Bmp7 regulates branching morphogenesis of the lacrimal gland by promoting mesenchymal proliferation and condensation

Charlotte Dean*†, Masataka Ito*‡, Helen P. Makarenkova*§, Sonya C. Faber and Richard A. Lang¶

Divisions of Developmental Biology and Ophthalmology, Children’s Hospital Research Foundation, 3333 Burnet Avenue, Cincinnati, OH 45229, USA

*These authors contributed equally to this work
†Present address: Molecular Biology Department, Sloan Kettering Institute, East 67th Street, New York, NY 10021, USA
‡Present address: Department of Anatomy, National Defense Medical College, 3-2 Namiki, Tokorozawa, 359-8513, Japan
§Present address: The Neurosciences Institute, 10640 John Jay Hopkins Drive, San Diego, CA 92121, USA
¶Author for correspondence (e-mail: richard.lang@chmcc.org)

Accepted 3 June 2004
Development 131, 4155-4165
Published by The Company of Biologists 2004
doi:10.1242/dev.01285

Summary

The lacrimal gland provides an excellent model with which to study the epithelial-mesenchymal interactions that are crucial to the process of branching morphogenesis. In the current study, we show that bone morphogenetic protein 7 (Bmp7) is expressed with a complex pattern in the developing gland and has an important role in regulating branching. In loss-of-function analyses, we find that Bmp7-null mice have distinctive reductions in lacrimal gland branch number, and that inhibition of Bmp activity in gland explant cultures has a very similar consequence. Consistent with this, exposure of whole-gland explants to recombinant Bmp7 results in increased branch number. In determining which cells of the gland respond directly to Bmp7, we have tested isolated mesenchyme and epithelium. We find that, as expected, Bmp4 can suppress bud extension in isolated epithelium stimulated by Fgf10, but interestingly, Bmp7 has no discernible effect. Bmp7 does, however, stimulate a distinct response in mesenchymal cells. This manifests as a promotion of cell division and formation of aggregates, and upregulation of cadherin adhesion molecules, the junctional protein connexin 43 and of α-smooth muscle actin. These data suggest that in this branching system, mesenchyme is the primary target of Bmp7 and that formation of mesenchymal condensations characteristic of signaling centers may be enhanced by Bmp7. Based on the activity of Bmp7 in promoting branching, we also propose a model suggesting that a discrete region of Bmp7-expressing head mesenchyme may be crucial in determining the location of the exorbital lobe of the gland.

Key words: Bone morphogenetic protein, Bmp, Branching morphogenesis, Lacrimal gland,

Introduction

The lacrimal gland is a structure that develops by branching morphogenesis. Its accessibility and ease of culture combined with the availability of convenient reporter constructs render it an excellent system for studying the branching process. Lacrimal gland development begins when the primary bud invaginates from the conjunctival epithelium at the temporal extremity of the eye (Govindarajan et al., 2000; Makarenkova et al., 2000). This invagination extends as a tubular sinus into the periorbital mesenchyme where it branches in two locations to form the intra- and exorbital lobes of the mature gland (Govindarajan et al., 2000; Makarenkova et al., 2000). The main function of the lacrimal gland is to produce secretions that lubricate and protect the ocular surface. Dysfunction of the lacrimal gland leads to the absence of corneal lubrication and, in severe cases, can result in ulceration and blindness.

In previous studies (Govindarajan et al., 2000; Makarenkova et al., 2000), it has been shown that fibroblast growth factor 10 (Fgf10) is expressed in temporal periorbital mesenchyme and has activity as an inducer of the lacrimal gland. In vitro inhibition studies show that Fgf10 promotes proliferative responses in lacrimal gland epithelium through Fgfr2IIIb (Makarenkova et al., 2000), a result consistent with the involvement of this pathway in many examples of branching morphogenesis (Arman et al., 1999; Cancilla et al., 1999; Sekine et al., 1999; Ohuchi et al., 2000). The epithelial expression of Pax6 in lacrimal gland (Kammandel et al., 1999; Makarenkova et al., 2000) has also implied a developmental role for this transcription factor and indeed, Pax6+/Sey−1Neu mice show vestigial glands (Makarenkova et al., 2000). The absence of any change in the pattern of expression of Fgf10 in periorbital mesenchyme of Pax6+/Sey−1Neu mice suggests that Pax6 might act as a lacrimal gland competence factor in conjunctival epithelium (Makarenkova et al., 2000).

The process of branching morphogenesis (Hogan, 1999) requires an exchange of signals between epithelium and mesenchyme. The end result is the reiterative production of a series of epithelial buds that have a characteristic distribution. Signaling molecules of the bone morphogenetic protein (Bmp) family have previously been implicated in the regulation of branching morphogenesis. For example, Bmp4 has a role in development of the lung (Bellusci et al., 1996), kidney (Raatikainen-Ahokas et al., 2000) and prostate gland (Lamm et al., 2001). In each case, Bmp4 appears to modulate
branching by suppressing proliferation of the epithelial component of the structure. Bmp7 has also been identified as an important regulator of branching morphogenesis. In the kidney, Bmp7 promotes growth and survival of the metanephric mesenchyme (Dudley et al., 1999), a result consistent with the effect of low doses of Bmp7 on the mIMCD-3 cell model of collecting duct morphogenesis (Piscione et al., 1997). Similarly, Bmp7-null mice have deficiencies in development of the submandibular gland (Jaskoll et al., 2002). An assessment of the role of Bmps in branching morphogenesis is complicated by their overlapping and dynamic expression patterns, their ability to heterodimerize (Suzuki et al., 1997), the variety of receptor heterodimers through which they can signal (Massague, 1998) and the possibility of activity modulation by secreted antagonists (Hemmati-Brivanlou et al., 1994; Piccolo et al., 1996; Zimmerman et al., 1996; Cho and Blitzy, 1998; Cancilla et al., 2001).

In the current study, we have investigated the function of Bmp7 in branching morphogenesis of the lacrimal gland. We show that Bmp7 is expressed with a complex pattern in the developing gland and that Bmp7-null mice have distinctive reductions in lacrimal gland size and branch number. Consistent with a role for Bmp7 in promoting branching is the observation that whole gland explant cultures exposed to recombinant Bmp7 show an increased number of lacrimal gland buds, while those exposed to the inhibitors noggin and follistatin show decreased budding. Explants also show that Bmp7 does not have a discernible effect on isolated epithelium but does stimulate a response in mesenchymal cells in the form of increased cell division, aggregation and upregulation of cadherins, connexin 43 and α-smooth muscle actin. These data suggest that mesenchyme is the primary target of Bmp7 and, in turn, that the effect of Bmp7 on epithelial responses is indirect. These data also suggest that through its activity in stimulating mesenchymal condensation, Bmp7 may be important for formation of signaling centers. This model can explain both the mesenchymal responses to Bmp7 and the gland development deficiency of the Bmp7-null mice.

Materials and methods

Mouse lines

P6 5.0-lacZ reporter carrying a Pax6 based reporter transgene (Williams et al., 1998) were used as described previously (Makarenkova et al., 2000) to visualize the epithelial component of the lacrimal gland. Genotyping of Bmp7nullRob animals was carried out essentially as described (Dudley et al., 1995). Genotyping of Bmp7loxP reporter carrying a Pax6 based reporter transgene (Williams et al., 1998) were used as described previously (Piscione et al., 1997). Similarly, Bmp7-null mice have deficiencies in development of the submandibular gland (Jaskoll et al., 2002). An assessment of the role of Bmps in branching morphogenesis is complicated by their overlapping and dynamic expression patterns, their ability to heterodimerize (Suzuki et al., 1997), the variety of receptor heterodimers through which they can signal (Massague, 1998) and the possibility of activity modulation by secreted antagonists (Hemmati-Brivanlou et al., 1994; Piccolo et al., 1996; Zimmerman et al., 1996; Cho and Blitzy, 1998; Cancilla et al., 2001).

In the current study, we have investigated the function of Bmp7 in branching morphogenesis of the lacrimal gland. We show that Bmp7 is expressed with a complex pattern in the developing gland and that Bmp7-null mice have distinctive reductions in lacrimal gland size and branch number. Consistent with a role for Bmp7 in promoting branching is the observation that whole gland explant cultures exposed to recombinant Bmp7 show an increased number of lacrimal gland buds, while those exposed to the inhibitors noggin and follistatin show decreased budding. Explants also show that Bmp7 does not have a discernible effect on isolated epithelium but does stimulate a response in mesenchymal cells in the form of increased cell division, aggregation and upregulation of cadherins, connexin 43 and α-smooth muscle actin. These data suggest that mesenchyme is the primary target of Bmp7 and, in turn, that the effect of Bmp7 on epithelial responses is indirect. These data also suggest that through its activity in stimulating mesenchymal condensation, Bmp7 may be important for formation of signaling centers. This model can explain both the mesenchymal responses to Bmp7 and the gland development deficiency of the Bmp7-null mice.

Lacrimal gland reporter gene visualization and explant cultures

Lacrimal glands were isolated and cultured as described previously (Brennan et al., 2000). Briefly, the isolated epithelium was placed in the center of one well of a four-well plate and covered with Matrigel or collagen gel. Once the gel had set, 30 μl of defined medium was added into the well. For some experiments, an in vitro epithelial bud extension assay was performed as previously described (Weaver et al., 1999). In these assays, heparin acrylic beads (Sigma) were loaded with recombinant Fgf10 (R&D systems) and placed ~100-150 μm from the anterior part of the epithelial bud. Explants were cultured in defined medium alone or in the same medium supplemented with either recombinant Bmp4 or Bmp7 (R&D systems).

Mesenchyme cultures

Lacrimal gland mesenchyme cultures were prepared in a similar manner to limb bud micromass cultures (Vogel and Tickle, 1993). Lacrimal glands were isolated from E15.5-16 embryos and placed in 2% trypsin solution on ice for 1 hour. The tissue was then placed in medium containing serum to stop the enzyme reaction and then the epithelium was mechanically separated from the surrounding mesenchyme using fine needles. The mesenchyme was triturated and then centrifuged at 400 g for 5 minutes. Cells were re-suspended in defined medium and plated at a density of 10,000 cells in 10 μl on Poly-I-Lysine and laminin-coated coverslips (Bicocat) in Nunc four-well plates and left to attach for 1 hour. Once the cells had attached, 300 μl defined medium or defined medium containing 1-100 ng/ml Bmp7 was added to each well. Cultures were maintained for 6, 24, 48 or 72 hours in an incubator at 37°C with 5% CO2 in air before being fixed and immunolabeled. For mesenchyme cell proliferation assays, the culture medium was replaced after 24 hours with DMEM containing 1% FCS and 10 μM BrdU with or without Bmp7 for 2 hours prior to fixation. Cells were fixed and labeled as described previously (Brennan et al., 2000).

Quantification

The degree of lacrimal gland development in explants was quantified simply by counting the number of terminal epithelial buds (acini). All error bars shown represent standard errors. Statistical significance of data was determined using the Student's t-test with the exception of Fig. 4L, which required the unpaired t-test, and of Fig. 5A, which was better suited to the Mann-Whitney U test. P values of less than 0.05 were considered to be significant and this was the case (as indicated in legends and Figures) for all data shown. For Fig. 3, the length of the lacrimal gland from the temporal fornix of the conjunctiva to the most distal end of the epithelial component of the gland was measured in mm (by placing a mm scale within the images of gland preparations). As budding of the lacrimal first occurs at E13.5, we considered to be significant and this was the case (as indicated in legends and Figures) for all data shown. For Fig. 3, the length of the lacrimal gland from the temporal fornix of the conjunctiva to the most distal end of the epithelial component of the gland was measured in mm (by placing a mm scale within the images of gland preparations). As budding of the lacrimal first occurs at E13.5, we defined the length as zero and the acinus number as one. In this case, statistical significance was determined using the unpaired t-test.

Preparation of tissue sections for immunostaining

Lacrimal glands were dissected and fixed in 4% paraformaldehyde for 1 hour on ice, washed in PBS and dehydrated through graded ethanol. Polyester wax (Polysciences) was melted at 37°C and diluted with an equal volume of ethanol. Lacrimal glands were then placed in the ethanol:wax mixture in small glass vials and left until the tissue had
sunk to the bottom of the vial. Half of the volume of the mixture was then removed and replaced with fresh wax until the tissue was impregnated with 100% wax. The tissue was then placed into moulds filled with fresh wax and left to set at room temperature before being stored at 4°C. Sections (7 or 10 μm) were cut using a Leica microtome and mounted onto Superfrost Plus microscopy slides (Fisher). Prior to immunostaining, the sections were de-waxed in 100% ethanol and dried at room temperature.

Whole-mount in situ hybridization

Whole-mount in situ hybridization was performed as described (Nieto et al., 1996). The Fgf10 probe has been described previously (Bellusci et al., 1997).

Antibodies and immunostaining

For immunostaining, the following primary antibodies were used: rabbit polyclonal antibody to Connexin 43 (Cx43) (GAP 15) (amino acids 131-142) was diluted to 1:200; mouse anti-BrdU antibody (Dakopatts) diluted 1:100 in PBS/BS (PBS containing 1% BSA and 0.2% Triton); mouse anti-α-smooth muscle actin (Clone 1A4 Sigma) diluted 1:500; rabbit polyclonal pan-cadherin (Sigma) diluted 1:500; mouse anti human Ki-67 (Novacraft laboratories, Newcastle upon Tyne, UK) diluted 1:250; mouse anti chick Pax6 (Developmental Hybridomas Studies Bank, Iowa, USA) diluted 1:500. All antibodies were diluted in TBST (TBS containing 1% Trition). All incubations with primary antibodies were carried out at 4°C overnight except for BrdU antibody which was added for 1 hour at room temperature.

Primary antibodies were revealed by either Alexa-, Rhodamine-, Cy3 or Texas Red-conjugated goat anti-mouse or goat anti-rabbit immunoglobulins (Molecular Probes Eugene, OR). Nuclei were counterstained with either OliGreen (Molecular Probes Eugene, OR) at a dilution of 1:5000 for 5 minutes or with Hoechst 33258. Labeled preparations were viewed on a Zeiss Axioplan microscope and digital images obtained with a Sony DKC5000 camera. Confocal images were obtained on a BioRad laser-scanning confocal microscope.

Results

Bmp7 is expressed in developing lacrimal gland

As a first step in determining whether Bmp7 might be involved in lacrimal gland development, we assessed the expression pattern of Bmp7 in both the induction and branching phases using heterozygous gene-targeted mice in which the lacZ-coding region has been inserted into the Bmp7 gene (Godin et al., 1998). We have confirmed, using Bmp7 probe whole-mount in situ hybridization on wild-type glands, that the Bmp7lacZ expression pattern reflects that of the endogenous gene (data not shown). At E13.0, when the lacrimal bud has not yet formed on the temporal side of the eye, Bmp7lacZ expression is observed in the periorbital epithelium and in the periorbicular mesenchyme (Fig. 1A). Interestingly, mesenchyme adjacent to the site of lacrimal gland budding appears to have only low level Bmp7lacZ expression (Fig. 1A, broken yellow lines). Sectioning confirms that at E13.0, a triangular domain of mesenchyme (Fig. 1B, arrow) located temporal to the invaginating presumptive conjunctival epithelium (Fig. 1B) expresses Bmp7lacZ at a low level. At this stage, the presumptive eyelid tissue (Fig. 1B, asterisks) also express Bmp7lacZ.

In mice that carry both the P6 5.0-lacZ reporter (a marker of lacrimal gland epithelium) as well as the Bmp7lacZ allele, the lacrimal bud is observed extending into a defined region of Bmp7lacZ-expressing mesenchyme at E14.5 (Fig. 1C, arrows). Sectioning confirms that at E14.5, the lacrimal bud (Fig. 1D, lb) is extending into the Bmp7lacZ mesenchymal expression domain (Fig. 1D, mes). At higher magnification (Fig. 1E), it can be observed that the lacrimal bud (Fig. 1E, lb) including the epithelial component (Fig. 1E, ep) is negative for Bmp7lacZ expression. One day later at E15.5, according to sections from Bmp7lacZ embryos (Fig. 1F) and whole-mounts from P6 5.0-lacZ, Bmp7lacZ embryos (Fig. 1G), extension of the lacrimal bud into the lacrimal mesenchyme has continued. At this stage, some glands show the first signs of secondary budding and branching.

As development proceeds through E17.0, Bmp7lacZ expression is observed in the lacrimal gland mesenchyme (Fig. 1H) with the strongest expression associated with the distal tips of the epithelial buds (Fig. 1J, red arrows) and with the midsection of the lacrimal duct (Fig. 1J, ld). Sectioning of whole X-gal-stained glands from E17.5 Bmp7lacZ embryos showed that Bmp7lacZ expression is observed not only in the mesenchyme (Fig. 1J, broken line) but also in some cells of the gland epithelium. This is apparent in the epithelium of the lacrimal duct (Fig. 1J, ld) and in the terminal epithelial buds (Fig. 1J, e.g. ep). Expression of Bmp7lacZ in condensing mesenchyme adjacent to epithelial buds (Fig. 1J, arrowheads) is consistent with the patterns observed in both E17.0 (Fig. 1J) and E17.5 (Fig. 1J) Bmp7lacZ whole-mount glands and is confirmed by higher-power magnifications of the lacrimal duct (Fig. 1K), an extended region of budding epithelium (Fig. 1L) and a terminal epithelial bud (Fig. 1M). A higher magnification view of the Bmp7lacZ+ lacrimal gland at E18.5 in excised whole-mount (Fig. 1N) also indicates that cells at the tip of developing branches are more strongly positive than at the branch points. This pattern of expression can be contrasted with the uniform X-gal labeling observed throughout the epithelium of the P6 5.0-lacZ mouse (Fig. 1O). Although sporadic epithelial cells express Bmp7lacZ, the overall pattern corresponds to the mesenchymal component of the so-called signaling centers (Hogan, 1999).

Bmp7 is essential for normal branching morphogenesis of the lacrimal gland

To determine whether Bmp7 functions in development of the lacrimal gland, we examined a second line of mice that carry a conventional targeted allele (designated Bmp7m1Rob) of the Bmp7 gene (Dudley et al., 1995). These animals were crossed with the P6 5.0-lacZ reporter to the F2 generation to produce Bmp7m1Rob/m1Rob, P6 5.0-lacZ, and Bmp7m1Rob+/+, P6 5.0-lacZ embryos. These could be stained with X-gal for easy visualization of gland structure (Makarenkova et al., 2000). Despite the microophthalmia that is characteristic of some Bmp7-null mice (Dudley et al., 1995; Wawersik et al., 1999) formation of the first lacrimal bud occurred with normal timing (E13.0-13.5) and in the normal location on the temporal side of the eye (compare Fig. 2A with 2B). By E19.5, the wild-type gland consists of two lobes: a small intraocular lobe derived from a single branch of the proximal duct (Fig. 2C, io and blue arrowhead); and an extensively branched exorbital lobe (Makarenkova et al., 2000) (Fig. 2C, xo). By contrast, the lacrimal gland in Bmp7-null animals showed varying degrees of deficiency. In some cases, both intraorbital (Fig. 2D, blue arrowhead) and exorbital lobes (Fig. 2D, xo) were near normal in size while in others, the gland was severely vestigial (Fig. 2E and F). The distribution of buds and branches in the lacrimal
glands of Bmp7-null mice was also abnormal; they were often observed in the primary duct region (Fig. 2F-H, red arrowheads). With dissection of glands from Bmp7\textsuperscript{m1Rob/m1Rob}, P6 5.0-lacZ, embryos, it was clear that absence of Bmp7 did not prevent formation of the mesenchymal sac (Fig. 2H, arrows). The degree to which development of the lacrimal gland was affected did not correlate with the variable degree of microphthalmia observed in Bmp7-null mice (Fig. 2D-G, mi), indicating that the two structures develop independently. Quantification of the gland length and the number of branches or acini in the lacrimal gland indicated that in the Bmp7-null mouse, while there was not a significant reduction in the overall length of the gland ($P=0.7$, $n=6$), the number of branches and acini was significantly reduced ($P<0.01$, $n=4$) (Fig. 3A,B). These results demonstrate that Bmp7 is required to establish the appropriate number and position of lacrimal gland branches.

As a further test of Bmp function in lacrimal gland development, we took advantage of the Bmp antagonists noggin and follistatin. Both Noggin and follistatin bind Bmp2,
Bmp7m1Rob/m1Rob (D-H) Lacrimal glands in E19.5 large exorbital lobe (xo). Unaffected in the Bmp7 be inhibited by noggin and follistatin in explants but were activity of additional Bmp family member ligands that could larger. We reasoned that this might be a consequence of the acini in noggin and follistatin-treated glands were much those that existed were of normal size and shape. By contrast, Bmp7 null, while there were fewer acini, Specifically, in the Bmp7 null, while there were fewer acini, those that existed were of normal size and shape. By contrast, the acini in noggin and follistatin-treated glands were much larger. We reasoned that this might be a consequence of the activity of additional Bmp family member ligands that could be inhibited by noggin and follistatin in explants but were unaffected in the Bmp7 null.

To investigate this possibility, we performed noggin inhibition studies on gland explants established at E16.5 from Bmp7m1Rob/m1Rob, P6 5.0-lacZ embryos. Again, whole gland explants were cultured for 48 hours in the presence or absence of noggin and as before, a quantitatively significant reduction in the number of acini was observed (Fig. 4L). Interestingly, the acini that did form in Bmp7m1Rob/m1Rob noggin-treated glands (Fig. 4K) were larger than those in the untreated controls (compare Fig. 4I with 4K) as had been observed in earlier inhibition experiments. When combined, these data indicate that at least one other Bmp family member functions in lacrimal gland development and is most probably involved in regulating epithelial cell proliferation.

Bmp4 and Bmp7. However, Noggin binds Bmp2/4 more strongly than it binds Bmp7, while follistatin binds Bmp7 more strongly than Bmp2/4 (Yamashita et al., 1995; Zimmerman et al., 1996; Balemans and Van Hul, 2002). To determine whether these antagonists could modulate development of the gland, we treated a series of whole-gland explant cultures with recombinant human noggin or follistatin. Explants were established from either E16.5 or E17.5 mice, and cultured with and without the Bmp-binding proteins for a period of 48 hours. We observed that application of either noggin or follistatin resulted in suppression of branching, as indicated by the reduced number of acini in the treated samples [compare Fig. 4A with B and C (noggin) and D with E (follistatin)]. The difference in the number of acini was quantified and shown to be statistically significant for both noggin (Fig. 4F) and follistatin (Fig. 4G) treatment.

A reduction in bud number in lacrimal gland explants treated with Bmp inhibitors is consistent with suppression of bud formation observed in the lacrimal gland of Bmp7-null mice. However, the morphology of acini in noggin/follistatin treated glands was very different from that observed in the Bmp7 null. Specifically, in the Bmp7 null, while there were fewer acini, those that existed were of normal size and shape. By contrast, the acini in noggin and follistatin-treated glands were much larger. We reasoned that this might be a consequence of the activity of additional Bmp family member ligands that could be inhibited by noggin and follistatin in explants but were unaffected in the Bmp7 null.

To assess the action of Bmp7 on the epithelial component of the gland, we performed a bud extension assay that has been used previously to characterize the responses of lung endoderm (Weaver et al., 2000). In both the lung and the lacrimal gland, Fgf10 is an endogenous stimulus for the epithelial proliferation and chemotaxis that drive epithelial extension (Makarenkova et al., 2000; Weaver, 2000). In the lung, Bmp4 can suppress Fgf10-mediated proliferation and as a result, suppress epithelial extension (Weaver et al., 2000). We used Fgf10-soaked heparin-sepharose beads to stimulate extension of epithelial

Lacrimal gland mesenchyme is a target for Bmp7 activity

As it was possible that the lacrimal gland branching defect in Bmp7lacZ mutant mice could reside in either epithelium or mesenchyme, we performed a series of gain-of-function experiments using explant cultures of whole glands or isolated gland epithelium and mesenchyme.

When whole-gland explants were established at E15.5 and cultured for 48 hours in the presence of recombinant Bmp7, we observed a modest but statistically significant increase in the number of branches formed following Bmp7 treatment (Fig. 5A). This was in agreement with assessment of the Bmp7-null mice indicating that the role of Bmp7 is to promote branching of the epithelium.

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explants from the lacrimal gland, and assessed the effect of adding either Bmp4 or Bmp7 to the media of these cultures.

E15.5 mesenchyme-free primary bud explants were established in collagen gel 100-150 μm from an Fgf10 bead and allowed to respond over a 48 hour period. Control explants were grown in defined medium only and showed the expected extension response (Fig. 5B). The addition of Bmp4 to the media suppressed growth and extension of the lacrimal gland epithelial explant in response to an Fgf10-soaked bead in the same manner as has been observed with lung epithelium (Weaver et al., 2000) (Fig. 5B). Interestingly however, addition of Bmp7 to media did not suppress extension or growth towards the Fgf10-soaked bead (Fig. 5B).

These data, combined with the knowledge that Bmp7 is expressed in gland mesenchyme, suggested that mesenchyme might be the crucial target of Bmp7 activity. To examine this possibility, we isolated mesenchymal cells from wild-type embryos at E15.5 and determined whether there were distinctive responses to 100 ng/ml Bmp7 in low density micromass cultures. In control cultures, mesenchymal cells were evenly distributed over the plating area even after 48 hours (Fig. 6A). By contrast, Bmp7 treatment caused dramatic changes in cell morphology and distribution. After 12 hours, the cells became elongated and formed multiple small aggregates; in 24-48 hours, these small cell aggregates had formed larger clusters (Fig. 6B). As we did not observe increased levels of apoptosis or a decrease in cell number in the Bmp7-treated cultures (data not shown), this changed distribution presumably required migration.

Bmp7 has been shown to act in a dose-dependent manner to stimulate proliferation of kidney mesenchyme (Piscione et al., 2001). To assess the possibility that this was also the case in the lacrimal gland, we performed BrdU labeling of Bmp7-treated and control cultures using both low (1 ng/ml) and high (100 ng/ml) doses of Bmp7. We found that Bmp7 induces cell proliferation and that the effect was dose dependent, with the highest levels of division being observed in cultures treated with high concentrations of Bmp7 (Fig. 6C). Mesenchymal proliferation and aggregation (condensation) are cell responses characteristic of the signaling centers that are critical for branching morphogenesis.

In a number of systems, mesenchymal condensation is associated with increased expression of the cadherin adhesion molecule family as well as junctional proteins such as connexin 43 (Cx43) (Minkoff et al., 1994; Haas and Tuan, 1999). To determine whether the Bmp7-stimulated aggregation of mesenchyme was associated with formation of cell contacts, we immunolabeled mesenchymal cell cultures for the gap junction protein Cx43 and for cadherins. This showed that the cells found in aggregates upregulated Cx43 (compare Fig. 6D with 6E) and cadherins (compare Fig. 6F with G) in response to Bmp7.

As many glandular structures contain cells that express smooth-muscle α-actin (α-SMA), we also determined whether Bmp7 might influence expression of this marker. In Bmp7-stimulated mesenchyme cultures, we observed an upregulation of α-smooth muscle actin (α-SMA) immunoreactivity in most cellular aggregates (Fig. 6H,I) and positive cells showed a network of well organized stress fibers (Fig. 6I). Only a few α-SMA-positive cells were detected in control cultures even after 72 hours in vitro and stress fibers were not observed (Fig. 6H). Interestingly, explanted lacrimal glands exposed to 100 ng/ml Bmp7 for 48 hours do not show an upregulated Cx43 and for cadherins. This showed that the cells found in aggregates upregulated Cx43 and for cadherins (compare Fig. 6F with G) in response to Bmp7.

These data implied that in the Bmp7 null gland, we might observe reduced proliferation as well as reduced expression of cadherins and α-SMA. To test this, we performed immunofluorescence detection for cadherins and α-SMA in
wild-type and Bmp7 null glands (Fig. 7). We also double-labeled with anti-Pax6 antibodies to identify epithelial cells. So that we could objectively compare levels of immunoreactivity, sections from wild-type and mutant embryos were processed and labeled in the same experiment, images were acquired digitally under identical lighting conditions and figure panels were adjusted en masse in the same digital image file. Cadherin immunoreactivity in wild-type glands shows the anticipated junctional pattern in Pax6-positive epithelial cells (Fig. 7A). By contrast, although Pax6 nuclear labeling is easily detected, Bmp7-null glands show a consistently reduced level of cadherin immunoreactivity (Fig. 7B). Similarly, when detecting α-SMA in both wild-type (Fig. 7C,E) and Bmp7-null glands (Fig. 7D and F) Pax6 and α-SMA positive cells are found in smaller numbers in the mutant (compare 7C with 7D, arrowheads). The α-SMA expression level in the positive cells of mutant glands is also very much lower. This is obvious when observing wild-type (Fig. 7E) and Bmp7-null (Fig. 7F) glands at higher magnification. Interestingly, the α-SMA positive cells are also positive for the Pax6 epithelial marker. An assessment of proliferation was performed using BrdU-labeling (Fig. 7G). This showed that in both the mesenchyme and epithelium of Bmp7-null glands, there were statistically significant reductions in the level of proliferation. The reduction was more dramatic in the mesenchyme. Given that Fgf10 has been identified as a proliferative stimulus for gland epithelium, we performed in situ hybridization for Fgf10 in both wild-type and Bmp7 mutant glands (Fig. 7H,I). This indicated that Fgf10 expression levels were not noticeably different in the absence of Bmp7, suggesting an alternative explanation for reduced epithelial proliferation levels.

These data indicate that the response of explanted whole glands and isolated gland mesenchyme to Bmp7 is consistent with responses observed in the Bmp7 mutant. Interestingly, however, for both cadherins and α-SMA, the immunoreactivity in both wild-type and Bmp7 null was associated with the epithelialized component of the gland and was found only at low levels in surrounding mesenchyme. This observation raises the interesting issue of the origin of epithelial cells in this system.
Discussion
In the current study, we have assessed the role of Bmp7 in development of the mouse lacrimal gland. We show, using a Bmp7lacZ allele (Godin et al., 1998) that Bmp7 has a dynamic expression pattern within the mesenchyme of the gland. At E14.5, when the primary epithelial bud has entered the mesenchymal sac, the mesenchyme but not the epithelium expresses Bmp7lacZ. From E15.5 and beyond, the strongest Bmp7lacZ expression is observed in mesenchymal cells that correspond to the signaling centers crucial for budding and branching (see below). Supporting an important role for Bmp7 in lacrimal gland branching morphogenesis is the distinctive, albeit variably penetrant gland deficiency observed in the Bmp7-null mice. This gland deficiency is consistent with the results of explant experiments where Bmp inhibition reduced, and Bmp7 oversupply increased, the number of branches and buds that formed. Ex vivo analysis of the responses of isolated lacrimal gland epithelium and mesenchyme has suggested that the primary target of Bmp7 is the mesenchyme and that epithelial responses are indirect. The activity of Bmp7 in stimulating branching, combined with the expression pattern in the developing head, suggests a mechanism by which the lobe pattern arises.

Bmp7 is required for normal morphogenesis of the lacrimal gland
Several lines of evidence indicate that Bmp7 has an important function in regulating the formation of buds and branches in the lacrimal gland. Morphological assessment of gland development in wild-type and Bmp7 null mice supports this proposal as there are many fewer buds and branches in Bmp7 null glands. Interestingly however, gland length is not significantly affected by the absence of Bmp7, and this suggests that Fgf10-driven primary and secondary branch extension occurs independently of Bmp7. This is also consistent with unchanged Fgf10 expression observed in the Bmp7 null. The appearance of primary lacrimal gland buds in all Bmp7 null mice also indicates that Bmp7 is not required during the inductive phases of lacrimal gland development and this, in turn, suggests that there may be distinct bud induction mechanisms employed at different stages of gland formation.

There are also likely to be multiple Bmp family members active during lacrimal gland development. Exposure of whole gland explants to the Bmp inhibitors noggin and follistatin produces fewer buds in a response that is consistent with Bmp7 function. However, the buds that do form have an unusual morphology in that they are larger than normal. This response is not a result of inhibition of Bmp7 activity as it is also seen when Bmp7-null glands are treated with noggin and follistatin and is a phenotype absent from the Bmp7-null mice. This is a clear indication that other Bmp family members are active in suppressing epithelial proliferation during lacrimal gland development.

Previous studies have demonstrated the importance of Bmp7 for the development of branched structures. In the kidney system, Bmp7 is involved in the early developmental stages in
mediating epithelial-mesenchymal interactions and stimulating survival of metanephric mesenchyme (Dudley et al., 1999). Although our experiments do not reveal a function for Bmp7 in stimulating mesenchymal survival, the positive effect of Bmp7 on lacrimal gland branching may be analogous to its function in the kidney. It has also been recorded that Bmp7-null mice have deficiencies in development of the submandibular gland (Jaskoll et al., 2002) and this too is consistent with the general effect of Bmp7 in the lacrimal gland system.

**Bmp7 stimulates lacrimal gland branching by signaling mesenchymal responses**

In attempting to understand the origin of the lacrimal gland development defect, we performed a series of explants of whole glands and of isolated mesenchyme and epithelium. Consistent with the phenotype of Bmp7-null mice, whole lacrimal glands exposed to Bmp7 showed a statistically significant increase in the number of epithelial buds. This indicates that Bmp7 is necessary for the formation of normal bud number and in the context of the explant assay, is sufficient to stimulate new bud formation. Furthermore, an Fgf10-driven bud extension assay (Weaver et al., 2000) was used to demonstrate that gland epithelium did not discernibly respond to Bmp7 (but did to Bmp4). By contrast, exposure of isolated mesenchyme to Bmp7 resulted in distinctive responses that included proliferation, aggregation and differentiation. These data argue that the primary target of Bmp7 in lacrimal gland development is the mesenchyme and that deficient epithelial responses are an indirect consequence of defective mesenchymal function.

The in vitro response of mesenchyme to Bmp7 is distinctive with dose-dependent increases in proliferation and the formation of cellular aggregates. Increased proliferation is presumably important for providing the numbers of cells required for expansion of the gland. The formation of aggregates is accompanied by upregulation of cadherin family adhesion molecules and the junctional protein Cx43; both have been associated with formation of condensed mesenchyme (Minkoff et al., 1994; Haas and Tuan, 1999). These data demonstrate that in response to Bmp7, gland mesenchymal cells form close contacts characteristic of the tissue structures found in the lacrimal gland.

However, the nature of the gland components that Bmp7-stimulated mesenchyme represents is currently open to interpretation. Two models can be proposed. In the first, we can suggest that the major function of Bmp7 is to facilitate the formation of signaling centers (Fig. 8). In the context of branching morphogenesis (Hogan, 1999) signaling centers are defined as small groups of closely associated cells that are able to secrete factors and respond to stimuli in a manner that directs the process of branching. Close association of a critical number of cells in signaling center-like structures is thought to be essential for providing the necessary level of signaling [the so-called community effect (Gurdon, 1988)] required for some developmental processes. Signaling centers are proposed to include both epithelial and mesenchymal cells in the region of the developing bud tip. Reiterative formation of signaling centers is crucial for the progression of a single epithelial bud into a multi-branched mature organ. The shape of signaling centers is also thought to influence the shape of the growing tissue (Hogan, 1999).

A number of factors suggest that one function of Bmp7 may be to enhance the formation of signaling centers. These include the spatial and temporal coincidence of Bmp7 expression with the signaling center, and that characteristics of the signaling center (proliferation, cell aggregation and condensation) are stimulated by Bmp7. In addition, most obviously, the Bmp7-null mice have reduced numbers of signaling centers as indicated by reduced bud number in the gland. Furthermore, the aberrant location of many buds in the lacrimal gland of Bmp7-null mice suggests that signaling center distribution is aberrant.

In an alternative, and arguably more speculative, model, we can propose that Bmp7 may function to stimulate a mesenchymal to epithelial transition. This developmental strategy has precedents in the formation of branched structures, notably in the kidney (Stark et al., 1994), where epithelial cells of the ureteric bud produce signals that stimulate mesenchymal
cells to condense and form the epithelial cells of the nephron. Suggestive evidence for this model in the context of the lacrimal gland comes from the observation that markers expressed at high levels in the epithelial component of the lacrimal gland (Connexin 43, cadherins and smooth muscle actin, Fig. 7) are upregulated when isolated mesenchymal cells are stimulated with Bmp7. In the wild-type gland, we also show, using the epithelial marker Pax6, that cadherin and α-SMA-positive cells have epithelial character. Thus, it is possible that the high expression level of Bmp7 found in the signaling centers is crucial to stimulate proliferation and a mesenchymal-epithelial transition that supplies the expanding gland with epithelial cells. Clearly, an assessment of the mesenchymal-to-epithelial transition model will require additional work developing strategies for fate-mapping different components of the gland.

**Localized Bmp7 may be crucial for patterning of the lacrimal gland**

A striking feature of structures that arise through branching morphogenesis is the reproducibility of the primary branching pattern and, as a consequence, the placement of organ lobes. The lung is a good example (Hogan et al., 1997), but this is also true for the lacrimal gland where both intraorbital and exorbital lobes arise and the timing and placement of branch initiation is highly reproducible. Interestingly, our current analysis suggests a mechanism by which Bmp7 can determine the location of the exorbital lobe of the gland (Fig. 7).

In Bmp7

\(^{+/+}\) embryos, it is clear that Bmp7 expression is absent from the periorbital mesenchyme adjacent to the initial lacrimal gland bud. However, strong Bmp7 expression is observed in a discrete patch of mesenchyme located between the eye and the pinna of the ear. After Fgf10-driven bud extension (Govindarajan et al., 2000; Makarenkova et al., 2000), during which the lacrimal gland epithelium extends away from the temporal side of the eye, the epithelium reaches and invades the Bmp7-expressing region of mesenchyme. Only when the epithelial bud has invaded does epithelial branching occur. When combined with evidence that Bmp7 is an important stimulus for branching, this sequence of events suggests that migration of the epithelial bud into a Bmp7 positive mesenchymal domain may determine the timing and location of primary branching. Further supporting this model is the loss of defined lobe structure in Bmp7

\(^{null}\) mice. Conceivably, other steps in lacrimal gland development, such as formation of the intraorbital lobe and secondary branching, may be regulated by similar, Bmp7-dependent mechanisms.

We thank Dr Elizabeth Robertson for the gift of the Bmp7

\(^{+/+}\) and Bmp7

\(^{null}\) mouse lines, Dr Lee Niswander for help in finalizing experimental work for this publication, Dr Richard Harland for noggin conditioned medium, and Dr W. H. Evans for a sample of the anti-Connexin-43 antibody. Recombinant human follistatin was generously provided through Dr Parlow, National Hormone and Pituitary Program of National Institute of Diabetes and Digestive and Kidney Diseases (NHPP, NIDDK). Recombinant human Bmp7 was kindly provided by Genetics Institute. The Lang laboratory is supported by grants from the National Institutes of Health (EY 14826, EY14102, EY11234 and EY10559) and by funds from the Abrahamson Pediatric Eye Institute Endowment at Cincinnati Children’s Hospital Medical Center.

**References**


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