Active immunization against the proregions of GDF9 or BMP15 alters ovulation rate and litter size in mice

C Joy McIntosh, Steve Lawrence¹, Peter Smith¹, Jennifer L Juengel¹ and Kenneth P McNatty

School of Biological Sciences, Victoria University of Wellington, Wellington 6140, New Zealand and ¹AgResearch, Invermay Agricultural Centre, Mosgiel 9053, New Zealand

Correspondence should be addressed to C J McIntosh, School of Biological Sciences, Victoria University of Wellington, Wellington 6140, New Zealand; Email: joy.mcintosh@vuw.ac.nz

Abstract

The transforming growth factor β (TGFβ) superfamily proteins bone morphogenetic protein 15 (BMP15) and growth differentiation factor 9 (GDF9), are essential for mammalian fertility. Recent in vitro evidence suggests that the proregions of mouse BMP15 and GDF9 interact with their mature proteins after secretion. In this study, we have actively immunized mice against these proregions to test the potential in vivo roles on fertility. Mice were immunized with either N- or C-terminus proregion peptides of BMP15 or GDF9, or a full-length GDF9 proregion protein, each conjugated to keyhole limpet hemocyanin (KLH). For each immunization group, ovaries were collected from ten mice for histology after immunization, while a further 20 mice were allowed to breed and litter sizes were counted. To link the ovulation and fertility data of these two experimental end points, mice were joined during the time period identified by histology as being the ovulatory period resulting in to the corpora lutea (CL) counted. Antibody titers in sera increased throughout the study period, with no cross-reactivity observed between BMP15 and GDF9 sera and antigens. Compared with KLH controls, mice immunized with the N-terminus BMP15 proregion peptide had ovaries with fewer CL (P < 0.05) and produced smaller litters (P < 0.05). In contrast, mice immunized with the full-length GDF9 proregion not only had more CL (P < 0.01) but also had significantly smaller litter sizes (P < 0.01). None of the treatments affected the number of antral follicles per ovary. These findings are consistent with the hypothesis that the proregions of BMP15 and GDF9, after secretion by the oocyte, have physiologically important roles in regulating ovulation rate and litter size in mice.

Introduction

Mammalian ovulation rate, oocyte competence, and fertility are regulated by multiple paracrine and endocrine pathways, including the oocyte-derived transforming growth factor β (TGFβ) superfamily signaling molecules, bone morphogenetic protein 15 (BMP15) and growth differentiation factor 9 (GDF9; Eppig et al. 2002, Juengel & McNatty 2005). Mouse gene knockout models have demonstrated that GDF9 is essential for ovarian follicular development and fertility (Dong et al. 1996, Elvin et al. 1999a, 1999b), whereas BMP15 is only partially required for ovulation and fertilization and is not essential for follicular development (Yan et al. 2001). In sheep, inactivating mutations in either BMP15 or GDF9 result in sterility in homozygous mutants or increased ovulation rate in heterozygous carriers (Galloway et al. 2000, Hanrahan et al. 2004). In women, BMP15 mutations lead to premature ovarian failure (Di Pasquale et al. 2004, 2006, Dixit et al. 2006), while GDF9 mutations are also linked with sterility (Laissue et al. 2006) and dizygotic twinning (Palmer et al. 2006).

The TGFβ superfamily of proteins are characteristically translated as precursor immature proteins that are enzymatically processed to produce a larger N-terminus proregion or prodomain and a smaller bioactive C-terminus mature protein. Intracellularly, the proregions of TGFβ proteins are known to facilitate protein folding, dimerization, secretion, and stability while interacting noncovalently with the respective mature protein (Gray & Mason 1990, Constam & Robertson 1999, Hashimoto et al. 2005, Walton et al. 2009). Additionally, a wide range of extracellular functions for proregions of several TGFβ family members interacting with mature domains has been observed (Bottinger et al. 1996, Hill et al. 2002, Haramoto et al. 2004, Jiang et al. 2004, Brown et al. 2005, Le Good et al. 2005, Anderson et al. 2008, Sengle et al. 2011). Recent evidence from the crystal structure of TGFβ1 supports a number of interactions occurring between proregion and mature proteins following cleavage of the precursor protein (Shi et al. 2011). Previously, we reported that transfected human embryonic kidney cells secreted mouse BMP15 and GDF9 as mixtures of processed mature and
proregion proteins, together with varying amounts of unprocessed precursor protein (McIntosh et al. 2008). Additionally, the cleaved proregions of BMP15 and GDF9 interacted noncovalently with their respective mature proteins, as well as forming heteromeric complexes between the BMP15 proregion and the GDF9 mature proteins (Liao et al. 2003, McIntosh et al. 2008). By using a proregion antibody to immuno-neutralize BMP15 activity with respect to thymidine incorporation into granulosa cells, we gained further evidence that the BMP15 proregion may have important extracellular functions. Moreover, in ovine follicular fluid, the predominant forms of both GDF9 and BMP15 were the unprocessed precursor proteins (McNatty et al. 2006).

To test whether these in vitro and in vivo findings have physiological relevance, we examined the potential roles of the proregions of BMP15 and GDF9 by immunizing mice against selected proregion peptide sequences or a recombinant full-length mouse proregion GDF9 protein. The end points assessed in this study were ovarian volume, the number of antral follicles and corpora lutea (CL; experiment 1), and corresponding litter sizes (experiment 2). Mouse CL remain visible in the ovary from the four most recent ovulatory cycles, with each cycle taking 4 days (Pedersen & Peters 1968). Therefore, by allowing mice to mate (experiment 2) during the 16 days before the time of ovary collection for histological analysis (experiment 1), we were able to link the CL numbers counted with the corresponding fertility outcome.

Results

Antibody titers

During the experimental timeline (see Fig. 1), antibody titers were measured in the pre-, mid-, and post-immunization sera of animals immunized with the GDF9 full-length proregion or BMP15 proregion N-terminus peptide. Titers were observed to increase consistently throughout the immunization period; for example, titers of post-immunization sera compared with mid-immunization sera significantly increased by 11-fold for the GDF9 full-length proregion (P<0.0001) and by twofold for the BMP15 N-terminus proregion peptide (P<0.01). Post-immunization antisera from all groups were then tested for specificity to the immunization antigen and for cross-reactivity to other antigens. All immunizations with keyhole limpet hemocyanin (KLH)-conjugated BMP15 or GDF9 proregion peptides (see Fig. 2 for peptide sequences) or the full-length GDF9 proregion protein resulted in significantly higher specific antibody titers against their respective antigens than when mice were immunized with KLH alone (P<0.0001, Table 1). No cross-reactivity was observed between BMP15 antisera and GDF9 antigens, or vice versa (Table 1).

![Figure 1 Experimental timeline for the immunization experiments. Mice were immunized four times with KLH-conjugated peptides or protein, or KLH as a control (n=30 per treatment group). Each treatment group was divided into two experiments: 1) where ovaries from ten mice per treatment group were collected a week after the final immunization for follicle and CL counts, and 2) where 20 mice per treatment group were allowed to breed and the number of pups born per litter were counted. In experiment 1, visible CL were linked to the last four ovulation cycles before ovary collection. Mating in experiment 2 was therefore allowed only during the same time period of these four ovulation cycles, in order to link the number of CL counted to fertility from the same cycles. Sera were collected after immunization for experiment 1, and pre-, mid-, and post-immunization for experiment 2.](https://www.reproduction-online.org)}
Values in bold represent $P<0.0001$ compared with KLH control within column, $n=28–30$ mice per group.
might involve intra-follicular paracrine effects since both the oocyte and the granulosa cells have membrane receptors for GDF9 and BMP15 (reviewed in Juengel & McNatty (2005) and Gilchrist et al. (2008)). Further evidence that the decreased number of CL observed in the BMP15 proregion-immunized groups could be related to interference with ovulation/luteinization was shown when normal ovulation and/or CL formation was impaired in ewes passively immunized with anti-plasma to BMP15 or GDF9 just before ovulation (Juengel et al. 2002).

Under normal physiological conditions in mice, levels of secreted BMP15 proteins are thought to be low (Hashimoto et al. 2005) until the preovulatory gonadotropin surge (Yoshino et al. 2006). In this case, it would be unlikely that BMP15 immunization would affect antral follicle numbers. The decreased ovulation rate we observed in mice immunized with BMP15 proregion peptides parallels the reported subfertility of Bmp15 knockout mice (Yan et al. 2001). Our data that GDF9 proregion-immunized mice developed increased CL numbers suggest that the GDF9 proregion might inhibit ovulation in some way, which is consistent with reports that proregions of some other TGFβ family proteins inhibit or antagonize their respective mature proteins (Bottinger et al. 1996, Hill et al. 2002, Jiang et al. 2004, Makanji et al. 2011). Alternatively, removal of the GDF9 proregion may negatively affect the concentration/dose of bioactive GDF9 mature protein available for signaling. In support of this, mice injected with an Fc fusion protein of the type II BMP receptor bone morphogenetic protein receptor, type II (serine/threonine kinase) (BMPR2) had increased the number of both antral follicles and CL (Myllymaa et al. 2010).

A key result from our studies was the decreased litter sizes of mice immunized with either the full-length GDF9 proregion or the BMP15 proregion N-terminus peptide. Since no differences between treatment groups were observed in the proportions of mice that became pregnant, or in the cycles in which fertilization occurred, it seems most likely that the proregion immunizations affected either the number of oocytes available for fertilization and/or the ability of oocytes to be fertilized and undergo normal development. Given the reduced number of CL observed in mice immunized against the BMP15 proregion N-terminus peptide, the subsequent reduced litter size is likely to be related to a decreased number of oocytes available for fertilization. A smaller litter size despite an increased CL number in mice immunized with the GDF9 proregion is consistent with the notion that some of the follicles and/or oocytes, and therefore the subsequent CL (Juengel et al. 2002), were abnormal at ovulation and compromised the pregnancy outcome. Moreover, this is also consistent with the finding that the addition of exogenous GDF9 to mouse oocytes during in vitro maturation resulted in an increased number of viable fetuses (Yeo et al. 2008).

**Table 2** Effect of immunization treatments on ovarian volume, number of corpora lutea (CL) and antral follicles, and litter size per mouse. Values are mean ± S.E.M.

<table>
<thead>
<tr>
<th>Immunization group</th>
<th>Ovarian volume (mm³)</th>
<th>Number of CL</th>
<th>Number of antral follicles</th>
<th>Litter size</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLH</td>
<td>2.17 ± 0.12 (10)</td>
<td>55.1 ± 3.3 (10)</td>
<td>116 ± 10 (5)</td>
<td>4.30 ± 0.40 (20)</td>
</tr>
<tr>
<td>GDF9 proregion</td>
<td>2.48 ± 0.12 (10)</td>
<td><strong>79.5 ± 3.5</strong> (10)</td>
<td>140 ± 12 (5)</td>
<td><strong>1.75 ± 0.25</strong> (19)</td>
</tr>
<tr>
<td>GDF9 C-terminus</td>
<td>2.23 ± 0.16 (10)</td>
<td>57.3 ± 3.3 (10)</td>
<td>171 ± 15 (5)</td>
<td>3.00 ± 0.65 (20)</td>
</tr>
<tr>
<td>GDF9 N-terminus</td>
<td>1.80 ± 0.09 (10)</td>
<td>49.2 ± 3.0 (10)</td>
<td>176 ± 23 (5)</td>
<td>4.11 ± 0.72 (19)</td>
</tr>
<tr>
<td>BMP15 C-terminus</td>
<td><strong>2.72 ± 0.14</strong> (8)</td>
<td><strong>41.8 ± 1.8</strong> (10)</td>
<td>149 ± 21 (5)</td>
<td>2.88 ± 0.55 (20)</td>
</tr>
<tr>
<td>BMP15 N-terminus</td>
<td>1.65 ± 0.37 (7)</td>
<td><strong>35.8 ± 4.3</strong> (9)</td>
<td>90 ± 22 (5)</td>
<td><strong>2.55 ± 0.39</strong> (19)</td>
</tr>
</tbody>
</table>

Values in bold represent *P<0.05, **P<0.01 compared with the KLH control group. The number of mice analyzed in each treatment group is shown in brackets.

*aFor calculation of mean values per immunization group, all visible CL and antral follicles of one ovary were counted for each mouse.

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**Figure 3** Number of corpora lutea (CL) according to ovulation cycle of CL origin. (A) Morphological classification of CL into groups to identify the ovulation cycle from which the CL developed. CL1, CL from the most recent ovulation cycle 1; CL2+3, combined CL from cycles 2 and 3 before the most recent ovulation; and CL4, the oldest visible CL from cycle 4. Scale = 50 μm. (B) Mean number of CL of mice within each immunization group, according to CL group. ± S.E.M. **P<0.01 and ***P<0.001 compared with KLH control groups.
**Table 3** Effect of immunization treatments on proportion of animals with copulatory plugs, pregnancy rate, and number of litters per ovulation cycle.

<table>
<thead>
<tr>
<th>Immunization group</th>
<th>Proportion of group with copulatory plugs (%)</th>
<th>Pregnancy rate of group (%)</th>
<th>Number of litters per group, per cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycle 4</td>
<td>Cycles 2 + 3</td>
<td>Cycle 1</td>
</tr>
<tr>
<td>KLH (20)</td>
<td>60*</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>GDF9 proregion (19)</td>
<td>75</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>GDF9 C-terminus (20)</td>
<td>95</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>GDF9 N-terminus (19)</td>
<td>79</td>
<td>47</td>
<td>3</td>
</tr>
<tr>
<td>BMP15 C-terminus (20)</td>
<td>85</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>BMP15 N-terminus (19)</td>
<td>95</td>
<td>58</td>
<td>3</td>
</tr>
</tbody>
</table>

*P < 0.05 χ² analysis. n, number of animals in each treatment group.

Proregion immunoneutralization of bioactivity is likely to occur through interactions between the proregion and mature proteins. It is anticipated that the antibodies generated by immunization would bind to proregion (free or interacting with mature proteins and other regulatory proteins) and precursor proteins. However, the physiological significance of secreted BMP15 and GDF9 precursor proteins is yet unknown. The N-terminus proregion peptides used for immunization includes a hydrophobic motif identified as binding to the mature protein at the same site that also interacts with BMPR2 (Walton *et al*., 2009). Antibodies generated against this region in BMP15 altered CL number, but there was no effect on CL number when mice were immunized with the corresponding GDF9 N-terminus peptide, suggestive of the *in vivo* interactions between the proregion and the mature proteins of mouse GDF9 and BMP15 being functionally different.

In summary, we have shown that active immunization against either the GDF9 or BMP15 proregion protein or peptides altered the number of CL and decreased the number of offspring, providing evidence that the proregions of both factors are important regulators of ovarian function *in vivo* in mice. Discovery of the functional mechanisms of these proregions will be a vital step to understand the full effects of BMP15 and GDF9 on oocyte maturation and gonadotropin responsiveness of both cumulus and granulosa cells.

**Materials and Methods**

**Generation of proregions and proregion peptides**

Mouse proregion GDF9 was amplified from the appropriate full-length mouse gene prepared as described previously (McIntosh *et al*., 2008). The Gdf9 PCR product (using Gdf9 primers 5'-CACCATGTCATCTCCAGAATCC-3', 5'-TC-GAGGCGCCCGG-3') was blunt-end cloned into the plasmid pET101 Direction TOPO (Invitrogen). The resulting GDF9 proregion protein was purified by immobilised metal ion chromatography (IMAC) and conjugated to equal quantities of KLH (Sigma-Aldrich) using glutaraldehyde, as described previously (Juengel *et al*., 2002). Preparation of a stable, full-length BMP15 proregion was unsuccessful. Proregion peptides were synthesized and conjugated to KLH through a C-terminus cysteine residue by Global Peptide, Fort Collins, CO, USA and GenScript, Piscataway, NJ, USA.

**Immunization procedures**

All animal immunizations and tissue recoveries were performed under approval of the Animal Ethics Committee of the Wallaceville Animal Research Centre, Upper Hutt, New Zealand, in accordance with the 1999 Animal Welfare Act (Part 6), New Zealand, and by the Victoria University of Wellington Animal Ethics Committee. The experimental design for the immunization experiments is outlined in Fig. 1. For each proregion or peptide antigen, 3-month-old Balb/c female mice (n=30 per treatment) were immunized with a total of 0.4 mg conjugated antigen (i.p.) over 6 weeks (0.2 mg in Freund’s complete adjuvant, with 2-weekly boosters of 0.1, 0.05, and 0.05 mg in a Span–Twee–Marcol adjuvant). Three separate immunization trials were undertaken, one trial for histological analyses (n=10 mice per treatment), and two trials for litter size analyses (data combined, n=20 mice per treatment). For histological analyses, ovaries were collected 1 week after the final booster. For litter size analyses, mice were allowed to mate during the 16-day period before immunization week 8, with the males being removed after mating.

**Measurement of antibody titers by ELISA**

Antisera from mice for litter size analyses were collected before immunization (pre), 2 days after immunization 3 (mid), and at killing (post). Antisera from mice for histological analyses were collected only after killing (post). To test sera (n=20–30 per treatment group) for reactivity to BMP15 and GDF9, wells of microtiter plates were coated at 4 °C overnight with 100 ng of unconjugated proregion protein or proregion peptide antigens in coating buffer (50 mmol/l carbonate–bicarbonate buffer, pH 9.6). GDF9 proregion protein was treated with 1% w/v SDS at 56 °C for 30 min before coating. Non-specific binding was blocked by incubation with 0.25 ml coating buffer containing 0.5% w/v gelatin for 30 min at room temperature. Wells were washed (three washes in PBS with 0.05% v/v Tween 20 for 3 min). Mouse sera were diluted 1:1000 in assay buffer (PBS with 0.05% v/v Tween 20 and 0.1% w/v gelatin), and 0.1 ml diluted sera incubated in each of the coated/washed wells of the microtiter plates for 2 h at 37 °C. The wells were washed.
and incubated with 0.1 ml HRP-conjugated goat anti-mouse immunoglobulin G (IgG) (1:10 000 dilution in assay buffer; Jackson ImmunoResearch Europe Ltd) for 1 h at 37 °C. Wells were washed and incubated with 0.1 ml of 50 mmol/l citrate buffer containing O-phenylenediamine (0.4 mg/ml; Sigma-Aldrich) and 0.04% v/v H_2O_2 for 30 min at room temperature in the darkness. Reactions were stopped by the addition of 0.05 ml of 2.5 mol/l H_2SO_4, and absorbance measured at 490 nm on a BioTek EL311 plate reader instrument (BioTek Instruments, Inc., Winooski, VT, USA). ELISA results were validated for multiplate assays with the coefficient of variation <6% between assay plates. Antisera from mice immunized with either BMP15 or GDF9 N-terminus proregion peptides were shown to specifically recognize the appropriate 293 HEK cell-expressed proregion and precursor premature proteins (McIntosh et al. 2008).

**Histological analyses**

Ovaries were collected from each treatment group, fixed in Bouin’s fluid, serially sectioned at 5 μm, and stained with hematoxylin and eosin. The volume of one ovary per mouse (n=7–10 per group) was measured by the Cavalieri principle using the formula V = 1/2 ah, where a, determined by point counting, is the cross-sectional area (μm^2) of every tenth section and h is the distance (μm) between sections used to determine a. The number of CL was counted (n=9–10 mice per group, see Table 2) by drawing CL outlines of each ovary in every 50th slide using a projection microscope. Counting every 50th slide was valid since the minimum CL size was observed to be >250 μm. In mice, CL progress to form corpora albicans over four consecutive estrous cycles from the most recent cycle (Pedersen & Peters 1968). For the purposes of this paper, all corpora luteal structures regardless of age are referred to as CL. The ovulation cycle of origin of each CL was determined at higher magnification using an Olympus BH-2 microscope (Olympus New Zealand Ltd, Upper Hutt, New Zealand), according to the criteria: CL1, from the most recent cycle, with large luteal cells and significant number of visible blood vessel epithelial cells; CL2+3, from cycles 2 and 3, with smaller luteal cells than in CL1, less vasculization, and presence of macrophages; CL4, from cycle 4, with luteal cells compacted, membranes disintegrating, and increased number of macrophages (Fig. 3A). While CL1 and CL4 were easy to distinguish, it was not always possible to distinguish CL2 and CL3; therefore, in this study, the data for CL2 and CL3 were combined. The number of antral follicles (non-atretic, atretic, or abnormal) in ovaries of five mice per group was measured by counting antral follicles in every tenth section. Follicular stage was classified according to that proposed for mouse follicles (Pedersen & Peters 1968).

**Pregnancy and litter size measurement**

Five days after immunization 3, female mice were housed with male mice (5:1 ratio). The presence of copulatory plugs was checked daily as an evidence of mating, noting the possibility of false negative data due to potential loss of plugs before observation. After 16 days, males were removed. From 18 days after immunization 3 onward, females were checked twice daily for parturition, when pups were counted and removed. Mothers were then killed, and post-immunization antisera were collected.

**Statistical procedures**

When comparing antibody titers, unpaired Student’s t-tests were performed between each of the treated groups and the control (KLH) group tested with the same antigen. To compare the ovarian effects and litter sizes between the treated groups and the control KLH group, the data were subjected to analysis of variance (ANOVA) and the Dunnett’s post-hoc test. To test differences between immunization groups for rates of copulatory plugs, pregnancy, or number of litters, data were subjected to x^2 analysis.

**Declaration of interest**

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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