, and thereby apical constriction. Moreover, our results show that epithelial invagination and acquisition of placode-specific identities are two separable developmental processes. Taken together, our results suggest a novel role for BMP activity in promoting a specific and cell type-independent mechanism for apical constriction, cell elongation and epithelial invagination.

**MATERIALS AND METHODS**

**Embryos**

Fertilized white Leghorn chicken eggs were obtained from Strömbäcks Ägg, Umeå, Sweden. Chick (Gallus gallus) embryos were staged according to the protocol of Hamburger and Hamilton (1951).

**In ovo electroporation**

Chick embryos were electroporated in the lens (stage 10/11), olfactory (stage 11-13) and hypophyseal (stage 12) ectoderm. Vectors used for electroporation were: pCAβ-EGFP-m5 (0.6-1 µg/µl) (Yaneza et al., 2002), pMW111–Noggin (0.61 µg/µl) (Timmer et al., 2002). Inhibition of BMP signaling by the Noggin-construct has previously been verified (Maier et al., 2010; Pandit et al., 2011). The DNA-constructs were transferred using an Electro Square Porator ECM 830 (BTX) by applying 5 pulses (9-15 V, 25 ms duration) at 1-s intervals. Embryos were further cultured in ovo to stage 15/16 for hypophyseal and lens studies, and stage 19/20 for olfactory placodal studies. Noggin/GFP-electroporated regions were compared with control GFP-electroporations.

**Ex ovo culture of the chick embryo**

The modified Cornish pasty method (Nagai et al., 2011), an in vivo/e ovo chick embryo culture technique, was used with slight changes. Briefly, stage 5-7 embryos were dissected and folded in half along the midline into a semi-circle, and cut along the outside edge. The embryos were allowed to rest undisturbed in Ringer’s solution at room temperature (RT) for approximately 45-60 min. Embryos were then transferred to a 4-well plate containing 500 µl of medium (a 2:1 mixture of thin albumen and Ringer’s solution with penicillin and streptomycin 5000 U/ml) alone or together with inhibitors. Each well contained one embryo. The cultures were grown at 37°C to approximately stage 9/10 for apoptosis and proliferation analyses in the otic placode, and to approximately stage 12/13 for all other otic studies. For olfactory and lens studies, embryo cultures were grown to stage 11, after which the embryos were exposed to Y27632 until the end of culture; stage 15/16 (lens) and stage 18 (olfactory). Inhibitors used were; Noggin conditioned medium, the BMP-receptor inhibitor Dorosomorphin (50 µM) (Stementg), and the ROCK inhibitor Y27632 (40 µM) (Abcam). Soluble Noggin conditioned medium were obtained from stably transfected Chinese hamster ovary (CHO) cells (Lamb et al., 1993) and cultured in CHO-S-SFM II media (Gibco). Noggin conditioned media was used at an estimated concentration of 50 ng/ml. Inhibition of BMP signaling by the use of Noggin conditioned medium has previously been verified (Maier et al., 2010; Patthey et al., 2009).

**3D analysis by optical projection tomography**

Tissue preparation of chick heads for OPT scanning was essentially performed as previously described (Alanentalo et al., 2008). OPT scanning, using the Biopontics 3001 OPT scanner (Biopontics) visualizing anti-GFP-antibodies using goat anti-rabbit Alexa Fluor 488 (1:400) (Molecular Probes) was performed as previously described (Alanentalo et al., 2008).

**In situ hybridization and immunohistochemistry**

In situ RNA hybridization and immunohistochemistry was performed essentially as described (Wilkinson and Nieto, 1993; Wittmann et al., 2014) on consecutive sections. Embryos were first fixed in 4% paraformaldehyde (PFA) for 1-2 h at 4°C, cryoprotected in 30% sucrose, embedded and cryosectioned at 10 µm. In situ hybridization was performed using the following Dig-labelled chick probes: Bmp4 (Francis et al., 1994), Bmp7 (Liem et al., 1995), Hes5 (Fior and Henrique, 2005), Id3 (Kee and Bronner-
significant. All statistical analyses were performed using Prism 5.

Morphometric analysis
Stage 11/12 embryos were electroporated in the olfactory with GFP alone or together with Noggin and cultured until stage 19/20. Whole embryos were fixed in 4% PFA for 2 h, treated in 30% sucrose, embedded and cryosectioned at 30 µm. GFP+ cells from the medial invaginated part of the olfactory pit were analyzed using a 20×/0.50 and 60×/1.40 numerical aperture lenses on a Nikon Eclipse E800 microscope, equipped with a CCD camera connected to a PC (Nikon Imaging Software NIS-Elements) at room temperature. Overly images were processed with Photoshop CS5 software (Adobe).

Statistics
aCaspase3 and pHH3 cells were quantified in the otic, lens and olfactory epithelium in control and BMP-inhibited embryos. In the electroporated (3D) volume scans (x,y,z) were done using Nikon elements software, and further processed in high technical assistance by; Harsha K. Nekkanti, Christoffer Nord and Saba Parween Noggin), J. Piatigorsky (P. Brickell (Irx1, Lmx1b (Abello et al., 2010), L-Maf (Reza and Yasuda, 2004), Bmp7 (Abello et al., 2010). Antibodies used were; anti-pHistoneH3 (Millipore, 1:500), anti-RhoA (Santa Cruz, 1:200) and anti-pSmad1/5/8 (Cell Signaling, 1:1000) rabbit antibodies, and anti-aCaspase3 (Cell Signaling, 1:1000) and anti-Hu/C (Molecular Probes, 1:200) mouse monoclonal antibodies, and anti-sheet δ-crystallin (Beeche and Pietagorsky, 1981; 1:1000). Secondary antibodies used were goat anti-rabbit Cy3 (1:400) (Molecular Probes), goat anti-mouse Alexa Fluor 594 (1:400) (Molecular Probes) and goat anti-sheet Alexa Fluor 594 (1:400) (Molecular Probes). Rhodamine Phalloidin were used to visualize F-actin (Molecular Probes), and nuclei were stained using DAPI (Sigma). Slides were mounted with Fluorescent or Glycergel mounting medium (Dako). Images were taken using a 20×/0.50 numerical aperture lens on a Nikon Eclipse E800 microscope and nuclei were stained using DAPI (Sigma). Images were taken with the total number of cells, determined by DAPI-stained nuclei. For cell morphology measurements the traces of the neighboring cells was determined by outlining the apical and basal surface in Volocity software. During each cell measurement the traces of the neighboring cells was avoided by moving the z series from z1 and z2 axis. To confirm the apical, basal width and the cell length, the measurements were finalized by observing the dimensions in 3D layout (x,y,z coordinates).

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Competing interests
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Author contributions
L.G. and C.P. conceived the project. V.K.J. performed the majority of the experiments. R.C.S. performed most of the Cornish pasty otic experiments. V.K.J. designed and prepared the images with minor assistance from L.G. and C.P. V.K.J. quantified the data and performed statistical analysis. L.G., C.P. and V.K.J. analyzed the data and wrote the paper.

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