



HAL
open science

Endothelial cell-derived fibroblast growth factor-18 regulates ovarian function in sheep

Anthony Estienne, Lauriane Relav, Morad Benkoura, Danielle Monniaux, Fanny Morin, Stéphane Fabre, Christopher Price

► **To cite this version:**

Anthony Estienne, Lauriane Relav, Morad Benkoura, Danielle Monniaux, Fanny Morin, et al.. Endothelial cell-derived fibroblast growth factor-18 regulates ovarian function in sheep. *Journal of Cellular Physiology*, 2022, 237 (5), pp.2528-2538. <10.1002/jcp.30718>. <hal-03616220>

HAL Id: hal-03616220

<https://hal.inrae.fr/hal-03616220v1>

Submitted on 12 Jul 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Copyright - All rights reserved

1 **Endothelial cell-derived fibroblast growth factor-18 regulates ovarian function in**
2 **sheep**

3

4 Anthony Estienne^{1,2}, Lauriane Relav^{1,4}, Morad Benkoura¹, Danielle Monniaux²,
5 Fanny Morin¹, Stéphane Fabre³ & Christopher A Price¹

6

7 ¹Centre de recherche en reproduction et fertilité (CRRF), Faculté de médecine
8 vétérinaire, Université de Montréal, 3200 Sicotte, St-Hyacinthe QC Canada.

9 ²UMR Physiologie de la Reproduction et des Comportements, INRAE Tours,
10 Nouzilly 37380, France

11 ³ GenPhySE, Université de Toulouse, INRAE, ENVT, 31326 Castanet-Tolosan,
12 France

13 ⁴ Current address: Institut de Pharmacologie Moléculaire et Cellulaire, CNRS
14 UMR7275, 660 route des Lucioles, Sophia Antipolis, 06560 Valbonne, France

15

16 Short title: Endothelial FGF18 & fertility

17

18 Keywords: fertility, ovary, fibroblast growth factors, bone morphogenetic proteins

19

20 Correspondence should be addressed to C A Price (christopher.price@umontreal.ca)

21

22

23 **Abstract**

24 Increasing the efficiency of farm animal reproduction is necessary to reduce the
25 environmental impact of food production systems. One approach is to increase the
26 number of healthy eggs (oocytes) produced per female for fertilization, thus it is
27 important to understand factors that decrease oocyte health. One paracrine factor that
28 decreases ovarian follicle growth is fibroblast growth factor 18 (FGF18) secreted by
29 cells in the theca layer of the ovarian follicle, however the factors that regulate FGF18
30 secretion are unknown. In this study we hypothesized that FGF18 secretion is
31 controlled by intrafollicular factors and is linked to fertility, which we tested by using
32 cell culture and sheep genetic models in vivo. Separation of theca cell populations
33 revealed that *FGF18* mRNA is located mainly in thecal endothelial rather than
34 endocrine cells, and immunohistochemistry localized FGF18 protein to microvessels
35 in the theca layer in situ. Culture of ovine theca-derived endothelial cells was used to
36 demonstrate stimulation of FGF18 mRNA and protein abundance by bone
37 morphogenetic protein-4 (BMP4), a growth factor derived from theca endocrine cells.
38 Taking advantage of a sheep genetic model, we demonstrate reduced ovarian and
39 peripheral FGF18 concentrations in the hyperproliferic Booroola ewe harboring the
40 *FecB^B* mutation in *BMPR1B*. These data suggest a novel control of fertility by
41 follicular endothelial cells, in which theca endocrine cells secrete BMP4 that
42 stimulates the secretion of FGF18 from thecal endothelial cells, which in turn diffuses
43 into the granulosa cell layer and promotes apoptosis.

44

45

46

47

48 **1. Introduction**

49 Modern agriculture contributes to climate change, and animal production
50 produces significant amounts of greenhouse gasses (Davis & White, 2020).
51 Approaches to mitigate the negative impacts of animal production are multifaceted,
52 but include improving reproductive efficiency by increasing the number of healthy
53 oocytes available for natural fertilization or assisted reproductive technologies,
54 particularly in monovulatory ruminants. The health of the oocyte is dependent on the
55 health of the ovarian follicle, and follicle growth is driven by hormones and growth
56 factors including follicle stimulating hormone (FSH) and insulin-like growth factor
57 (IGF) (Webb et al., 2016); maintaining granulosa cell health is critical for follicle
58 development (Hughes & Gorospe, 1991).

59 The microenvironment within the follicle also affects follicle development,
60 and factors secreted locally by either granulosa or theca cells can have stimulatory or
61 inhibitory effects on granulosa cell proliferation and follicle function (Juengel et al.,
62 2021). Stimulatory factors include bone morphogenetic protein 4 (BMP4) secreted
63 from theca cells and BMP15 from the oocyte that stimulate granulosa cell
64 proliferation and suppress apoptosis in cattle (Glister et al., 2004; Hussein et al., 2005;
65 McNatty et al., 2005; Shimizu et al., 2012). The signaling pathway of BMPs involves
66 forming a complex at the cell surface with a type I receptor and a type II receptor,
67 such as BMPRII and BMPRII for BMP4. Activated receptor complexes then
68 phosphorylate SMAD1/5/8 or SMAD2/8 intracellular messengers (Mazerbourg &
69 Hsueh, 2006), which then associate with SMAD4 in order to bind to SMAD-response
70 elements in gene promoters. The importance of BMP signaling for fertility is
71 illustrated by the loss-of-function mutation in the *BMPRII* gene (*FecB*) that leads to

72 hyperproliferacy in sheep (McNatty et al., 1986; Mulsant et al., 2001; Wilson et al.,
73 2001)

74 A potential inhibitory factor is theca-derived fibroblast growth factor-18
75 (FGF18) that increases bovine granulosa cell apoptosis in vitro and causes follicle
76 regression when injected directly into a growing follicle in vivo in cattle (Portela et
77 al., 2015; Portela et al., 2010). The theca layer of atretic follicles contains greater
78 amounts of *FGF18* mRNA than the theca layer of healthy growing follicles, but it is
79 unclear how the production of FGF18 secretion is controlled as mRNA abundance in
80 cultured bovine theca cells is not altered by physiological concentrations of
81 luteinizing hormone (LH) (Portela et al., 2010). It is also unclear which cell types
82 within the theca express FGF18 as this cell layer is complex, consisting of endocrine
83 cells, immune cells, fibroblasts and endothelial cells, (Richards et al., 2017).

84 Rodent and human endothelial cells contain *FGF18* mRNA (Antoine et al.,
85 2006; Antoine et al., 2005), therefore we hypothesized that FGF18 is derived from
86 thecal endothelial cells and is a novel endothelial-to-granulosa cell signaling molecule
87 that contributes to the modulation of fertility. The objectives of the present study were
88 to determine which cell types of the ovine theca layer express FGF18 and to identify
89 which paracrine factors regulate FGF18 mRNA/protein. In addition, taking advantage
90 of genetic models of fecundity, we reveal a unique link between thecal endothelial
91 cells and prolificacy in sheep.

92

93 **2. Materials and methods**

94 2.1 Experimental design

95 Localization of FGF18 protein was determined with immunohistochemistry
96 performed on mixed-breed sheep ovaries obtained from an abattoir, and which were

97 fixed in Bouin's fixative and embedded in paraffin. Immunohistofluorescence was
98 used on different ovaries to examine in more detail the localization of FGF18 in small
99 blood vessels. Ovaries were fixed in formalin and embedded in paraffin for FGF18
100 detection, and endothelial cells were identified by localization with the endothelial
101 cell marker, von Willebrand factor. To assess which cell types within the theca layer
102 express *FGF18* mRNA, a cell-enrichment approach was taken to enrich or deplete
103 endothelial cells from a theca layer digest using CD29-coated beads as described
104 below, followed by qPCR for *FGF18* and the endothelial cell marker, coagulation
105 factor VIII (*F8*).

106 The regulation of *FGF18* mRNA and protein abundance was measured in vitro
107 by culturing thecal endothelial cells from abattoir-derived ovaries. Passaged cells
108 were serum-starved and then treated with Transforming Growth Factor- β (TGF β)
109 family members as detailed below. The intracellular pathways employed by BMPs to
110 regulate *FGF18* expression were determined in endothelial cells after short-term
111 incubation with BMPs, and cell protein was harvested for the measurement of
112 phosphorylated second messengers. Involvement of the SMAD signaling pathway
113 was investigated by knocking-down SMAD4 through siRNA before the addition of
114 BMP.

115 The role FGF18 may play in follicle development *in vivo* was then assessed
116 using a genetic sheep model of partial loss-of-function of BMP signaling. First,
117 cycling Lacaune ewes were used to measure plasma FGF18 concentrations during an
118 estrous cycle. Then, Mérinos d'Arles ewes with or without the *FecB^B* mutation in the
119 *BMPRII* receptor were used to collect blood samples and ovaries, to measure plasma
120 FGF18 concentrations by ELISA and tissue FGF18 protein abundance by
121 immunohistochemistry, respectively.

122

123 2.2 Immunohistochemistry and Immunohistofluorescence

124 For immunohistochemistry, ovaries were serially sectioned at a thickness of 7
125 μm with a microtome and sections were deparaffinized in toluene, rehydrated, and
126 incubated in antigen unmasking solution (Vector Laboratories, Burlingame, VT) for 4
127 min in a microwave and then left for 2 h at room temperature. Sections were washed
128 three times in PBS with 0.1% saponin and then treated with 0.3% H_2O_2 for 30 min at
129 4°C in the dark to remove endogenous peroxidase. Then sections were washed three
130 times in PBS with 0.1% saponin again and then treated with PBS with 0.1% saponin
131 and mare's serum diluted at 1/15 for 30 min at 4°C in the dark to block nonspecific
132 sites. After sections were washed three times, they were incubated with mouse
133 monoclonal anti-FGF18 (Biorbyt # orb1778; 1:2000 in PBS, 0.1% saponin & 5%
134 mare serum) in a humidified chamber overnight at 4°C . Sections were washed three
135 times and then incubated with donkey anti-mouse peroxidase-conjugated secondary
136 antibody (Jackson ImmunoResearch Laboratories, West Grove, PA) diluted 1:800 in
137 PBS, saponin 0.1% and BSA 0.1% at room temperature for 4 h.

138 Immunostaining was developed by incubating sections in 50 mM Tris-HCl
139 (pH 7.8) containing 0.4 mg/ml 3,3'-diaminobenzidine tetrahydrochloride dehydrate
140 (Sigma) and 0.012% H_2O_2 for 10 min at room temperature. Negative control sections
141 involved omitting the primary antibody.

142 Immunohistofluorescence was performed on 7 μm sections of ovary that were
143 deparaffinized in toluene, rehydrated, boiled in 10 mM sodium citrate (pH 6) for 30
144 minutes, and then cooled to room temperature. Non-specific sites were blocked for 1 h
145 at room temperature in 5% normal goat serum (NGS) (Jackson ImmunoResearch;
146 005-020-121, FGF18) or 5% mare serum, followed by incubation with anti-FGF18

147 goat polyclonal antibody (Bioss; 1:200) or donkey polyclonal antibody raised against
148 von Willebrand factor (VWF; Abcam #ab6994; 1:400) diluted in 5% goat or mare
149 serum respectively, in PBS plus 0.1% Tween20 overnight at 4°C. Negative control
150 sections were incubated with 5% NGS only. Sections were washed and incubated with
151 cyanine 3 (Cy3)-conjugated anti-goat or anti-donkey IgG (Jackson ImmunoResearch)
152 diluted 1:300 in PBS with 5% bovine serum albumin (BSA) (A3294; Sigma) for 1 h
153 at room temperature. After incubation, sections were washed and counterstained with
154 4,6-diamidino-2-phenylindole (DAPI) (Sigma) diluted 1:1000 in PBS for 5 min, then
155 slides were mounted in Permafluor (Thermo Fisher Scientific).

156

157 2.3 Cell isolation and culture

158 All materials were obtained from Life Technologies Inc. (Burlington, ON,
159 Canada) unless otherwise stated. Mixed-breed sheep ovaries were obtained from
160 cycling ewes, irrespective of stage of the estrous cycle, at a slaughterhouse near the
161 University of Montréal Faculty of Veterinary Medicine. Theca layers were peeled
162 from the stroma of follicles 2-6 mm diameter, granulosa cells were scraped off, and
163 the theca shell incubated in a solution of 1mg/ml collagenase type IV (Sigma–Aldrich,
164 Oakville ON, Canada) and 100µg/ml trypsin inhibitor (Sigma–Aldrich) at 37°C for 45
165 minutes. The supernatant was centrifuged for 10 minutes at 800g, and the cells
166 resuspended. An endothelial cell-enriched fraction and an endothelial-depleted
167 fraction of theca-derived cells was prepared with the sheep CD29 pluriBead kit
168 according to the manufacturer's instructions (pluriSelect, El Cajon CA). The optimal
169 recovery of endothelial cells was obtained by incubation of 4×10^6 theca-derived cells
170 with 80µl pluriBeads in 2ml incubation buffer. Cells from both fractions were pelleted
171 by centrifugation and frozen for RNA extraction and RT-PCR (n=7).

172 Cells from the endothelial-rich fraction were seeded in 15 cm² gelatin-coated
173 flasks in endothelial cell culture medium (M199 with L-glutamine, 25 mM HEPES
174 and Hanks salts; Invitrogen), supplemented with antibiotics and 10% FBS and 100
175 µg/ml endothelial cell growth supplement (ECGS; Sigma) until confluence, and then
176 passaged up to three times. Aliquots were frozen in culture medium:DMSO (1:1
177 vol:vol) before experimental treatments.

178 Cells were thawed and cultured in gelatin-coated 24-well plates at a density of
179 0.5 x 10⁶ cells/well in 1 ml supplemented endothelial cell culture medium until 60%
180 confluence (24-48 h) at 37 °C and under 5% CO₂ atmosphere. Cells were then
181 'starved' for 9 h in endothelial cell culture medium without FBS or ECGS, after which
182 cells were challenged with the growth factors Transforming Growth Factor β (TGFβ),
183 BMP4, BMP5, BMP15, Growth Differentiation Factor 9 (GDF9) or anti-Müllerian
184 hormone (AMH) (all from R&D Systems) for times and concentrations shown in the
185 legends to figures 2 and 3 before harvesting for RNA or protein extraction.
186 Experiments were performed with 4 wells per treatment that were pooled to obtain a
187 single RNA or protein sample per treatment. Cultures were performed on 4-5
188 independent cell cultures.

189 To measure abundance of FGF18 protein, thecal endothelial cells were
190 cultured in Lab-Tek chamber slides (ThermoFisher) at 1 x 10⁵ cells/well in 0.5 ml
191 supplemented endothelial cell culture medium as above. After treatment with 50
192 ng/ml BMP4 for 48 h, cells were fixed in 10% formalin and stained with anti-FGF18
193 (Biorbyt; 1:2000) as described above. All images were obtained using Axio Imager
194 M1 (Zeiss Microscopy, Toronto, ON, Canada) and immunostaining was quantified
195 using ImageJ (U.S. National Institutes of Health, Bethesda, Maryland, USA,

196 <http://imagej.nih.gov/ij/>, 1997–2015) on photomicrographs of Lab-Tek chamber
197 slides.

198

199 2.4 RNA interference

200 Endothelial cells were cultured in supplemented endothelial cell culture
201 medium as above until 60% confluence, after which 100µl Opti-MEM premixed with
202 3µl Lipofectamine RNAiMAX and siRNA (10 nM final concentration) were added
203 for 48 h. Culture medium was then replaced with medium without FBS or ECGS,
204 after which cells were challenged with BMP4 (50 ng/ml) for 24 h. Cells were then
205 harvested for RNA or protein extraction. Four wells per treatment were combined to
206 form a single sample, and experiments were performed on 5 independent culture
207 replicates.

208

209 2.5 Animals, blood collection and FGF18 assay

210 Lacaune ewes (n=9, 2 years-old, primiparous, cycling) were housed at INRAE
211 experimental facilities in Toulouse, and estrus was synchronized during the breeding
212 season by insertion of intravaginal progestagen sponges (fluogestone acetate FGA, 20
213 mg; Intervet) for 14 days. Blood (4 ml into heparinized tubes) was sampled at 12-h
214 intervals from intravaginal sponge removal (Day 0) to Day 4 (96h) along the follicular
215 and periovulatory phases of the estrus cycle, and plasma was used to measure FGF18
216 by ELISA.

217 Mérinos d'Arles (n=28, 6-8 years-old, multiparous, cycling) were housed at
218 INRAE experimental facilities in Tours, and 14 homozygous carrier of the *FecB^B*
219 mutation in *BMPR1B* (*FecB^{B/B}*) and 14 non-carrier (*FecB^{+/+}*) ewes were used. Estrous
220 cycles were synchronized as above, and a blood sample was collected 36 h after

221 sponge removal. One week after sponge removal, animals were sacrificed and the
222 mean number of corpora lutea observed in the ovaries were 1.75 ± 0.13 and $5.92 \pm$
223 0.34 for *FecB*^{+/+} and *FecB*^{B/B} ewes, respectively (Estienne et al., 2015). Ovaries from
224 3 *FecB*^{+/+} and 3 *FecB*^{B/B} ewes were fixed in Bouin's fixative and embedded in paraffin
225 for immunohistochemistry as described above.

226 All experiments were performed in accordance with French guidelines for
227 Care and Use of Agricultural Animals in Agricultural Research and Teaching
228 (approval numbers C37-175-2 and D31-429-01), and jugular vein puncture procedure
229 for blood sampling was approved by the French Ministry of Teaching and Scientific
230 Research and local ethical committee (approval number 01171.02).

231 For all blood samples, plasma was stored at -20°C until assay for FGF18 with
232 a commercial sheep FGF18 ELISA (MBS027703; MyBioSource, San Diego, CA,
233 USA); preliminary experiments determined that samples were parallel with the
234 standard curve between dilutions of 1:1 and 1:4 in assay diluent. All samples were
235 analysed on a single plate with a coefficient of variation of 2%.

236

237 2.6 Total RNA extraction and real-time RT-PCR

238 Total RNA from cell cultures was extracted using PureLink RNA mini
239 extraction kit according to the manufacturer's instructions (12183025, Ambion by Life
240 Technologies). Reverse transcription was performed on 1 µg RNA with SuperScript
241 Vilo cDNA synthesis kit (Thermo Fisher Scientific). Real-time PCR was performed
242 with 10µl SsoAdvanced Universal SYBR Green Supermix (Bio-Rad, Mississauga
243 ON), 6µl of cDNA, 10 pmol primers (1.5 µl) and 1µl water in a CFX96 Touch
244 thermocycler (Bio-Rad). Primers were designed to measure mRNA encoding ovine
245 F8, luteinizing hormone receptor (LHCGR), FGF18, endothelin-1 (EDN1), SMAD4

246 and SMAD6 (Table 1). Common thermal cycling parameters (3 min at 95°C, 40
247 cycles of 15 s at 95°C, 30 s at 60°C and 30 s at 72°C) were used to amplify each
248 transcript. Melting curve analyses were performed to verify production of single
249 amplicons, and amplification efficiency of primer pairs was between 2.0 and 2.15
250 measured as described (Monniaux et al., 2008). Samples were run in duplicate, and
251 were expressed relative to the geometric mean of *RPL19*, *SDHA* and *YWHAZ* as
252 housekeeping genes and expressed as the ratio $R = [E_{Ref}^{Ct(Ref)} / E_{target}^{Ct(target)}]$
253 (Estienne et al., 2015).

254

255 2.7 Immunoblotting

256 Cells were lysed in 100 µl/well cold RIPA buffer (25 mM Tris-HCl pH 7.6,
257 150 mM NaCl, 1% NP-40, 1% sodium deoxycholate, 0.1% SDS, phosphatase
258 inhibitor cocktail, and protease inhibitor cocktail) and protein concentrations were
259 determined by BCA protein assay (Pierce, Rockford, IL). Proteins were resolved on
260 10% SDS-PAGE gels (3.5 µg total protein per lane) and transferred onto PVDF
261 membrane in a Bio-Rad wet Blot Transfer Cell apparatus (transfer buffer: 39 mM
262 glycine, 48 mM Tris-base, 20% methanol, pH 8.3). After 2 hours of transfer, the
263 membranes were blocked in 5% non-fat dry milk in TTBS (10 mM Tris-HCl, 150
264 mM NaCl, 0.1% Tween-20, pH 7.5) for 1 hour. Membranes were cut horizontally
265 between molecular mass markers according to the size of the target proteins, and
266 strips incubated for 1 h with rabbit polyclonal antibodies raised against phospho-
267 SMAD1/5/8 (1:1000, Cell Signaling, 13820), phospho-SMAD2/3 (1:1000, Cell
268 Signaling, 3108), total-SMAD1/5/8 (0.625µg/ml, Abcam, ab66737) and total-
269 SMAD2/3 (0.625µg/ml, Abcam, ab47083). After three washes in TTBS, membranes
270 were incubated for 1 hour at room temperature with 1:10 000 HRP-conjugated anti-

271 rabbit IgG (GE Healthcare Canada). Protein bands were revealed by
272 chemiluminescence (ECL, Bio-Rad Laboratories Ltd, CA, USA). Semi-quantitative
273 analysis was performed with Image Lab software (Bio-Rad).

274

275 2.8 Statistical analysis

276 Data were tested for homogeneity of variance by Bartlett's test, and for normal
277 distribution by Shapiro-Wilk test, and log transformations were performed as
278 appropriate. One-way ANOVA were performed with Tukey-Kramer multiple
279 comparisons tests (effects of TGFB ligands on *FGF18* mRNA), Dunnett's test to
280 compare each treatment with control (signaling pathway analyses), t-tests to compare
281 gene expression in cell-enriched and depleted fractions, and Mann-Whitney test to
282 compare FGF18 protein abundance between sheep genotypes. Culture data included
283 culture replicate as a random variable. Data are presented as means \pm SEM with $P <$
284 0.05 considered significant.

285

286 3. Results

287 3.1 FGF18 is expressed in ovarian endothelial cells

288 After fractionation of the cells from the theca cell layer, the endothelial-
289 enriched fraction contained significantly more mRNA encoding the endothelial
290 marker F8 and significantly less mRNA encoding the LH receptor gene (LHCGR)
291 compared with the endothelial-depleted fraction (Fig 1A). Abundance of *FGF18*
292 mRNA was significantly higher in the endothelial-enriched fraction, suggesting that
293 endothelial cells rather than endocrine cells are a major source of thecal FGF18. This
294 was supported by immunohistochemical analysis, which demonstrated FGF18
295 staining in the endothelium and smooth muscle layer of blood vessels of the ovarian

296 medulla and cortex with little to no staining in the oocyte or granulosa cells (Fig 1B).
297 The endothelium of blood venules in the stroma and theca cell layer stained for
298 FGF18 as detected by immunofluorescence, and cell identity was confirmed by
299 immunofluorescence for VWF (Fig 1C).

300

301 3.2 Theca-derived endothelial cell FGF18 expression is stimulated by BMPs

302 The regulation of FGF18 expression by thecal endothelial cells was then
303 assessed *in vitro*. Cells responded to TGFB1 and to BMP4 with dose-dependent
304 increases in *FGF18* mRNA levels after 24 h culture (Fig 2). Abundance of mRNA
305 encoding a known TGF-responsive endothelial protein, endothelin-1 (EDN1), was
306 significantly stimulated by BMP4 (Fig 2) but not by TGFB1. Treatment with other
307 members of the TGF superfamily, BMP5, BMP15 or BMP15+GDF9 for 24 h
308 significantly increased the abundance of *FGF18* mRNA, whereas AMH or GDF9
309 alone were without effect (Fig 3A). Immunocytochemistry demonstrated that of the
310 TGFB family members tested, only BMP4 increased the abundance of FGF18 protein
311 in cultured cells (Fig 3B).

312 The intracellular pathway used by BMPs to increase FGF18 expression was
313 investigated by Western blotting. Challenge of thecal endothelial cells with BMP4,
314 BMP5 or BMP15 for 30 min significantly increased phosphorylation of SMAD1/5/8
315 (Fig 3C), as did combinations of BMP15 with GDF9 or AMH, but neither GDF9 nor
316 AMH alone significantly stimulated SMAD1/5/8 phosphorylation although a
317 numerical increase was observed. The activation of the SMAD1/5/8 pathway was
318 corroborated by measuring abundance of *SMAD6* mRNA after 24 h of treatment,
319 which was significantly increased by BMP4, BMP5, BMP15 and the combinations of
320 BMP15 with GDF9 or AMH, but not by GDF9 or AMH alone (Fig 3D). Treatment

321 with GDF9 or AMH increased the levels of phospho-SMAD2/3 protein, whereas
322 neither BMP4, BMP5 nor BMP15 had any effect (data not shown).

323 To demonstrate that the SMAD pathway was necessary for BMP regulation of
324 endothelial *FGF18* mRNA levels, *SMAD4* mRNA was knocked-down to 22% of
325 control levels with an siRNA approach. Addition of BMP4 increased the abundance
326 of *FGF18* and *SMAD6* mRNA in scrambled RNA-transfected cells as expected, and
327 did not alter *SMAD4* mRNA levels compared with controls (Fig 4). Knockdown of
328 *SMAD4* abolished the ability of BMP4 to stimulate *FGF18* and *SMAD6* mRNA levels
329 (Fig 4). As a negative control, cells were also treated with GDF9 that did not increase
330 *FGF18* mRNA levels compared with controls, and the siRNA had no effect on
331 *FGF18* mRNA abundance in the presence of GDF9 compared with GDF9 alone or
332 controls (Fig 4).

333

334 3.3 Ovarian and plasma FGF18 levels are reduced in hyperprolific sheep harboring a
335 mutation in the BMP receptor gene.

336 As BMP4 appeared to be a major regulator of FGF18 protein production, we
337 used a genetic sheep model (*FecB^{B/B}*) of partial loss-of-function of BMP signaling to
338 assess the role of FGF18 in ovarian function. Plasma concentrations of FGF18 in
339 wild-type Lacaune ewes (*FecB^{+/+}*) did not change during the follicular phase of the
340 estrus cycle and the peri-ovulatory period (Fig 5A). Immunohistochemistry revealed
341 significantly less staining for FGF18 protein in *FecB^{B/B}* ovaries compared with
342 *FecB^{+/+}* ovaries in medullary blood vessels (Fig 5B, C), and this was mirrored by
343 significantly lower plasma FGF18 concentrations in *FecB^{B/B}* compared to *FecB^{+/+}*
344 ewes (Fig 5D).

345

346 **4. Discussion**

347 Paracrine signaling is likely involved in the fine tuning of follicle development
348 and fertility, and the atypical growth factor FGF18 has been shown to cause apoptosis
349 in granulosa cells. In the present work, we present three lines of evidence that FGF18
350 is part of a novel link between endothelial cells and fertility in sheep. Firstly, FGF18
351 is produced mainly in the endothelial cells rather than in the endocrine cells of the
352 theca layer. Secondly, FGF18 mRNA and protein abundance in thecal endothelial
353 cells are stimulated mainly by BMP4, and as BMP4 is secreted by theca endocrine
354 cells, this suggests a novel cell-cell communication within the theca cell layer.
355 Thirdly, ovarian and circulating FGF18 protein concentrations are reduced in
356 hyperprolific ewes carrying a loss-of-function mutation in BMP signaling, which
357 suggests a novel control of fertility by endothelial cells.

358 Within the ovarian follicle, FGF18 has previously been localized to the theca
359 cell layer in cattle, although mRNA levels were not regulated by gonadotropins (LH)
360 in thecal endocrine cells *in vitro* (Portela et al., 2010). This can be explained by the
361 present data showing that endothelial cells and not endocrine cells are the primary
362 source of FGF18. Localization of the protein demonstrated clear presence in the
363 endothelium and smooth muscle layer in blood vessels in the ovarian cortex and
364 medulla, and immunofluorescence detected FGF18 protein in the endothelium of
365 thecal venules. This is consistent with data showing FGF18 expression in human and
366 rat vascular endothelial cells (Antoine et al., 2006; Antoine et al., 2005).

367 Endothelial cells play a vital role in folliculogenesis, as reduced
368 vascularization of the theca is associated with follicular atresia (reviewed in
369 (Robinson et al., 2009), and follicular capillary formation is stimulated by granulosa
370 and theca cells through the secretion of VEGF and FGF2 (Mattar et al., 2020;

371 Reynolds & Redmer, 1998; Robinson et al., 2009). A major regulator of endothelial
372 cell function is TGFB1, which controls the expression and secretion of endothelial-
373 specific molecules including endothelin-1 (EDN1) (Castañares et al., 2007; Star et al.,
374 2009). Although *EDN1* mRNA abundance was not significantly increased by TGFB1
375 in endothelial cells in the present study, the cells responded to BMP4 with a 4-fold
376 increase in *EDN1* mRNA levels. This stands in contrast to data with human lung
377 microvessel or aortic endothelial cells in which BMP4 had no effect on EDN1
378 secretion (Park et al., 2012; Star et al., 2010).

379 In addition to EDN1, the present data show that FGF18 is also a target of
380 TGFB family signalling in endothelial cells. Although TGFB1, BMP4, BMP5 and
381 BMP15 all increased the abundance of *FGF18* mRNA in thecal endothelial cells,
382 BMP4 was the most potent and the only BMP that also increased FGF18 protein
383 abundance. The main ovarian source of BMP4 is generally considered to be theca
384 endocrine cells (Knight & Glister, 2006), suggesting that endocrine cells signal to
385 endothelial cells within the theca layer, however as BMP4 is also expressed in
386 endothelial cells (Sorescu et al., 2003), an autocrine component to BMP4 - FGF18
387 signaling is also possible. This signaling pathway involves phosphorylation of
388 SMAD1/5/8, and knock-down of *SMAD4* indicated that the SMAD4 pathway is
389 necessary for BMP4 regulation of *FGF18* expression. Although TGFB1 has been
390 shown to increase *Fgf18* mRNA in a rat chondrocyte cell line (Reinhold et al., 2004),
391 no such effect was noted in a microarray study with human microvessel endothelial
392 cells (Wu et al., 2006). Neither GDF9 nor AMH, primarily activators of the Smad2/3
393 pathway, altered *FGF18* mRNA levels in the present study, whereas activation of the
394 SMAD2/3 pathway increased *FGF18* mRNA levels in human microvessel endothelial
395 cells (Wu et al., 2006). Collectively, the present data on EDN1 and FGF18 regulation

396 suggest that theca endothelial cells have specialized functional properties that differ
397 from some other endothelial cells, as has been suggested for other organ systems
398 (Rafii et al., 2016).

399 As FGF18 has been shown to promote apoptosis in granulosa (Portela et al.,
400 2010) but not in theca cells (Han et al., 2018), the present data suggest a three-cell
401 signaling network in the follicle in which endocrine theca cells act on endothelial cells
402 through BMP4, and endothelial cells then act on granulosa cells through FGF18 to
403 increase the rate of apoptosis. Although most coculture studies have focused on the
404 role of theca, granulosa or luteal cells on endothelial cell function (Mattar et al., 2020;
405 Woad et al., 2009), a few previous investigated the role of endothelial cell-derived
406 (angiocrine) factors ; endothelial cells had a positive effect on bovine granulosa cell
407 proliferation in coculture (Spaniel-Borowski et al., 1994) and ovarian endothelial cells
408 expressing constitutively active AKT promoted primary follicle growth in mice
409 (Kedem et al., 2017). Together, these observations indicate a complex role of
410 endothelial cells in follicular development, likely involving the secretion of both
411 promoting and suppressive factors.

412 Altered BMP signaling may play a role in fertility, particularly in sheep where
413 the *FecB^B* loss-of-function mutation in *BMPRI1B* increases ovulation rate (McNatty et
414 al., 1986; Mulsant et al., 2001; Wilson et al., 2001). The current model for the
415 mechanism of the *FecB^B* mutation is that BMP4 signaling is defective leading to
416 increased sensitivity to FSH and to decreased secretion of AMH, which in turn
417 increase follicle activation and survival (Estienne et al., 2015; Fabre et al., 2006). The
418 present study shows that abundance of FGF18 protein is also reduced in the ovarian
419 blood vessels of *FecB^B* ewes, indicating that it likely contributes to the hyperprolific
420 phenotype. As FGF18 has been shown to promote apoptosis in granulosa cells

421 (Portela et al., 2010), a reduction in ovarian FGF18 content is entirely consistent with
422 the reduced incidence of apoptosis observed in *FecB^B* follicles (Driancourt et al.,
423 1985; Mandiki et al., 2000; Sheena et al., 2015).

424 The reduction in follicular FGF18 protein in *FecB^B* ewes was associated with a
425 reduction in FGF18 concentrations in peripheral blood, as is the case for AMH
426 (Estienne et al., 2015). It is unlikely that decreased FGF18 concentrations are a result
427 of decreased AMH concentrations as AMH did not alter endothelial FGF18 mRNA or
428 protein abundance in the present study. This would imply a potential effect of the
429 mutation on other organ systems, however the only other tissues known to be affected
430 by this mutation are the fetal heart and the adult adrenal gland, both of which are
431 smaller but not functionally compromised in *FecB^B* carriers (McNatty et al., 1995;
432 Souza & Baird, 2004). Peripheral plasma FGF18 concentrations did not change during
433 the follicular and peri-ovulatory phases of the estrus cycle, which again is similar to
434 the situation with AMH (Rico et al., 2011).

435 In summary, this study demonstrates that follicular FGF18 originates from
436 endothelial cells within the ovary and may play a role in controlling fertility. The
437 present data suggest a three-cell signaling network in which theca endocrine cells
438 secrete BMP4 that stimulates the secretion of FGF18 from thecal endothelial cells,
439 which in turn diffuses into the granulosa cell layer and promotes apoptosis. Reduced
440 BMP signaling, as seen in hyperprolific sheep harboring a mutation in *BMPRI1B*,
441 could attenuate FGF18 secretion leading to a reduced granulosa cell apoptosis rate,
442 thus allowing increased follicle development.

443

444 **Declaration of interest.**

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

447

448 **Acknowledgements.**

449 This work was supported by the Natural Science and Engineering Research Council
450 (NSERC) Canada (CAP), Agence Nationale pour la Recherche (ANR-12-BSV1-
451 0034-02, AMHAROC) France (DM, SF), European Funds for Regional Development
452 (FEDER) through the Interreg POCTEFA programme (EFA103/15, PIRINNOVI)
453 (SF) and Fonds de recherche du Québec - Nature et technologies/Réseau Québécois
454 en Reproduction (CAP, SF). We gratefully acknowledge the technical assistance of
455 Peng Han, Hilda Guerrero-Netro, Peggy Jarrier and Louise Chantepie.

456

457 **Data sharing statement**

458 The data that support the findings of this study are available from the corresponding
459 author upon reasonable request.

460

461 **References**

462

- 463 Antoine, M., Wirz, W., Tag, C. G., Gressner, A. M., Wycislo, M., Müller, R., & Kiefer, P.
464 (2006). Fibroblast growth factor 16 and 18 are expressed in human
465 cardiovascular tissues and induce on endothelial cells migration but not
466 proliferation. *Biochemical and Biophysical Research Communications*, *346*(1),
467 224-233. doi:<http://dx.doi.org/10.1016/j.bbrc.2006.05.105>
- 468 Antoine, M., Wirz, W., Tag, C. G., Mavituna, M., Emans, N., Korff, T., . . . Kiefer, P.
469 (2005). Expression pattern of fibroblast growth factors (FGFs), their receptors
470 and antagonists in primary endothelial cells and vascular smooth muscle cells.
471 *Growth Factors*, *23*(2), 87-95. doi:10.1080/08977190500096004
- 472 Castañares, C., Redondo-Horcajo, M., Magán-Marchal, N., ten Dijke, P., Lamas, S., &
473 Rodríguez-Pascual, F. (2007). Signaling by ALK5 mediates TGF- β -induced ET-
474 1 expression in endothelial cells: a role for migration and proliferation.
475 *Journal of Cell Science*, *120*(7), 1256. doi:10.1242/jcs.03419
- 476 Davis, T. C., & White, R. R. (2020). Breeding animals to feed people: The many roles
477 of animal reproduction in ensuring global food security. *Theriogenology*, *150*,
478 27-33. doi:<https://doi.org/10.1016/j.theriogenology.2020.01.041>

479 Driancourt, M. A., Cahill, L. P., & Bindon, B. M. (1985). Ovarian follicular populations
480 and preovulatory enlargement in Booroola and control Merino ewes. *Journal*
481 *of Reproduction and Fertility*, *73*, 93-107. doi:DOI: 10.1530/jrf.0.0730093

482 Estienne, A., Pierre, A., di Clemente, N., Picard, J.-Y., Jarrier, P., Mansanet, C., . . .
483 Fabre, S. (2015). Anti-Müllerian hormone regulation by the bone
484 morphogenetic proteins in the sheep ovary: deciphering a direct regulatory
485 pathway. *Endocrinology*, *156*(1), 301-313. doi:10.1210/en.2014-1551

486 Fabre, S., Pierre, A., Mulsant, P., Bodin, L., Di Pasquale, E., Persani, L., . . .
487 Monniaux, D. (2006). Regulation of ovulation rate in mammals: contribution
488 of sheep genetic models. *Reproductive Biology and Endocrinology*, *4*, 20-20.
489 doi:10.1186/1477-7827-4-20

490 Glistler, C., Kemp, C. F., & Knight, P. G. (2004). Bone morphogenetic protein (BMP)
491 ligands and receptors in bovine ovarian follicle cells: actions of BMP-4, -6 and
492 -7 on granulosa cells and differential modulation of Smad-1 phosphorylation
493 by follistatin. *Reproduction*, *127*(2), 239-254. doi: DOI: 10.1530/rep.1.00090

494 Han, P., Guerrero-Netro, H., Estienne, A., & Price, C. A. (2018). Effects of fibroblast
495 growth factors and the transcription factor, early growth response 1, on
496 bovine theca cells. *Molecular and Cellular Endocrinology*, *476*, 96-102.
497 doi:<https://doi.org/10.1016/j.mce.2018.04.013>

498 Hughes, F. M. J., & Gorospe, W. C. (1991). Biochemical Identification of Apoptosis
499 (Programmed Cell Death) in Granulosa Cells: Evidence for a Potential
500 Mechanism Underlying Follicular Atresia. *Endocrinology*, *129*(5), 2415-2422.
501 doi:10.1210/endo-129-5-2415

502 Hussein, T. S., Froiland, D. A., Amato, F., Thompson, J. G., & Gilchrist, R. B. (2005).
503 Oocytes prevent cumulus cell apoptosis by maintaining a morphogenic
504 paracrine gradient of bone morphogenetic proteins. *Journal of Cell Science*,
505 *118*(22), 5257-5268. doi:10.1242/jcs.02644

506 Juengel, J. L., Cushman, R. A., Dupont, J., Fabre, S., Lea, R. G., Martin, G. B., . . .
507 Smith, P. (2021). The ovarian follicle of ruminants: the path from conceptus
508 to adult. *Reproduction, Fertility and Development*, *33*, 621-642.
509 doi:doi.org/10.1071/RD21086

510 Kedem, A., Aelion-Brauer, A., Guo, P., Wen, D., Ding, B.-S., Lis, R., . . . Rosenwaks,
511 Z. (2017). Activated ovarian endothelial cells promote early follicular
512 development and survival. *Journal of Ovarian Research*, *10*(1), 64.
513 doi:10.1186/s13048-017-0354-z

514 Knight, P. G., & Glistler, C. (2006). TGF- β superfamily members and ovarian follicle
515 development. *Reproduction*, *132*(2), 191-206. doi:DOI: 10.1530/rep.1.01074

516 Mandiki, S. N. M., Noël, B., Bister, J. L., Peeters, R., Beerlandt, G., Decuyper, E., . . .
517 Paquay, R. (2000). Pre-ovulatory follicular characteristics and ovulation rates
518 in different breed crosses, carriers or non-carriers of the Booroola or
519 Cambridge fecundity gene. *Animal Reproduction Science*, *63*(1), 77-88.
520 doi:[https://doi.org/10.1016/S0378-4320\(00\)00147-0](https://doi.org/10.1016/S0378-4320(00)00147-0)

521 Mattar, D., Samir, M., Laird, M., & Knight, P. G. (2020). Modulatory effects of TGF- β 1
522 and BMP6 on thecal angiogenesis and steroidogenesis in the bovine ovary.
523 *Reproduction*, *159*(4), 397-408. doi:10.1530/REP-19-0311

524 Mazerbourg, S., & Hsueh, A. J. (2006). Genomic analyses facilitate identification of
525 receptors and signalling pathways for growth differentiation factor 9 and
526 related orphan bone morphogenetic protein/growth differentiation factor
527 ligands. *Human Reproduction Update*, *12*(1355-4786 (Print)), 373-383.
528 doi:es10.1093/humupd/dml014

529 McNatty, K. P., Juengel, J. L., Reader, K. L., Lun, S., Myllymaa, S., Lawrence, S.
530 B., . . . Laitinen, M. P. (2005). Bone morphogenetic protein 15 and growth

531 differentiation factor 9 co-operate to regulate granulosa cell function in
532 ruminants. *Reproduction*, 129(4), 481-487. doi:DOI: 10.1530/rep.1.00517

533 McNatty, K. P., Lun, S., Heath, D. A., Ball, K., Smith, P., Hudson, N. L., . . .
534 Henderson, K. M. (1986). Differences in ovarian activity between booroola X
535 merino ewes which were homozygous, heterozygous and non-carriers of a
536 major gene influencing their ovulation rate. *Journal of Reproduction and
537 Fertility*, 77(0022-4251 (Print)), 193-205. doi:DOI: 10.1530/jrf.0.0770193

538 McNatty, K. P., Smith, P., Hudson, N. L., Heath, D. A., Tisdall, D. J., O, W. S., &
539 Braw-Tal, R. (1995). Development of the sheep ovary during fetal and early
540 neonatal life and the effect of fecundity genes. *Journal of Reproduction and
541 Fertility. Supplement*, 49, 123-135.

542 Monniaux, D., Clemente, N. d., Touzé, J.-L., Belville, C., Rico, C., Bontoux, M., . . .
543 Fabre, S. (2008). Intrafollicular steroids and anti-Müllerian hormone during
544 normal and cystic ovarian follicular development in the cow. *Biology of
545 Reproduction*, 79(2), 387-396. doi:10.1095/biolreprod.107.065847

546 Mulsant, P., Lecerf, F., Fabre, S., Schibler, L., Monget, P., Lanneluc, I., . . . Elsen, J.-
547 M. (2001). Mutation in bone morphogenetic protein receptor-IB is associated
548 with increased ovulation rate in Booroola Mérino ewes. *Proceedings of the
549 National Academy of Sciences*, 98(9), 5104. doi: doi:
550 10.1073/pnas.091577598

551 Park, J. E. S., Shao, D., Upton, P. D., deSouza, P., Adcock, I. M., Davies, R. J., . . .
552 Wort, S. J. (2012). BMP-9 induced endothelial cell tubule formation and
553 inhibition of migration involves Smad1 driven endothelin-1 production. *PLoS
554 ONE*, 7(1), e30075. doi:10.1371/journal.pone.0030075

555 Portela, V. M., Dirandeh, E., Guerrero-Netro, H. M., Zamberlam, G., Barreta, M. H.,
556 Goetten, A. F., & Price, C. A. (2015). The role of fibroblast growth factor-18
557 in follicular atresia in cattle. *Biology of Reproduction*, 92(1), 14, 11-18.
558 doi:10.1095/biolreprod.114.121376

559 Portela, V. M., Machado, M., Buratini, J., Jr., Zamberlam, G., Amorim, R. L.,
560 Goncalves, P., & Price, C. A. (2010). Expression and function of fibroblast
561 growth factor 18 in the ovarian follicle in cattle. *Biology of Reproduction*,
562 83(3), 339-346. doi:10.1095/biolreprod.110.084277

563 Rafii, S., Butler, J. M., & Ding, B.-S. (2016). Angiocrine functions of organ-specific
564 endothelial cells. *Nature*, 529(7586), 316-325. doi:10.1038/nature17040

565 Reinhold, M. I., Abe, M., Kapadia, R. M., Liao, Z., & Naski, M. C. (2004). FGF18
566 Represses Noggin Expression and Is Induced by Calcineurin *Journal of
567 Biological Chemistry*, 279(37), 38209-38219. doi:10.1074/jbc.M404855200

568 Reynolds, L. P., & Redmer, D. A. (1998). Expression of the angiogenic factors, basic
569 fibroblast growth factor and vascular endothelial growth factor, in the ovary.
570 *Journal of Animal Science*, 76(6), 1671-1681. doi:10.2527/1998.7661671x

571 Richards, J. S., Ren, Y. A., Candelaria, N., Adams, J. E., & Rajkovic, A. (2017).
572 Ovarian Follicular Theca Cell Recruitment, Differentiation, and Impact on
573 Fertility: 2017 Update. *Endocrine Reviews*, 39(1), 1-20. doi:10.1210/er.2017-
574 00164

575 Rico, C., Médigue, C., Fabre, S., Jarrier, P., Bontoux, M., Clément, F., & Monniaux, D.
576 (2011). Regulation of anti-Müllerian hormone production in the cow: a
577 multiscale study at endocrine, ovarian, follicular, and granulosa cell levels.
578 *Biology of Reproduction*, 84(3), 560-571. doi:10.1095/biolreprod.110.088187

579 Robinson, R. S., Woad, K. J., Hammond, A. J., Laird, M., Hunter, M. G., & Mann, G. E.
580 (2009). Angiogenesis and vascular function in the ovary. *Reproduction*,
581 138(6), 869-881. doi:10.1530/REP-09-0283

- 582 Sheena, L. P. R., James, R. M., Tim, O. S., Nicholas, A., Frank, A., Arun, D., &
583 Ghanim, A. (2015). Flow cytometric analysis of FSHR, BMRR1B, LHR and
584 apoptosis in granulosa cells and ovulation rate in merino sheep. *Reproduction*,
585 *150*(2), 151-163. doi:10.1530/REP-14-0581
- 586 Shimizu, T., Kayamori, T., Murayama, C., & Miyamoto, A. (2012). Bone
587 morphogenetic protein (BMP)-4 and BMP-7 suppress granulosa cell apoptosis
588 via different pathways: BMP-4 via PI3K/PDK-1/Akt and BMP-7 via PI3K/PDK-
589 1/PKC. *Biochemical and Biophysical Research Communications*, *417*(2), 869-
590 873. doi:<https://doi.org/10.1016/j.bbrc.2011.12.064>
- 591 Sorescu, G. P., Sykes, M., Weiss, D., Platt, M. O., Saha, A., Hwang, J., . . . Jo, H.
592 (2003). Bone Morphogenic Protein 4 Produced in Endothelial Cells by
593 Oscillatory Shear Stress Stimulates an Inflammatory Response *Journal of*
594 *Biological Chemistry*, *278*(33), 31128-31135. doi:10.1074/jbc.M300703200
- 595 Souza, C. J. H., & Baird, D. T. (2004). The Booroola (FecB) mutation is associated
596 with smaller adrenal glands in young adult ewes. *Reproductive BioMedicine*
597 *Online*, *8*(4), 414-418. doi:[https://doi.org/10.1016/S1472-6483\(10\)60925-X](https://doi.org/10.1016/S1472-6483(10)60925-X)
- 598 Spanel-Borowski, K., Ricken, A. M., Saxer, M., & Huber, P. R. (1994). Long-term co-
599 culture of bovine granulosa cells with microvascular endothelial cells: effect
600 on cell growth and cell death. *Molecular and Cellular Endocrinology*, *104*(1),
601 11-19. doi:[https://doi.org/10.1016/0303-7207\(94\)90046-9](https://doi.org/10.1016/0303-7207(94)90046-9)
- 602 Star, G. P., Giovinazzo, M., & Langleben, D. (2009). Effects of bone morphogenic
603 proteins and transforming growth factor-beta on In-vitro production of
604 endothelin-1 by human pulmonary microvascular endothelial cells. *Vascular*
605 *Pharmacology*, *50*(1), 45-50. doi:<https://doi.org/10.1016/j.vph.2008.09.001>
- 606 Star, G. P., Giovinazzo, M., & Langleben, D. (2010). Bone morphogenic protein-9
607 stimulates endothelin-1 release from human pulmonary microvascular
608 endothelial cells: A potential mechanism for elevated ET-1 levels in pulmonary
609 arterial hypertension. *Microvascular Research*, *80*(3), 349-354.
610 doi:<https://doi.org/10.1016/j.mvr.2010.05.010>
- 611 Webb, R., Buratini, J., Hernandez-Medrano, J. H., Gutierrez, C. G., & Campbell, B. K.
612 (2016). Follicle development and selection: past, present and future. *Animal*
613 *Reproduction*, *13*(3), 234-249. doi:
- 614 <http://dx.doi.org/10.21451/1984-3143-AR883>
- 615 Wilson, T., Wu, X.-Y., Juengel, J. L., Ross, I. K., Lumsden, J. M., Lord, E. A., . . .
616 Montgomery, G. W. (2001). Highly Prolific Booroola Sheep Have a Mutation in
617 the Intracellular Kinase Domain of Bone Morphogenetic Protein IB Receptor
618 (ALK-6) That Is Expressed in Both Oocytes and Granulosa Cells. *Biology of*
619 *Reproduction*, *64*(4), 1225-1235. doi:10.1095/biolreprod64.4.1225
- 620 Woad, K. J., Hammond, A. J., Hunter, M., Mann, G. E., Hunter, M. G., & Robinson, R.
621 S. (2009). FGF2 is crucial for the development of bovine luteal endothelial
622 networks in vitro. *Reproduction*, *138*(3), 581-588. doi:10.1530/rep-09-0030
- 623 Wu, X., Ma, J., Han, J.-D., Wang, N., & Chen, Y.-G. (2006). Distinct regulation of
624 gene expression in human endothelial cells by TGF- β and its receptors.
625 *Microvascular Research*, *71*(1), 12-19.
626 doi:<https://doi.org/10.1016/j.mvr.2005.11.004>

627

628

629 **Figure legends**

630 Fig 1. Localization of FGF18 mRNA and protein in the ovary. **A**, cells of the theca
631 layer were dispersed and endothelial cell enriched (Enr) and depleted (Depl) fractions
632 were obtained with anti-CD29 coated beads. Enrichment was assessed by qPCR for
633 the endothelial marker Factor VIII (F8) and the steroidogenic marker LH receptor
634 (LHCGR). Data are means \pm SEM of 7 replicates, and asterisks identify means that
635 are significantly different (Student's t test). **B**, immunohistochemistry for FGF18
636 demonstrated staining in small blood vessels around follicles (left panel, arrows) but
637 not in oocytes (o) or granulosa (gc) cells, and in larger vessels in the medulla (right
638 panel). Inset shows a negative control without primary antibody. **C**,
639 immunohistofluorescence for VWF and FGF18 in the endothelium of venules in the
640 ovarian medulla and in the theca layer ; nuclei are stained with DAPI, and specific
641 antigens are stained red.

642

643 Fig 2. TGFB1 and BMP4 stimulate *FGF18* mRNA levels in a dose-dependent
644 manner. Bovine thecal endothelial cells were cultured with the given doses of human
645 recombinant TGFB1 or BMP4 for 24 h and mRNA extracted for qPCR analysis of
646 *FGF18* and *EDNI* mRNA levels. Data are means \pm SEM of 4 (TGFB1) and 5
647 (BMP4) replicates. Bars with different letters are significantly different (Tukey-
648 Kramer HSD test); asterisk, orthogonal contrast showed a significant difference
649 between control and cells treated with 1, 10 and 100 ng/ml TGFB1.

650

651 Fig 3. Effect of different TGFB family ligands on FGF18 expression and signaling
652 pathways in thecal endothelial cells. Cells were cultured with 50 ng/ml of human
653 recombinant BMP4, BMP5, BMP15, AMH or GDF9 alone, or a combination of
654 BMP15 and AMH (B15+A) or BMP15 and GDF9 (B15+G9). Cells were recovered

655 after 24 h for mRNA extraction (panels A, D), after 48 h to measure FGF18 protein
656 by immunocytochemistry (B) or after 30 min for assay of SMAD1/5/8
657 phosphorylation (C). Inset in B shows staining in representative control and BMP4-
658 treated cells. Inset in C shows representative immunoblots of one replicate culture.
659 Data are means \pm SEM of 5 replicates, and asterisks identify means that are
660 significantly different from control (Dunnett's test).

661

662 Fig 4. The SMAD signaling pathway is essential for BMP4 regulation of *FGF18*
663 mRNA abundance in thecal endothelial cells. Cells were transfected with siRNA
664 targeting SMAD4 or scrambled siRNA, and then treated with BMP4 (50 ng/ml; grey
665 bars, B4), GDF9 (50 ng/ml; black bars, G9) or medium controls (hollow bars) for 24
666 h. Data are means \pm SEM of 5 replicates. Asterisks identify significant effects of
667 siRNA within ligand treatment, or effect of ligand compared to control (Dunnett's
668 test).

669

670 Fig 5. Abundance of FGF18 protein is lower in hyperprolific ewes carrying a
671 mutation in *BMPRI1B*. **A**, plasma FGF18 concentration in wild-type Lacaune ewes
672 (n=9) at times (h) after FGA sponge removal. **B**, immunohistochemistry showing
673 staining for FGF18 in ovarian blood vessels in non-carriers (*FecB^{+/+}*) and
674 homozygous carriers (*FecB^{B/B}*) of a mutation in *BMPRI1B*. **C**, quantification of
675 immunostaining in the blood vessel wall of 3 *FecB^{+/+}* and 3 *FecB^{B/B}* ewes. **D**,
676 measurement by ELISA of blood FGF18 concentrations 36h after FGA sponge
677 removal in carrier and non-carrier *FecB* ewes (n=14/genotype). Data are means \pm
678 SEM and asterisks identify means that are significantly different (Mann-Whitney).

679

Fig 1

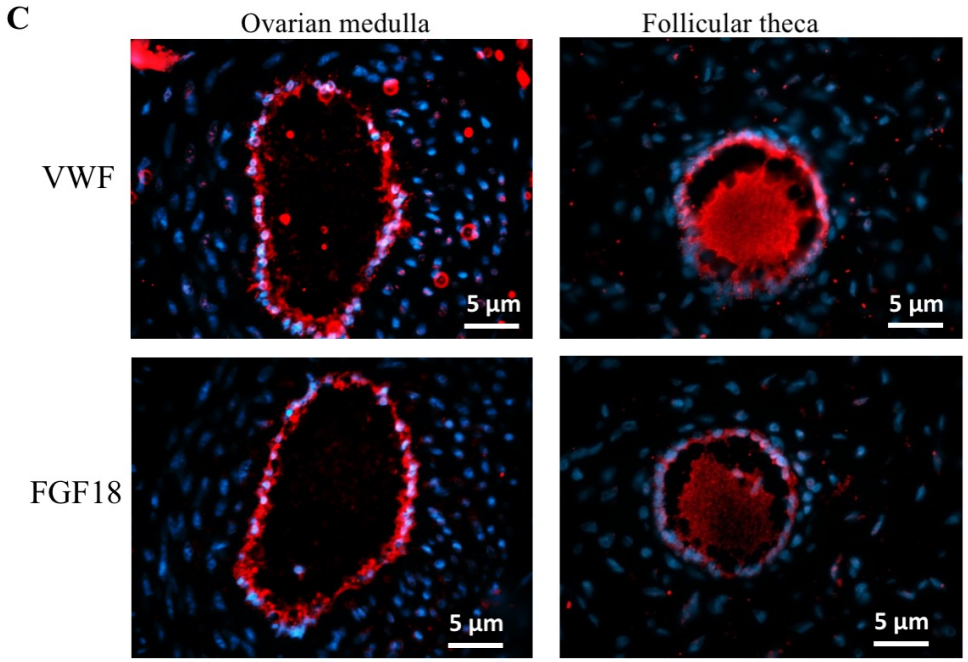
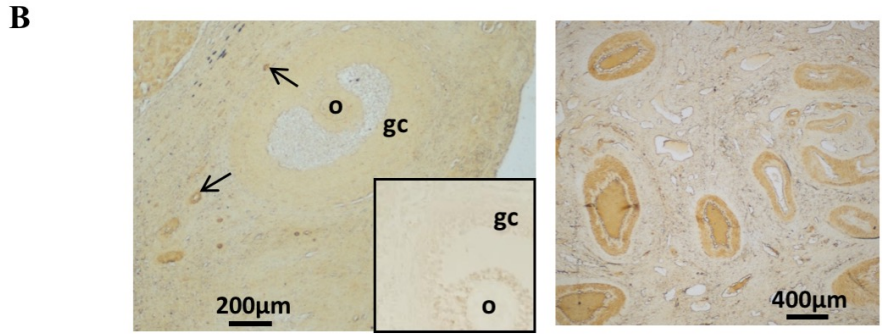
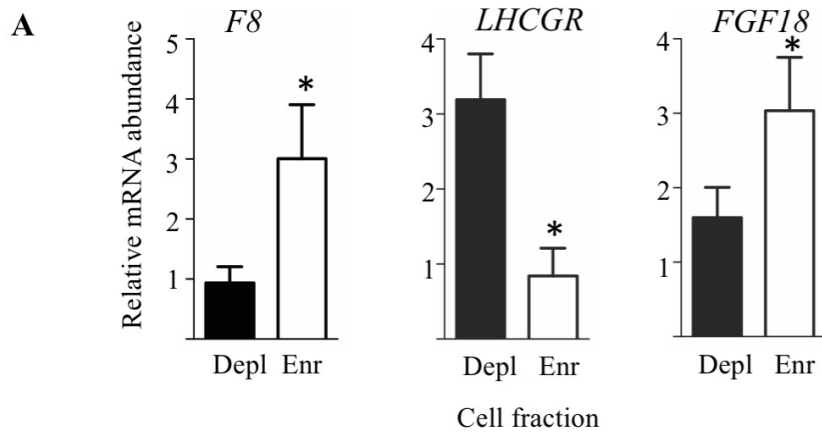


Fig 2

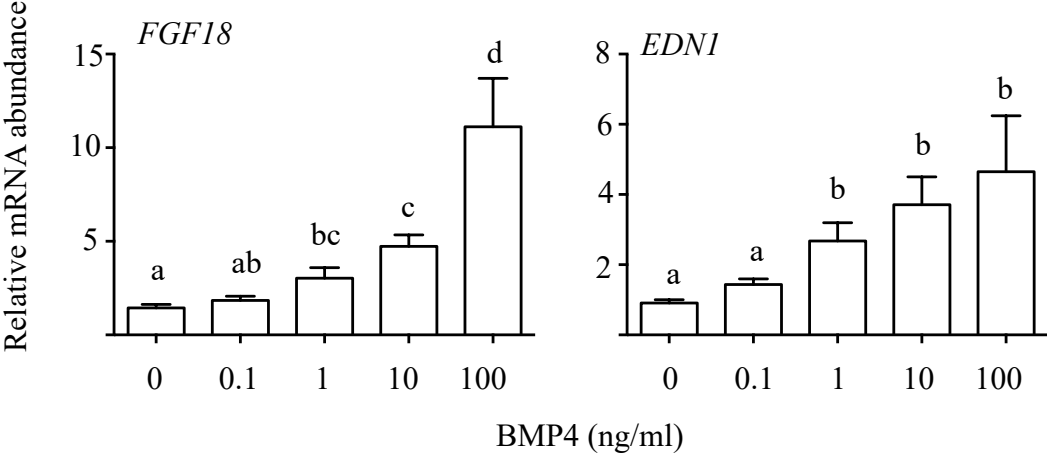


Fig 3

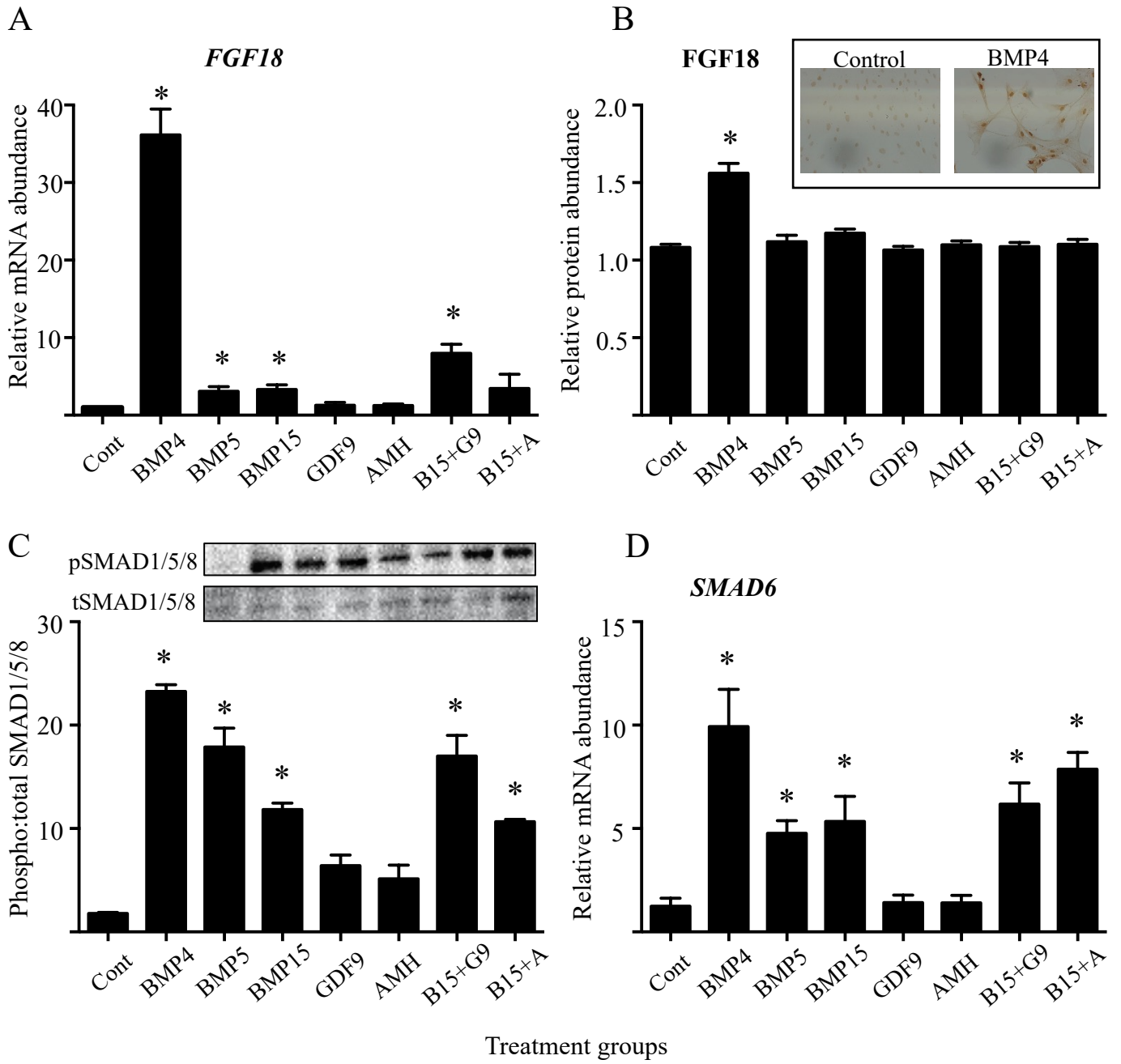


Fig 4

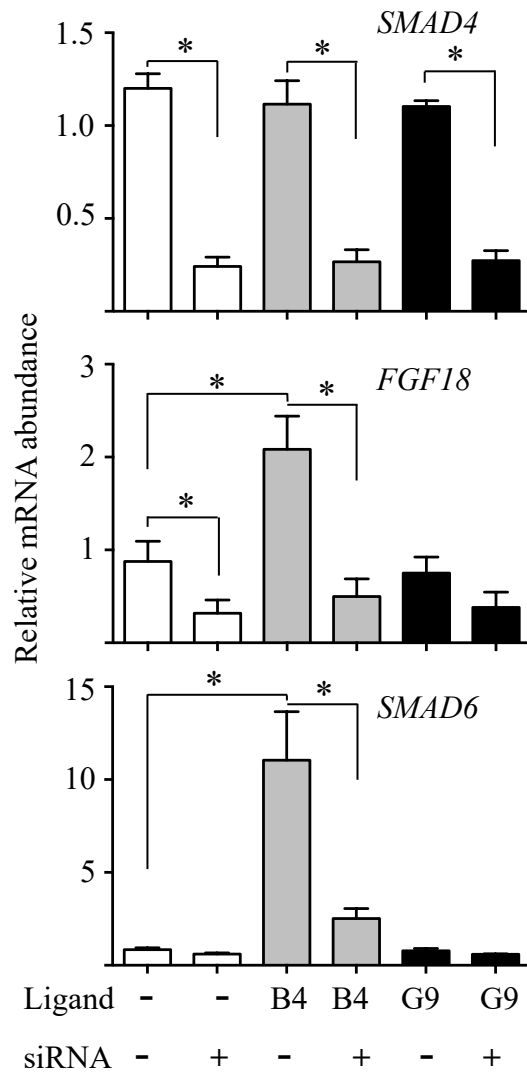
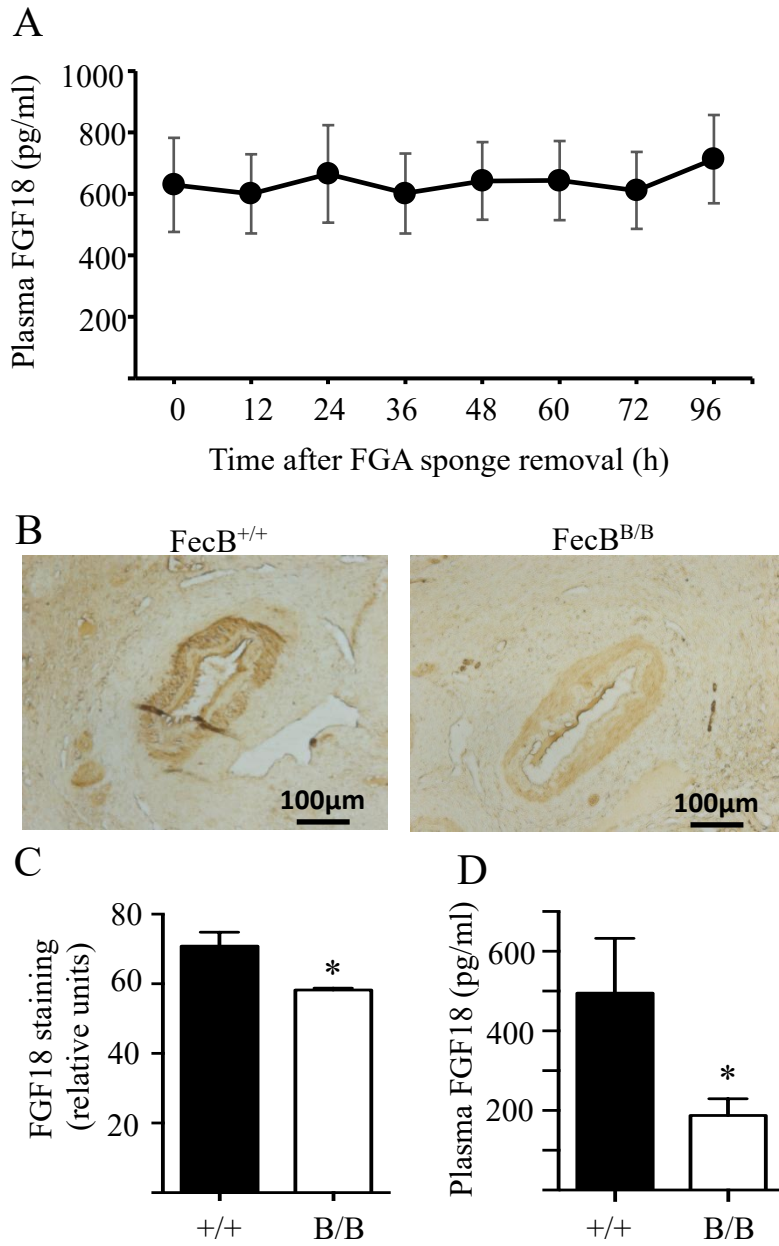


Fig 5



Gene	Primer forward	Primer reverse	Amplicon lenght	Efficiency
Factor 8	AAGAGGATGACTGGGACTAT	AAGTCTGTATCTGAACCACG	78	2,02
LHCGR	GGAGACCAAATAATGAAACAC TT	GATTATGACTATGGTTTCTGCTC	85	2,01
FGF18	CCTTCGGTAGTCAAGTCC	GTGTTCAATTGAGAAGGTTCTG	128	2,05
EDN1				
SMAD4	TGTCGACGGATATGTAGACCC	GGTCAGGTGCCTTAGTGACC	167	2,11
SMAD6	TCTGATTCCACATTGTCTTA	TTCTACGACCTACCTCAG	207	2,13
YWHAZ	ACCAACACATCCTATCAGAC	GCTAATAATGCAGTTACTGAGA G	185	2,04
SDHA	GAATGGTCTGGAACACTGA	GGTTGACGAGTACGATTACT	156	2,1
RPL19	TATGGGTATAGGTAAGCGAAA G	CTAAGAAGATTGACCGCCA	129	2,15