

Myostatin is expressed in bovine ovarian follicles and modulates granulosa and thecal steroidogenesis

Article

Accepted Version

Cheewasopit, W., Laird, M., Glistler, C. and Knight, P. G. (2018) Myostatin is expressed in bovine ovarian follicles and modulates granulosa and thecal steroidogenesis. *Reproduction*, 156 (4). pp. 375-386. ISSN 1741-7899 doi: <https://doi.org/10.1530/REP-18-0114> Available at <https://centaur.reading.ac.uk/79544/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1530/REP-18-0114>

Publisher: Society for Reproduction and Fertility

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

Central Archive at the University of Reading

Reading's research outputs online

1 **Myostatin is expressed in bovine ovarian follicles and**
2 **modulates granulosa and thecal steroidogenesis**

3 Warakorn Cheewasopit^{1,2}, Mhairi Laird¹, Claire Glister¹ and Phil G Knight¹

4 ¹*School of Biological Sciences, Hopkins Building, University of Reading, Whiteknights,*
5 *Reading RG6 6UB, UK*

6 ²*WC is now at Department of Biology, Ramkhamhaeng University, Bangkok, Bangkok,*
7 *Thailand*

8

9 *Correspondence: Phil G Knight, School of Biological Sciences, Hopkins Building,*
10 *University of Reading, Whiteknights, Reading RG6 6UB, UK*

11 *Email: p.g.knight@reading.ac.uk*

12

13

14 *Short title: myostatin and ovarian steroidogenesis*

15 *Keywords: GDF8, estrogen, androgen, ovary, cow*

16 Abstract

17 Myostatin plays a negative role in skeletal muscle growth regulation but its potential
18 role in the ovary has received little attention. Here, we first examined relative
19 expression of myostatin (MSTN), myostatin receptors (ACVR1B, ACVR2B and
20 TGFBR1) and binding protein, follistatin (FST), in granulosa (GC) and theca (TC) cells
21 of developing bovine follicles. Secondly, using primary GC and TC cultures, we
22 investigated whether myostatin affects steroidogenesis and cell number. Thirdly, effects
23 of gonadotropins and other intrafollicular factors on MSTN expression in GC and TC
24 were examined. MSTN, ACVR1B, TGFBR1, ACVR2B and FST mRNA was detected
25 in both GC and TC at all follicle stages. Immunohistochemistry confirmed follicular
26 expression of myostatin protein. Interestingly, MSTN mRNA expression was lowest in
27 GC of large estrogen-active follicles while GC FST expression was maximal at this
28 stage. In GC, myostatin increased basal CYP19A1 expression and estradiol secretion
29 whilst decreasing basal and FSH-induced HSD3B1 expression and progesterone
30 secretion and increasing cell number. Myostatin also reduced IGF-induced progesterone
31 secretion. FSH and dihydrotestosterone had no effect on granulosa MSTN expression
32 whilst insulin-like growth factor and tumour necrosis factor- α suppressed MSTN
33 level. In TC, myostatin suppressed basal and LH-stimulated androgen secretion in a
34 follistatin-reversible manner and increased cell number, without affecting progesterone
35 secretion. LH reduced thecal MSTN expression whilst BMP6 had no effect.
36 Collectively, results indicate that, in addition to being potentially responsive to muscle-
37 derived myostatin from the circulation, myostatin may have an intra-ovarian
38 autocrine/paracrine role to modulate thecal and granulosa steroidogenesis and cell
39 proliferation/survival.

40 **Introduction**

41 Ovarian follicle development is dependent on the actions and interactions of systemic
42 and intra-ovarian regulatory signals. Whilst pituitary gonadotrophins (FSH, LH) are the
43 key endocrine signals driving follicle development, a complex array of locally-produced
44 growth factors also contribute to the modulation of follicular somatic cell proliferation
45 and differentiation, 'initial' and 'cyclic' follicle recruitment, steroidogenesis, dominant
46 follicle selection and ovulation (Campbell *et al.* 2003, Webb *et al.* 2003). Prominent
47 amongst these are various members of the transforming growth factor- β (TGF- β)
48 superfamily including growth and differentiation factor-9 (GDF9), anti-mullerian
49 hormone (AMH), inhibins, activins and several bone morphogenetic proteins (BMP)
50 including BMP2, BMP4, BMP6 and BMP7 (Shimasaki *et al.* 2004, Knight & Glister
51 2006). In the present study we examined the potential involvement of another TGF- β
52 superfamily member, myostatin (also known as GDF8) in regulating ovarian follicle
53 function.

54 Myostatin is well-recognised for its negative autocrine/paracrine role in skeletal muscle
55 development (Otto & Patel 2010, Schiaffino *et al.* 2013). Myostatin-null mice show a
56 pronounced increase in muscle mass due to muscle fibre hyperplasia and hypertrophy
57 (McPherron *et al.* 1997). Naturally occurring inactivating mutations in the myostatin
58 gene are also evident in several species including bovine (Kambadur *et al.* 1997), ovine
59 (Clop *et al.* 2006), canine (Mosher *et al.* 2007) and human (Schuelke *et al.* 2004) and
60 these also display a phenotype of substantially increased muscle mass. Conversely,
61 upregulation of myostatin is associated with pathological conditions characterised by
62 muscle wasting, notably sarcopenia and cachexia arising from late-stage cancer, chronic
63 kidney failure and congestive heart failure (Elkina *et al.* 2011, Elliott *et al.* 2012).

64 Apart from skeletal muscle, myostatin has also been implicated in the regulation of
65 cardiomyocyte and adipocyte function (review: (Elliott *et al.* 2012)), Moreover,
66 investigations into the expression and potential functional role(s) of myostatin in
67 reproductive organs including the human ovary have recently been reported (Chang *et*
68 *al.* 2015, Fang *et al.* 2015, Chang *et al.* 2016a, Chang *et al.* 2016b).

69 Myostatin signals through the activin receptor type 2B (ACTR2B), forming a signalling
70 complex with ACVR1B (ALK4) and/or TGFBR1(ALK5) that activates an intracellular
71 Smad 2/3-dependent signal transduction pathway. Myostatin receptor activation can
72 also signal in a Smad-independent manner via activation of MAPK and inhibition of
73 Akt pathways (Rebbapragada *et al.* 2003). Binding of myostatin to its signalling
74 receptors is modulated by follistatin (Amthor *et al.* 2004). Follistatin was initially
75 identified as a secreted activin-binding protein but has since been shown to bind several
76 other TGF- β ligands including BMP-2,-4,-6 and -7 (Fainsod *et al.* 1997, Iemura *et al.*
77 1998, Glister *et al.* 2004). Follistatin-null mice show decreased muscle mass (Matzuk *et*
78 *al.* 1995) likely arising from diminished antagonism of myostatin signalling. Conversely,
79 transgenic overexpression of follistatin promotes a hypermuscular phenotype
80 resembling that of myostatin-null mice (Lee & McPherron 2001).

81 Global microarray studies of the bovine ovary revealed that myostatin mRNA is
82 expressed in follicular granulosa (Skinner *et al.* 2008, Glister *et al.* 2014, Hatzirodos *et*
83 *al.* 2014b) and theca cells (Glister *et al.* 2013, Hatzirodos *et al.* 2014a) although studies
84 to confirm expression and explore the potential functional role(s) of myostatin in the
85 bovine ovary have not been reported. Myostatin mRNA expression has also been
86 documented in human reproductive tissues including ovary (Chang *et al.* 2015),
87 myometrium (Islam *et al.* 2014) and trophoblast (Peiris *et al.* 2014) and recent evidence

88 from studies on luteinized granulosa cells supports various functional roles. For instance,
89 treatment of human granulosa-lutein cells with myostatin down-regulated expression of
90 steroidogenic acute regulatory protein (STAR) and reduced progesterone secretion,
91 whilst increasing cytochrome P450 aromatase (CYP19A1) expression, FSHR
92 expression and estradiol secretion (Chang *et al.* 2015, Fang *et al.* 2015, Chang *et al.*
93 2016a). An anti-proliferative effect of myostatin on human granulosa-lutein cells was
94 also reported (Chang *et al.* 2016b). To our knowledge, there have been no reports on
95 effects of myostatin on non-luteinized granulosa cells, nor on theca cells from any
96 species.

97 Given the paucity of information on the ovarian expression and possible intraovarian
98 role(s) of myostatin, particularly in relation to actions on non-luteinized follicular cells,
99 the aims of the present study were to: (1) examine mRNA expression profiles for
100 myostatin, its signalling receptors and binding protein (follistatin; FST) in granulosa
101 (GC) and theca (TC) cells across different stages of bovine antral follicle development;
102 (2) use non-luteinized bovine GC and TC culture models to investigate whether
103 myostatin affects steroid production; (3) determine whether the effect of myostatin can
104 be attenuated by follistatin; (4) investigate whether thecal and granulosal expression of
105 myostatin mRNA is modulated by gonadotropins and several intrafollicular factors
106 implicated in the regulation of follicular steroidogenesis.

107

108 **Materials and Methods**

109 *Relative expression of myostatin, follistatin and myostatin receptor mRNAs in* 110 *developing bovine antral follicles.*

111 Relative mRNA expression for myostatin (MSTN), myostatin receptors (ACVR2B,
112 ACVR1B and TGFBR1) and follistatin (FST) in theca and granulosa layers from
113 bovine antral follicles was determined using RT-qPCR. Ovaries from randomly cycling
114 cattle were obtained from an abattoir (Anglo Beef Processors, Guildford, UK) and
115 selected for follicle dissection as described previously (Glister et al 2001; 2004; 2010).
116 Briefly, antral follicles of diameter 3-18mm were dissected out and sorted by size into
117 small (3-6mm; n = 30), medium (7-10mm; n = 43) and large (11-18mm; n = 37)
118 categories. For each follicle GC and TC layers were retrieved for RNA extraction and
119 follicular fluid recovered for steroid hormone analysis. Follicles in the large (11-18mm)
120 category were subdivided retrospectively into large estrogen-active (LEA; E:P ratio >1)
121 and large estrogen-inactive (LEI; E:P ratio <1) categories according to their
122 intrafollicular ratio of estrogen to progesterone (E:P ratio). Isolated GC and TC were
123 homogenised in 0.5ml of Tri reagent (Sigma UK Ltd, Poole) and stored at -80⁰C for
124 subsequent RNA purification. The number of GC and TC RNA extracts recruited to the
125 study (n = 82 GC samples; n = 87 TC samples; see fig. 1 for n-values for individual
126 follicle categories) was lower than the number of extracts processed because samples
127 indicating >5% GC/TC cross contamination were rejected during an initial quality
128 control screen. This involved a RT-qPCR-based comparison of relative transcript
129 abundance of four GC/TC-specific 'marker' transcripts (FSHR and CYP19A1 for GC,
130 CYP17A1 and INSL3 for TC) each normalized to β -actin transcript abundance (data not
131 shown).

132 ***Primary granulosa and theca cell culture models***

133 Ovaries from randomly cycling cattle were collected from a local abattoir. As described
134 previously (Glister *et al.* 2001, Glister *et al.* 2005) GC and TC were isolated from 4-
135 6mm diameter follicles, plated out in either 96-well (75,000 cells/well; for steroid
136 secretion experiments) or 24-well (250,000 cells/well; for RNA extraction experiments)
137 plates and cultured for 7 days. To preserve a non-luteinized cellular phenotype
138 (Gutierrez *et al.* 1997, Campbell *et al.* 1998, Glister *et al.* 2001, Glister *et al.* 2005,
139 Sahmi *et al.* 2006) chemically-defined serum-free media was used throughout the
140 culture period. This consisted of McCoy's 5A modified medium supplemented with 1%
141 (v/v) antibiotic-antimycotic solution, 10 ng/ml bovine insulin, 2 mM L-glutamine, 10
142 mM Hepes, 5 µg/ml apotransferrin, 5 ng/ml sodium selenite, 0.1% BSA. In the case of
143 GC cultures, media was also supplemented with 10^{-7} M androstenedione as aromatase
144 substrate (all media and supplements were purchased from Sigma). Media were
145 replenished and treatments added on days 2 and 4 (see below). Cultures were terminated
146 on day 7 when conditioned media were retained for hormone assays and viable cell
147 number was determined by neutral red uptake assay as described elsewhere (Glister *et*
148 *al.* 2001)

149 ***Effects of myostatin on granulosal and thecal steroid secretion and viable cell***
150 ***number***

151 Recombinant human myostatin (R&D Systems; 94% amino acid sequence homology
152 with bovine myostatin) was added to wells to give final concentrations of 0.08, 0.4, 2,
153 10, 50 and 100ng/ml in the presence and absence of gonadotropin (FSH or LH). Highly
154 purified ovine FSH (oFSH 19SIAPP) and LH (oLH-S-16) were provided by the NHPP
155 (Torrance, CA, USA). In GC cultures, FSH was used at a final concentration of 0.3

156 ng/ml, shown previously to elicit optimal estradiol secretion (Glister *et al.* 2001, Glister
157 *et al.* 2004). GC were also treated with myostatin (100ng/ml) in the presence and
158 absence of LR3 IGF-1 analogue (Sigma; 10 and 50 ng/ml) since IGF-1 is also a potent
159 stimulator of estradiol secretion (Gutierrez *et al.* 1997, Glister *et al.* 2001). In the case
160 of TC cultures, LH was used at a final concentration of 150 pg/ml, shown previously to
161 elicit maximal androstenedione secretion (Glister *et al.* 2005). Control wells received an
162 equivalent volume of culture medium as vehicle.

163

164 ***Can follistatin neutralize the effect of myostatin on thecal androstenedione secretion?***

165 To examine whether follistatin can neutralize the suppressive effects of myostatin on
166 thecal androgen secretion, TC were treated with myostatin (100ng/ml) in the
167 presence/absence of recombinant human follistatin-288 (R&D systems; 96% amino acid
168 sequence homology with bovine follistatin) at 0.25 and 1.25µg/ml. These
169 concentrations were shown previously to reverse the effects of 50 ng/ml activin and
170 BMP6 on bovine GC (Glister *et al.* 2004).

171

172 ***Effect of myostatin on granulosa expression of steroidogenic pathway components***

173 To evaluate the effects of myostatin on expression of key transcripts involved in
174 steroidogenesis (CYP11A1, HSD3B1, CYP19A1, FSHR) GC were cultured in 24-well
175 plates (250,000 cells/well) and exposed to fixed concentrations of myostatin (100
176 ng/ml) in the presence and absence of an optimal concentration of FSH (300 pg/ml). At
177 the end of culture, media were removed and cell lysates were prepared for total RNA
178 extraction and RT-qPCR analysis.

179

180 ***Do gonadotropins and other factors modulate MSTN expression by cultured GC and***
181 ***TC?***

182 GC (n> 4 independent batches of cells) plated out in 24-well plates were cultured in the
183 presence/absence of FSH (300 pg/ml) and several other intrafollicular factors shown
184 previously to modulate steroidogenesis at the concentrations used here, including LR3
185 IGF-1 analogue at 10 ng/ml (Glister *et al.* 2001), TNF α at 10 ng/ml (Glister *et al.* 2014)
186 and DHT at 100nM (Wu *et al.* 2011, Hasegawa *et al.* 2017). RNA was harvested at the
187 end of culture for evaluation of relative gene expression by RT-qPCR. TC (n=9
188 independent batches of cells) plated out in 96-well plates were treated with LH (150
189 pg/ml) in the presence/absence of BMP6 (10 ng/ml) shown previously to suppress
190 thecal androgen production (Glister *et al.* 2005, Glister *et al.* 2013).

191

192 ***RNA isolation, cDNA synthesis and real-time PCR***

193 Total RNA was isolated using Tri-reagent as described previously (Glister *et al.* 2010).
194 cDNA was synthesized from 1 μ g of RNA using the AB High Capacity cDNA synthesis
195 kit (Thermo Fisher Scientific; used according to manufacturers protocol) in a 20 μ l
196 reaction primed with random hexamers. PCR primers (see table 1) were designed using
197 Primer-BLAST' (<http://www.ncbi.nlm.nih.gov/tools/primer-blast>) with BLAST
198 specificity checking against all known bovine (*Bos taurus*) transcripts to exclude
199 potential amplification of off-target sequences. Primer pairs were also validated using
200 agarose gel electrophoresis to demonstrate amplification of a single product of the
201 predicted size. Melt curve analyses was included in each PCR assay to confirm the

202 amplification of a single product in each sample. cDNA template log-dilution curves
203 were used to demonstrate satisfactory PCR efficiency and linearity. PCR assays were
204 carried out in a volume of 14 μ l containing 5 μ l cDNA template, 1 μ l each forward and
205 reverse primers (final concentration 0.36 μ M) and 7 μ l QuantiTect SYBR Green QPCR
206 2x Master Mix (Qiagen, Crawley, W. Sussex, UK). Samples were processed on a
207 StepOne Plus thermal cycler (Applied Biosystems) with cycling conditions: 15min at
208 95°C (one cycle only) followed by 15s at 95°C and 1min at 60°C for 40 cycles. The
209 $\Delta\Delta$ Ct method (Livak & Schmittgen 2001) was used to compare the relative abundance
210 of each mRNA transcript. Ct values for each transcript in a given sample were first
211 normalized to the corresponding β -actin Ct value (i.e. Δ Ct value). In the case of theca
212 and granulosa tissue samples Δ Ct values for each transcript in a given sample were then
213 normalized to the mean Δ Ct value for that transcript in all tissue samples. Resultant
214 $\Delta\Delta$ Ct values were converted to fold-differences using the formula: fold-difference = $2^{-\Delta\Delta\text{Ct}}$
215 $\Delta\Delta\text{Ct}$). In the case of cell culture experiments Δ Ct values were normalized to the
216 corresponding Δ Ct value for vehicle-treated control cells. $\Delta\Delta$ Ct values were then
217 converted to fold-differences using the formula: fold-difference = $2^{-\Delta\Delta\text{Ct}}$.

218

219 ***Steroid hormone assays***

220 Steroid concentrations were determined by competitive ELISA as described previously
221 (Glister *et al.* 2010, Glister *et al.* 2013, Glister *et al.* 2014). The progesterone assay had
222 a detection limit of 20pg/ml and intra- and inter-assay CVs were 8% and 10%
223 respectively. The androstenedione ELISA had a detection limit of 30 pg/ml and intra-
224 and inter-assay CVs were 7% and 10% respectively. The estradiol ELISA had a
225 detection limit of 15 pg/ml and intra- and inter-assay CVs were 6% and 9% respectively.

226

227 ***Immunohistochemistry***

228 Bovine ovaries were dissected into segments and fixed in formalin for 48 hours, before
229 being dehydrated through an alcohol series, embedded in wax and sectioned (5µm) onto
230 Superfrost charged slides (VWR, Lutterworth, UK). Sections were dewaxed and
231 rehydrated prior to boiling in citrate buffer (10mM citric acid, pH6.0), blocking of
232 endogenous peroxidase (3% H₂O₂ in methanol) and blocking of nonspecific binding
233 with 20% normal goat serum (NGS, Vector Laboratories Ltd, Peterborough, UK). After
234 this, sections were incubated overnight at 4°C in rabbit antibody against GDF8 (1:200;
235 sc-28910, Santa Cruz) diluted in 2% NGS. Control sections were incubated with normal
236 rabbit serum (1:200) diluted in 2% NGS. Primary antibody binding was detected using
237 biotinylated goat anti-rabbit diluted 1:250 in 2% NGS and Vector Elite ABC reagents
238 (Vector), prepared as per manufacturers instructions. Visualization of bound antibodies
239 was achieved using 3,3'-diaminobenzidine tetrahydrochloride (DAB; Vector), prior to
240 slides being counterstained with haematoxylin, dehydrated through an alcohol series
241 and mounted with coverslips using DPX mounting medium. Sections were imaged
242 using a Zeiss Axioscop 2 microscope and AxioCam digital camera.

243

244 ***Statistical analysis***

245 Steroid concentrations were log-transformed prior to statistical analysis to reduce
246 heterogeneity of variance. RT-qPCR data were analysed as $\Delta\Delta C_t$ values (i.e. log₂
247 values) before conversion to fold-difference values for graphical presentation of relative
248 transcript abundance. ACTB was used as the normalization control and showed uniform

249 expression level across experimental groups being compared. Results were evaluated
250 using one- and/or two-way ANOVA and, where indicated, post-hoc pairwise
251 comparisons were made using Fisher's protected least significant difference (PLSD) test.
252 Results of cell culture experiments are based on a minimum of three replicate
253 experiments using independent batches of cells (see figure legends for numbers of
254 replicates)

255

256 **Results**

257

258 *Relative expression of myostatin, follistatin and myostatin receptors in theca and* 259 *granulosa layers*

260 *Myostatin*

261 MSTN mRNA expression was found in both TC and GC of all antral follicles examined
262 and overall expression level was higher in TC than GC (Figure 1A). Interestingly, while
263 MSTN expression level in TC was uniform across antral follicle development,
264 expression in GC fell ~15-fold to a nadir in large estrogen active (LEA) follicles.
265 However, a higher expression level was maintained in GC of large estrogen inactive
266 (LEI) follicle. (Fig. 1A). Immunohistochemistry confirmed myostatin protein
267 expression in both TC and GC of antral follicles (Fig. 2). In addition myostatin
268 immunoreactivity was evident in preantral follicles and in vascular smooth muscle cells.
269 Both oocytes and granulosa cells of primordial, primary and secondary follicles
270 exhibited positive immunostaining for myostatin (Fig 2)

271 ***Follistatin***

272 FST mRNA expression was found in both TC and GC at all stages of follicle
273 development examined with much higher expression levels in GC than TC (Fig. 1B).
274 Interestingly, the expression of FST in GC sharply increased in LEA follicles but
275 remained low in LEI follicles; this was opposite to what was observed for MSTN.

276 ***Myostatin receptors (ACVR2B, ACVR1B and TGFBR1)***

277 ACVR1B, TGFBR1 and ACVR2B mRNA expression was found in both TC and GC at
278 all stages of follicle development examined. The expression of ACVR2B and ACVR1B
279 was generally higher in GC than TC while TGFBR1 expression levels were broadly
280 similar in the two cell types. No notable changes in cell-specific patterns of expression
281 of these receptors between each stages of follicle development were evident (Fig.
282 1C,D,E respectively).

283

284 ***Effect of myostatin on basal and FSH-induced steroid secretion by GC***

285 Myostatin promoted a marked increase in basal estradiol secretion by cultured GC (~12-
286 fold; $P < 0.0001$; Fig. 3A) but did not modulate the >30-fold increase in estradiol
287 secretion elicited by FSH. Myostatin suppressed both basal ($P < 0.01$) and FSH-induced
288 ($P < 0.001$) progesterone secretion (Fig. 3B). In addition, myostatin promoted a modest
289 though significant increase in cell number under basal conditions (~20% increase;
290 $P < 0.001$), but not under FSH-stimulated conditions (Fig. 3C).

291

292 ***Effects of myostatin on GC expression of steroidogenesis-related transcripts***

293 The stimulatory action of myostatin on basal estradiol secretion was accompanied by a
294 ~10-fold increase in CYP19A1 expression level ($P < 0.05$; Fig. 3D). Concomitantly, a
295 reduction in CYP11A1 and HSD3B1 expression level was observed ($P < 0.05$; Fig. 3EF)
296 that mirrored the myostatin-induced decrease in progesterone secretion. Myostatin did
297 not affect FSHR expression (data not shown).

298

299 ***Effect of myostatin on basal and IGF1-induced secretion of estradiol and***
300 ***progesterone by GC***

301 Fig.4 confirms the stimulatory effect of myostatin treatment (100 ng/ml) on basal
302 estradiol secretion by GC. However, myostatin did not modulate the stimulatory effect
303 of the LR3-IGF1 analogue on estradiol secretion or viable cell number. Myostatin
304 reduced both basal and IGF-induced progesterone secretion ($P < 0.05$) but did not modify
305 the IGF-induced increase in viable cell number.

306

307 ***Effects of FSH, LR3 IGF-1, TNF α and DHT on expression of MSTN mRNA by***
308 ***cultured GC***

309 Fig. 5 shows that treatment of cultured GC with FSH elicited a ~50-fold upregulation of
310 CYP19A1 expression ($p < 0.05$) and estradiol secretion but did not affect MSTN
311 expression. Treatment with IGF-1 analogue also promoted a marked increase in
312 CYP19A1 expression (~10-fold; $P < 0.05$) and estradiol secretion that was accompanied
313 by a 60% reduction in MSTN expression ($P < 0.05$). Treatment with TNF α had no effect
314 on basal CYP19A1 expression but abolished FSH-induced upregulation of CYP19A1

315 expression and estradiol secretion. TNF α suppressed MSTN expression by ~80%
316 (P<0.05) under both basal and FSH-stimulated conditions. Treatment with DHT did not
317 affect expression of either MSTN or CYP19A1.

318 ***Effects of myostatin on thecal steroid secretion and viable cell number***

319 Myostatin suppressed androstenedione secretion in a dose-dependent manner (P<0.001)
320 with an IC₅₀ of ~10 ng/ml under LH-stimulated conditions (Fig. 6A). No effect of
321 myostatin on progesterone secretion was observed (Fig. 6B). Viable cell number was
322 increased (~25%; P<0.0001) by myostatin under both basal and LH-stimulated
323 conditions (Fig. 6C). LH increased both androstenedione and progesterone secretion but
324 did not affect viable cell number.

325 ***Can follistatin neutralize the effect of myostatin on androstenedione secretion?***

326 Treatment of cells with myostatin alone decreased androstenedione secretion by ~80%
327 (P<0.000; Fig. 7). Co-treatment with follistatin partially reversed this inhibitory action
328 (P<0.001). Treatment with follistatin alone tended to increase androstenedione secretion
329 but the effect was not statistically significant.

330

331 ***Effects of LH and BMP6 on MSTN mRNA expression by cultured TC***

332 Fig. 8 shows that treatment of cultured TC with LH elicited a 4-fold increase in
333 CYP17A1 expression and androstenedione secretion that was accompanied by a 40%
334 suppression of MSTN expression (p<0.05). Treatment with BMP6 profoundly
335 suppressed basal and LH-induced CYP17A1 expression and androstenedione secretion.
336 Whilst BMP6 alone did not affect MSTN expression, it reversed the suppressive effect
337 of LH on MSTN expression.

338

339 **Discussion**

340

341 In this study, we first provide novel information on the spatio-temporal pattern of
342 mRNA expression of myostatin, its signalling receptors and the binding protein (FST),
343 at different stages of bovine antral follicles development. Expression of mRNA for
344 MSTN and its receptors was found in both GC and TC at all antral follicle stages
345 examined, consistent with and extending previous evidence from global microarray
346 studies (Skinner *et al.* 2008, Glister *et al.* 2013, Glister *et al.* 2014, Hatzirodos *et al.*
347 2014a, Hatzirodos *et al.* 2014b). Immunohistochemistry confirmed corresponding
348 expression of myostatin protein in follicular granulosa and theca interna layers of antral
349 follicles. Moreover, myostatin immunoreactivity was observed at earlier follicle stages
350 than those we analysed for mRNA expression, with positive staining in both oocytes
351 and GC of primordial, primary and secondary follicles and both GC and TC of late
352 preantral and early antral follicles. The inverse mRNA expression pattern of MSTN and
353 FST we observed in GC of large estrogen-active follicles is of interest since follistatin is
354 known to bind to and inhibit myostatin signaling (Lee & McPherron 2001, Amthor *et al.*
355 2004), a finding confirmed in this study by its ability to attenuate the effect of myostatin
356 on thecal androgen production. These results suggest, therefore, that GC-derived
357 myostatin and follistatin interact to regulate ovarian follicle physiology. In particular,
358 these observations suggest that autocrine/paracrine signalling by GC-derived myostatin
359 is attenuated in large healthy follicles (i.e. low myostatin/high follistatin), such as those
360 reaching the preovulatory stage of development. By contrast, at earlier antral follicle
361 stages (i.e. high myostatin/low follistatin), myostatin signalling via a Smad 2/3

362 dependent pathway may contribute to the suppression of thecal androgen production
363 whilst upregulating granulosa estradiol production and down-regulating progesterone
364 production. Thus, myostatin appears to act to prevent/delay premature follicle
365 maturation and luteinisation in a similar manner to that suggested previously for
366 activins and BMPs (Findlay *et al.* 2002, Knight & Glister 2006), both of which can
367 attenuate thecal androgen production, enhance granulosa estrogen output whilst
368 suppressing granulosa progesterone output.

369 The present results from experiments on non-luteinized ovarian cell models clearly
370 support the above with myostatin suppressing androgen secretion by theca cells. In the
371 case of granulosa cells, myostatin enhanced basal CYP19A1 expression and estradiol
372 secretion whilst suppressing CYP11A1 and HSD3B1 expression and secretion of
373 progesterone. In addition, treatment of human granulosa-lutein cells with myostatin was
374 recently reported to enhance FSH-induced upregulation of aromatase/estradiol
375 production, while inhibiting LH-induced upregulation of StAR/progesterone production
376 (Chang *et al.* 2016a). Moreover, the present study found that myostatin increased viable
377 cell number in both TC and GC cultures suggesting a positive effect on cell
378 proliferation and/or survival. This finding contrasts with a report that myostatin reduces
379 proliferation of human granulosa-lutein cells, evidently by upregulating connective
380 tissue growth factor expression (Chang *et al.* 2016b). The reason for this discrepancy is
381 not known but may reflect the effect of luteinisation, or a species difference.

382 An intrafollicular IGF system is firmly implicated in the autocrine/paracrine regulation
383 of follicle development, steroidogenesis and dominant follicle selection (Campbell *et al.*
384 1995, Glister *et al.* 2001, Silva & Price 2002, Webb *et al.* 2003). Like FSH, IGF-1 can
385 upregulate granulosa estradiol secretion; moreover, IGF-1 can augment follicular

386 responsiveness to FSH, providing a potential mechanism for selecting the dominant
387 follicle from the cyclically-recruited growing cohort (Campbell *et al.* 1995, Webb *et al.*
388 2003). It was therefore pertinent to investigate whether myostatin affected the GC
389 response to IGF-1 treatment. Although the results showed no effect on IGF-induced
390 estradiol production or cell number, myostatin increased basal estradiol production and
391 cell number whilst reducing basal and IGF-induced progesterone production. As such,
392 these observations further support the notion that myostatin has a role to delay
393 premature follicle maturation and luteinisation.

394 Whilst circulating or intrafollicular concentrations of myostatin in cattle have not been
395 reported to our knowledge, serum concentrations of 10-20 ng/ml in cynomolgus
396 monkey and human, ~24 ng/ml in rat and ~80 ng/ml in mouse have been documented
397 (Furihata *et al.* 2016, Hedayati *et al.* 2016, Palandra *et al.* 2016). A myostatin
398 concentration of ~3 ng/ml has been reported for human follicular fluid (Chen *et al.*
399 2012). Since myostatin suppressed thecal androgen production and granulosa
400 progesterone production in vitro with an IC50 value of ~10 ng/ml, it seems plausible
401 that levels reaching the well-vascularized theca interna from peripheral blood could be
402 sufficient to exert a regulatory action, regardless of the additional 'local' contribution
403 (perhaps considerable?) of TC and/or GC-derived myostatin. On the other hand, given
404 the greater diffusional barrier needed to reach the avascular granulosa layer, combined
405 with the somewhat higher myostatin concentration (~50 ng/ml) needed to upregulate
406 GC estradiol production, it is possible that GC are primarily responsive to locally
407 produced myostatin acting in an autocrine/paracrine manner. The establishment of a
408 bovine myostatin assay to allow comparison of endogenous concentrations in peripheral

409 blood and ovarian follicular fluid of cattle in different physiological states and in
410 follicles at different stages of development, would be useful in this regard.

411 As a first step towards investigating which endocrine and local paracrine and/or
412 autocrine signals regulate myostatin expression in bovine ovarian follicles, we found
413 that an LH-induced increase in thecal CYP17A1 expression and androstenedione
414 secretion was accompanied by reduced MSTN expression level, consistent with a
415 negative autocrine/paracrine action of myostatin on thecal androgen production, and
416 with in the findings of our myostatin dose-response study. Indeed, it is possible that the
417 stimulatory action of LH on thecal androgen production could be due, in part, to LH-
418 induced suppression of myostatin expression. The finding of a reduced MSTN mRNA
419 abundance in TC producing more androgen could reflect increased androgen receptor-
420 mediated signalling since raised androgen levels are also associated with decreased
421 MSTN expression in rat skeletal muscle tissue (Mendler *et al.* 2007). However, another
422 intraovarian growth factor, BMP6, shown here and elsewhere (Glister *et al.* 2005,
423 Glister *et al.* 2013) to greatly reduce thecal CYP17A1 expression and androstenedione
424 secretion, did not affect thecal MSTN expression, casting doubt on androgen having a
425 direct effect. Furthermore, treatment of cultured GC with the potent non-aromatisable
426 androgen DHT had no effect on MSTN expression, suggesting an absence of androgen
427 receptor-dependent regulation of granulosa MSTN expression. Consistent with
428 previous findings (Gutierrez *et al.* 1997, Glister *et al.* 2001) treatment of GC with FSH
429 and IGF analogue both promoted substantial increases in estradiol secretion but only
430 IGF analogue modulated MSTN expression, eliciting a ~60% reduction. This suggests
431 a possible interaction between IGF and myostatin signalling at the intrafollicular level
432 that warrants further investigation. In skeletal muscle IGF-1 is a prominent positive

433 regulator of muscle cell proliferation and differentiation whilst myostatin opposes this
434 action (Valdes *et al.* 2013). Despite this, IGF signalling upregulates myostatin
435 expression in skeletal muscle tissue models, suggesting an inhibitory auto-regulatory
436 loop (Yang *et al.* 2007, Kurokawa *et al.* 2009, Valdes *et al.* 2013).

437 The pro-inflammatory cytokine, TNF α , is also expressed at the intraovarian level and is
438 implicated in the regulation of follicle and luteal growth/regression and steroidogenesis
439 (Sheldon *et al.* 2014, Samir *et al.* 2017). Consistent with earlier findings (Glister *et al.*
440 2014) we showed that TNF α abolished FSH-induced upregulation of CYP19A1 and
441 estradiol secretion by GC. This was accompanied by a marked reduction in MSTN
442 expression reinforcing the view that myostatin has a positive role in granulosa estrogen
443 production. In skeletal muscle models, activation of the TNF α pathway suppresses
444 myogenesis but upregulates myostatin expression (Ono & Sakamoto 2017). Moreover,
445 IGF can reverse the TNF- α induced suppression of myogenesis (Zhao *et al.* 2015)
446 indicating interactions between positive (IGF1) and negative (myostatin, TNF- α)
447 regulators of myogenesis. Further studies are needed to decipher the regulatory signals
448 that contribute to the regulation of myostatin expression by ovarian follicular cells and
449 to place these in a physiological context.

450 With respect to myostatin-null mice, there are few, if any, references to their ovarian
451 phenotype and the potential impact of the mutation on gonadal function and fertility is
452 unknown to us. However, an *in vivo* study involving active immunization of female
453 mice against myostatin, showed that the number of developing ovarian follicles in their
454 female progeny was ~50% lower than that of control mice, with a similar diminution in
455 litter size (Liang *et al.* 2007). Double-muscled cattle with myostatin mutations,
456 reportedly show delayed puberty, reduced female fertility and a higher incidence of

457 dystocia and perinatal calf mortality/morbidity is associated with the large size of calves
458 (McPherron & Lee 1997). However, we are not aware of any studies examining whether
459 perturbations in ovarian follicle dynamics or steroidogenesis occur in double-muscled
460 cattle. Whilst information is currently lacking on the above, it is possible that the
461 physiological actions of myostatin in the ovary are functionally redundant owing to
462 compensatory effects of other TGF- β ligands (e.g activins) that can signal via the same,
463 or overlapping, receptors to elicit similar regulatory actions on theca and granulosa cells.

464 In summary, this study provides novel information on the expression of myostatin, its
465 signalling receptors and the binding protein, follistatin, in theca and granulosa cells of
466 developing bovine antral follicles. Myostatin expression in GC declined to a very low
467 level in large estrogen-active follicles in which expression of follistatin was maximal,
468 suggesting attenuation of GC-derived myostatin signalling at this stage. Since myostatin
469 suppressed thecal androgen production in a dose-dependent manner, an effect partially
470 rescued by follistatin, it is hypothesised that attenuation of myostatin signalling in large
471 antral follicles could facilitate thecal androgen production required as a substrate for
472 granulosa aromatase enzyme and estrogen synthesis. Paradoxically, however,
473 myostatin was found to promote CYP19A1 expression and estradiol production by
474 granulosa cells under 'basal' conditions whilst suppressing CYP11A1 and HSD3B1
475 expression and progesterone production (see Fig. 9). Taken together, this suggests a role
476 for myostatin in delaying follicle progression towards pre-ovulatory maturation and
477 luteinisation, in a manner similar to that suggested for granulosa-derived activin
478 (Findlay *et al.* 2002, Knight & Glister 2006). Further in-depth studies in other species,
479 including whole animal models, are required to confirm and extend these *in vitro*
480 observations based on bovine ovarian cell culture models. It is also speculated that

481 muscle-derived myostatin conveyed to the ovary via the systemic circulation may
482 contribute to the regulation of follicle function. In a similar manner, testicular
483 steroidogenesis and gametogenesis may be influenced by circulating and/or locally-
484 produced myostatin although we are not aware of any studies, to date, examining this
485 possibility.

486

487 **Declaration of interests**

488 The authors declare that there is no perceived conflict of interest that would prejudice
489 the impartiality of this scientific work

490 **Funding**

491 Supported by BBSRC (grant number BB/M001369 to PGK). WC was supported by a
492 postgraduate scholarship from the Thai Ministry of Science and Technology

493 **Acknowledgements**

494 We thank D Butlin and AD Simmonds for skilled technical assistance.

495

496 **References**

497

- 498 **Anthor H, Nicholas G, McKinnell I, Kemp CF, Sharma M, Kambadur R & Patel**
499 **K** 2004 Follistatin complexes Myostatin and antagonises Myostatin-
500 mediated inhibition of myogenesis. *Dev Biol* **270** 19-30.
501 **Campbell BK, Scaramuzzi RJ & Webb R** 1995 Control of antral follicle
502 development and selection in sheep and cattle. *J Reprod Fertil Suppl* **49** 335-
503 350.

- 504 **Campbell BK, Baird DT & Webb R** 1998 Effects of dose of LH on androgen
505 production and luteinization of ovine theca cells cultured in a serum-free
506 system. *J Reprod Fertil* **112** 69-77.
- 507 **Campbell BK, Souza C, Gong J, Webb R, Kendall N, Marsters P, Robinson G,**
508 **Mitchell A, Telfer EE & Baird DT** 2003 Domestic ruminants as models for
509 the elucidation of the mechanisms controlling ovarian follicle development
510 in humans. *Reprod Suppl* **61** 429-443.
- 511 **Chang HM, Fang L, Cheng JC, Klausen C, Sun YP & Leung PC** 2015 Growth
512 differentiation factor 8 down-regulates pentraxin 3 in human granulosa
513 cells. *Mol Cell Endocrinol* **404** 82-90.
- 514 **Chang HM, Fang L, Cheng JC, Taylor EL, Sun YP & Leung PC** 2016a Effects of
515 growth differentiation factor 8 on steroidogenesis in human granulosa-
516 lutein cells. *Fertil Steril* **105** 520-528.
- 517 **Chang HM, Pan HH, Cheng JC, Zhu YM & Leung PCK** 2016b Growth
518 differentiation factor 8 suppresses cell proliferation by up-regulating CTGF
519 expression in human granulosa cells. *Mol Cell Endocrinol* **422** 9-17.
- 520 **Chen MJ, Han DS, Yang JH, Yang YS, Ho HN & Yang WS** 2012 Myostatin and its
521 association with abdominal obesity, androgen and follistatin levels in
522 women with polycystic ovary syndrome. *Hum Reprod* **27** 2476-2483.
- 523 **Clop A, Marcq F, Takeda H, Pirottin D, Tordoir X, Bibe B, Bouix J, Caiment F,**
524 **Elsen JM, Eyche F et al.** 2006 A mutation creating a potential
525 illegitimate microRNA target site in the myostatin gene affects muscularity
526 in sheep. *Nat Genet* **38** 813-818.
- 527 **Elkina Y, von Haehling S, Anker SD & Springer J** 2011 The role of myostatin in
528 muscle wasting: an overview. *J Cachexia Sarcopenia Muscle* **2** 143-151.
- 529 **Elliott B, Renshaw D, Getting S & Mackenzie R** 2012 The central role of
530 myostatin in skeletal muscle and whole body homeostasis. *Acta Physiol*
531 *(Oxf)* **205** 324-340.
- 532 **Fainsod A, Deissler K, Yelin R, Marom K, Epstein M, Pillemer G, Steinbeisser H**
533 **& Blum M** 1997 The dorsalizing and neural inducing gene follistatin is an
534 antagonist of BMP-4. *Mech Dev* **63** 39-50.
- 535 **Fang L, Chang HM, Cheng JC, Yu Y, Leung PC & Sun YP** 2015 Growth
536 Differentiation Factor-8 Decreases StAR Expression Through ALK5-
537 Mediated Smad3 and ERK1/2 Signaling Pathways in Luteinized Human
538 Granulosa Cells. *Endocrinology* **156** 4684-4694.
- 539 **Findlay JK, Drummond AE, Dyson ML, Baillie AJ, Robertson DM & Ethier JF**
540 2002 Recruitment and development of the follicle; the roles of the
541 transforming growth factor-beta superfamily. *Mol Cell Endocrinol* **191** 35-
542 43.
- 543 **Furihata T, Kinugawa S, Fukushima A, Takada S, Homma T, Masaki Y, Abe T,**
544 **Yokota T, Oba K, Okita K et al.** 2016 Serum myostatin levels are
545 independently associated with skeletal muscle wasting in patients with
546 heart failure. *Int J Cardiol* **220** 483-487.
- 547 **Glister C, Tannetta DS, Groome NP & Knight PG** 2001 Interactions between
548 follicle-stimulating hormone and growth factors in modulating secretion of
549 steroids and inhibin-related peptides by nonluteinized bovine granulosa
550 cells. *Biol Reprod* **65** 1020-1028.

- 551 **Glister C, Kemp CF & Knight PG** 2004 Bone morphogenetic protein (BMP) ligands
 552 and receptors in bovine ovarian follicle cells: actions of BMP-4, -6 and -7 on
 553 granulosa cells and differential modulation of Smad-1 phosphorylation by
 554 follistatin. *Reproduction* **127** 239-254.
- 555 **Glister C, Richards SL & Knight PG** 2005 Bone morphogenetic proteins (BMP) -4,
 556 -6, and -7 potentially suppress basal and luteinizing hormone-induced
 557 androgen production by bovine theca interna cells in primary culture: could
 558 ovarian hyperandrogenic dysfunction be caused by a defect in thecal BMP
 559 signaling? *Endocrinology* **146** 1883-1892.
- 560 **Glister C, Satchell L & Knight PG** 2010 Changes in expression of bone
 561 morphogenetic proteins (BMPs), their receptors and inhibin co-receptor
 562 betaglycan during bovine antral follicle development: inhibin can
 563 antagonize the suppressive effect of BMPs on thecal androgen production.
 564 *Reproduction* **140** 699-712.
- 565 **Glister C, Satchell L, Bathgate RA, Wade JD, Dai Y, Ivell R, Anand-Ivell R,**
 566 **Rodgers RJ & Knight PG** 2013 Functional link between bone
 567 morphogenetic proteins and insulin-like peptide 3 signaling in modulating
 568 ovarian androgen production. *Proc Natl Acad Sci U S A* **110** E1426-1435.
- 569 **Glister C, Hatzirodos N, Hummitzsch K, Knight PG & Rodgers RJ** 2014 The
 570 global effect of follicle-stimulating hormone and tumour necrosis factor
 571 alpha on gene expression in cultured bovine ovarian granulosa cells. *BMC*
 572 *Genomics* **15** 72.
- 573 **Gutierrez CG, Campbell BK & Webb R** 1997 Development of a long-term bovine
 574 granulosa cell culture system: induction and maintenance of estradiol
 575 production, response to follicle-stimulating hormone, and morphological
 576 characteristics. *Biol Reprod* **56** 608-616.
- 577 **Hasegawa T, Kamada Y, Hosoya T, Fujita S, Nishiyama Y, Iwata N, Hiramatsu Y**
 578 **& Otsuka F** 2017 A regulatory role of androgen in ovarian steroidogenesis
 579 by rat granulosa cells. *J Steroid Biochem Mol Biol* **172** 160-165.
- 580 **Hatzirodos N, Hummitzsch K, Irving-Rodgers HF & Rodgers RJ** 2014a
 581 Transcriptome profiling of the theca interna in transition from small to
 582 large antral ovarian follicles. *PLoS One* **9** e97489.
- 583 **Hatzirodos N, Irving-Rodgers HF, Hummitzsch K, Harland ML, Morris SE &**
 584 **Rodgers RJ** 2014b Transcriptome profiling of granulosa cells of bovine
 585 ovarian follicles during growth from small to large antral sizes. *BMC*
 586 *Genomics* **15** 24.
- 587 **Hedayati M, Nozhat Z & Hannani M** 2016 Can the Serum Level of Myostatin be
 588 Considered as an Informative Factor for Cachexia Prevention in Patients
 589 with Medullary Thyroid Cancer? *Asian Pac J Cancer Prev* **17** 119-123.
- 590 **Iemura S, Yamamoto TS, Takagi C, Uchiyama H, Natsume T, Shimasaki S,**
 591 **Sugino H & Ueno N** 1998 Direct binding of follistatin to a complex of bone-
 592 morphogenetic protein and its receptor inhibits ventral and epidermal cell
 593 fates in early *Xenopus* embryo. *Proc Natl Acad Sci U S A* **95** 9337-9342.
- 594 **Islam MS, Catherino WH, Protic O, Janjusevic M, Gray PC, Giannubilo SR,**
 595 **Ciavattini A, Lamanna P, Tranquilli AL, Petraglia F et al.** 2014 Role of
 596 activin-A and myostatin and their signaling pathway in human myometrial
 597 and leiomyoma cell function. *J Clin Endocrinol Metab* **99** E775-785.

- 598 **Kambadur R, Sharma M, Smith TP & Bass JJ** 1997 Mutations in myostatin
599 (GDF8) in double-muscled Belgian Blue and Piedmontese cattle. *Genome Res*
600 **7** 910-916.
- 601 **Knight PG & Glister C** 2006 TGF-beta superfamily members and ovarian follicle
602 development. *Reproduction* **132** 191-206.
- 603 **Kurokawa M, Sato F, Aramaki S, Soh T, Yamauchi N & Hattori MA** 2009
604 Monitor of the myostatin autocrine action during differentiation of
605 embryonic chicken myoblasts into myotubes: effect of IGF-I. *Mol Cell*
606 *Biochem* **331** 193-199.
- 607 **Lee SJ & McPherron AC** 2001 Regulation of myostatin activity and muscle growth.
608 *Proc Natl Acad Sci U S A* **98** 9306-9311.
- 609 **Liang YC, Yeh JY & Ou BR** 2007 Effect of maternal myostatin antibody on
610 offspring growth performance and body composition in mice. *J Exp Biol* **210**
611 477-483.
- 612 **Livak KJ & Schmittgen TD** 2001 Analysis of relative gene expression data using
613 real-time quantitative PCR and the 2(-Delta Delta C(T)) Method. *Methods* **25**
614 402-408.
- 615 **Matzuk MM, Lu N, Vogel H, Sellheyer K, Roop DR & Bradley A** 1995 Multiple
616 defects and perinatal death in mice deficient in follistatin. *Nature* **374** 360-
617 363.
- 618 **McPherron AC, Lawler AM & Lee SJ** 1997 Regulation of skeletal muscle mass in
619 mice by a new TGF-beta superfamily member. *Nature* **387** 83-90.
- 620 **McPherron AC & Lee SJ** 1997 Double muscling in cattle due to mutations in the
621 myostatin gene. *Proc Natl Acad Sci U S A* **94** 12457-12461.
- 622 **Mendler L, Baka Z, Kovacs-Simon A & Dux L** 2007 Androgens negatively
623 regulate myostatin expression in an androgen-dependent skeletal muscle.
624 *Biochem Biophys Res Commun* **361** 237-242.
- 625 **Mosher DS, Quignon P, Bustamante CD, Sutter NB, Mellersh CS, Parker HG &**
626 **Ostrander EA** 2007 A mutation in the myostatin gene increases muscle
627 mass and enhances racing performance in heterozygote dogs. *PLoS Genet* **3**
628 e79.
- 629 **Ono Y & Sakamoto K** 2017 Lipopolysaccharide inhibits myogenic differentiation
630 of C2C12 myoblasts through the Toll-like receptor 4-nuclear factor-kappaB
631 signaling pathway and myoblast-derived tumor necrosis factor-alpha. *PLoS*
632 *One* **12** e0182040.
- 633 **Otto A & Patel K** 2010 Signalling and the control of skeletal muscle size. *Exp Cell*
634 *Res* **316** 3059-3066.
- 635 **Palandra J, Quazi A, Fitz L, Rong H, Morris C & Neubert H** 2016 Quantitative
636 measurements of GDF-8 using immunoaffinity LC-MS/MS. *Proteomics Clin*
637 *Appl* **10** 597-604.
- 638 **Peiris HN, Salomon C, Payton D, Ashman K, Vaswani K, Chan A, Rice GE &**
639 **Mitchell MD** 2014 Myostatin is localized in extravillous trophoblast and up-
640 regulates migration. *J Clin Endocrinol Metab* **99** E2288-2297.
- 641 **Rebbapragada A, Benchabane H, Wrana JL, Celeste AJ & Attisano L** 2003
642 Myostatin signals through a transforming growth factor beta-like signaling
643 pathway to block adipogenesis. *Mol Cell Biol* **23** 7230-7242.

- 644 **Sahmi M, Nicola ES & Price CA** 2006 Hormonal regulation of cytochrome P450
645 aromatase mRNA stability in non-luteinizing bovine granulosa cells in vitro.
646 *J Endocrinol* **190** 107-115.
- 647 **Samir M, Glister C, Mattar D, Laird M & Knight PG** 2017 Follicular expression of
648 pro-inflammatory cytokines tumour necrosis factor-alpha (TNFalpha),
649 interleukin 6 (IL6) and their receptors in cattle: TNFalpha, IL6 and
650 macrophages suppress thecal androgen production in vitro. *Reproduction*
651 **154** 35-49.
- 652 **Schiaffino S, Dyar KA, Ciciliot S, Blaauw B & Sandri M** 2013 Mechanisms
653 regulating skeletal muscle growth and atrophy. *FEBS J* **280** 4294-4314.
- 654 **Schuelke M, Wagner KR, Stolz LE, Hubner C, Riebel T, Komen W, Braun T,**
655 **Tobin JF & Lee SJ** 2004 Myostatin mutation associated with gross muscle
656 hypertrophy in a child. *N Engl J Med* **350** 2682-2688.
- 657 **Sheldon IM, Cronin JG, Healey GD, Gabler C, Heuwieser W, Strey D, Bromfield**
658 **JJ, Miyamoto A, Fergani C & Dobson H** 2014 Innate immunity and
659 inflammation of the bovine female reproductive tract in health and disease.
660 *Reproduction* **148** R41-51.
- 661 **Shimasaki S, Moore RK, Otsuka F & Erickson GF** 2004 The bone morphogenetic
662 protein system in mammalian reproduction. *Endocr Rev* **25** 72-101.
- 663 **Silva JM & Price CA** 2002 Insulin and IGF-I are necessary for FSH-induced
664 cytochrome P450 aromatase but not cytochrome P450 side-chain cleavage
665 gene expression in oestrogenic bovine granulosa cells in vitro. *J Endocrinol*
666 **174** 499-507.
- 667 **Skinner MK, Schmidt M, Savenkova MI, Sadler-Riggleman I & Nilsson EE** 2008
668 Regulation of granulosa and theca cell transcriptomes during ovarian antral
669 follicle development. *Mol Reprod Dev* **75** 1457-1472.
- 670 **Valdes JA, Flores S, Fuentes EN, Osorio-Fuentealba C, Jaimovich E & Molina A**
671 2013 IGF-1 induces IP3 -dependent calcium signal involved in the
672 regulation of myostatin gene expression mediated by NFAT during
673 myoblast differentiation. *J Cell Physiol* **228** 1452-1463.
- 674 **Webb R, Nicholas B, Gong JG, Campbell BK, Gutierrez CG, Garverick HA &**
675 **Armstrong DG** 2003 Mechanisms regulating follicular development and
676 selection of the dominant follicle. *Reprod Suppl* **61** 71-90.
- 677 **Wu YG, Bennett J, Talla D & Stocco C** 2011 Testosterone, not 5alpha-
678 dihydrotestosterone, stimulates LRH-1 leading to FSH-independent
679 expression of Cyp19 and P450scc in granulosa cells. *Mol Endocrinol* **25** 656-
680 668.
- 681 **Yang W, Zhang Y, Li Y, Wu Z & Zhu D** 2007 Myostatin induces cyclin D1
682 degradation to cause cell cycle arrest through a phosphatidylinositol 3-
683 kinase/AKT/GSK-3 beta pathway and is antagonized by insulin-like growth
684 factor 1. *J Biol Chem* **282** 3799-3808.
- 685 **Zhao Q, Yang ST, Wang JJ, Zhou J, Xing SS, Shen CC, Wang XX, Yue YX, Song J,**
686 **Chen M et al.** 2015 TNF alpha inhibits myogenic differentiation of C2C12
687 cells through NF-kappaB activation and impairment of IGF-1 signaling
688 pathway. *Biochem Biophys Res Commun* **458** 790-795.
- 689

690

691 **Table 1** List of primers used for real-time PCR

692

693

694

695 **Figure Legends**

696 **Fig. 1.** Relative abundance of mRNA transcripts for (A) MSTN, (B) FST, (C)
 697 ACVR1B, (D) TGFBR1 and (E) ACVR2B in theca and granulosa layers of small (3-
 698 6mm), medium (7-10mm) and large (11-18mm) bovine antral follicles. Large follicles
 699 are subdivided into estrogen active (E:P ratio >1) and estrogen-inactive (E:P ratio <1)
 700 categories referred to as LEA and LEI follicles, respectively. Intrafollicular E:P ratios
 701 for each follicle category are shown in panel F. Numbers in parenthesis in panel A are
 702 n-values for each group. Values are mean \pm SEM and summarized two-way ANOVA
 703 results are shown. Within each cell type means without a common letter are
 704 significantly different ($P < 0.05$).

705

706 **Fig. 2** Immunohistochemical staining of bovine ovary sections showing myostatin
 707 immunoreactivity (brown) in oocyte and granulosa cells of primordial (pF) and primary
 708 (PrF) follicles (A), secondary (SF) follicles (B,C) and in thecal (T) and granulosal (G)
 709 layers of antral follicles (AF) (D,E). Myostatin immunoreactivity was also evident in
 710 vascular smooth muscle cells (bv) (E). No staining was observed in control sections
 711 treated with normal rabbit serum instead of primary antibody (F).

712

713 **Fig. 3** Effect of myostatin on basal and FSH-induced secretion of (A) estradiol and (B)
 714 progesterone by bovine granulosa cells, and on (C) viable cell number; Panels (D-F)
 715 show the effect of myostatin \pm FSH on expression of CYP19A1, CYP11A1 and
 716 HSD3B1 mRNA, respectively. Values are means \pm sem ($n = 5$ independent cultures).

717 Results of 2-way ANOVA are summarized; *P<0.01, **P<0.01 ***P<0.001 compared
718 to respective control with zero myostatin (panels A, B, C). In panels D-F means without
719 a common letter are significantly different (P<0.05).

720

721

722 **Fig. 4** Effect of myostatin on basal and LR3 IGF-1-induced secretion of (A) estradiol
723 and (B) progesterone by bovine granulosa cells and on (C) viable cell number. Values
724 are means \pm SEM (n = 3 independent cultures). Means without a common letter are
725 significantly different (P<0.05).

726

727 **Fig. 5** Effect of different treatments known to modulate GC steroidogenesis on
728 granulosa expression of (A) MSTN and (B) CYP19A1 and on (C) secretion of estradiol.
729 Values are means \pm SEM (n = 4 independent cultures); Means without a common letter
730 are significantly different (p<0.05).

731

732 **Fig. 6** The effects of myostatin on basal and LH-induced secretion of (A)
733 androstenedione and (B) progesterone by bovine theca cells. Panel (C) shows effects on
734 viable cell number. Values are mean \pm SEM (n=12 independent cultures); Two-way
735 ANOVA p-values are shown

736

737 **Fig. 7** Ability of follistatin to antagonize myostatin-induced suppression of thecal
738 androstenedione secretion. Values are means \pm SEM (n=6 independent cultures)

739

740 **Fig. 8** Effect of LH and BMP6 on thecal expression of (A) MSTN and (B)
741 CYP17A1 and on (C) secretion of androstenedione. Values are means \pm SEM (n = 8
742 independent cultures); means without a common letter are significantly different
743 (p<0.05).

744

745 **Fig. 9** Schematic diagram illustrating potential involvement of systemic and/or locally
746 produced myostatin in the modulation of thecal and granulosa steroidogenesis.

| Target | Accession number | Forward primer 5' to 3' | Reverse primer 5' to 3' | Amplicon size (bp) |
|---------|------------------|------------------------------|-------------------------------|--------------------|
| LHCGR | NM_174381.1 | ATTGCCTCAGTCGATGCCAGACC | AAAAAGCCAGCCGCGCTGC | 92 |
| STAR | NM_174189 | TTTTTTCCTGGGTCTGACAGCGTC | ACAACCTGATCCTTGGGTTCTGCACC | 103 |
| CYP11A1 | NM_176644 | CAGTGTCCTCTGCTCAACGTCC | TTATTGAAAATTGTGTCCCATGCGG | 99 |
| HSD3B1 | NM_174343.2 | GCCACCTAGTGA CTCTTTCCAACAGCG | TGGTTTCTGCTTGGCTTCTCCC | 111 |
| FSHR | NM_174061.1 | GCCAGCCTCACCTACCCAGC | AATTGGATGAAGGTCAGAGGTTTGCC | 75 |
| CYP17A1 | NM_174304 | GACAAAGGCACAGACGTTGTGGTCA | TGATCTGCAAGACGAGACTGGCATG | 301 |
| CYP19A1 | NM_174365 | TCTGTCCCCACTGAATCCTCCTGG | GGGTTTCATGGTGCTGTGTGGC | 102 |
| MSTN | NM_001001525.2 | GTTCGATGTCCAGAGAGATGCCAGC | ACTTGC GTTAGAAGATCAGACTCCGTGG | 114 |
| ACTB | NM_173979.3 | ATCACCATCGGCAATGAGCGGTTC | CGGATGTCGACGTCACACTTCATGA | 128 |

Table 1: List of primers used for quantitative RT-PCR

Fig 1

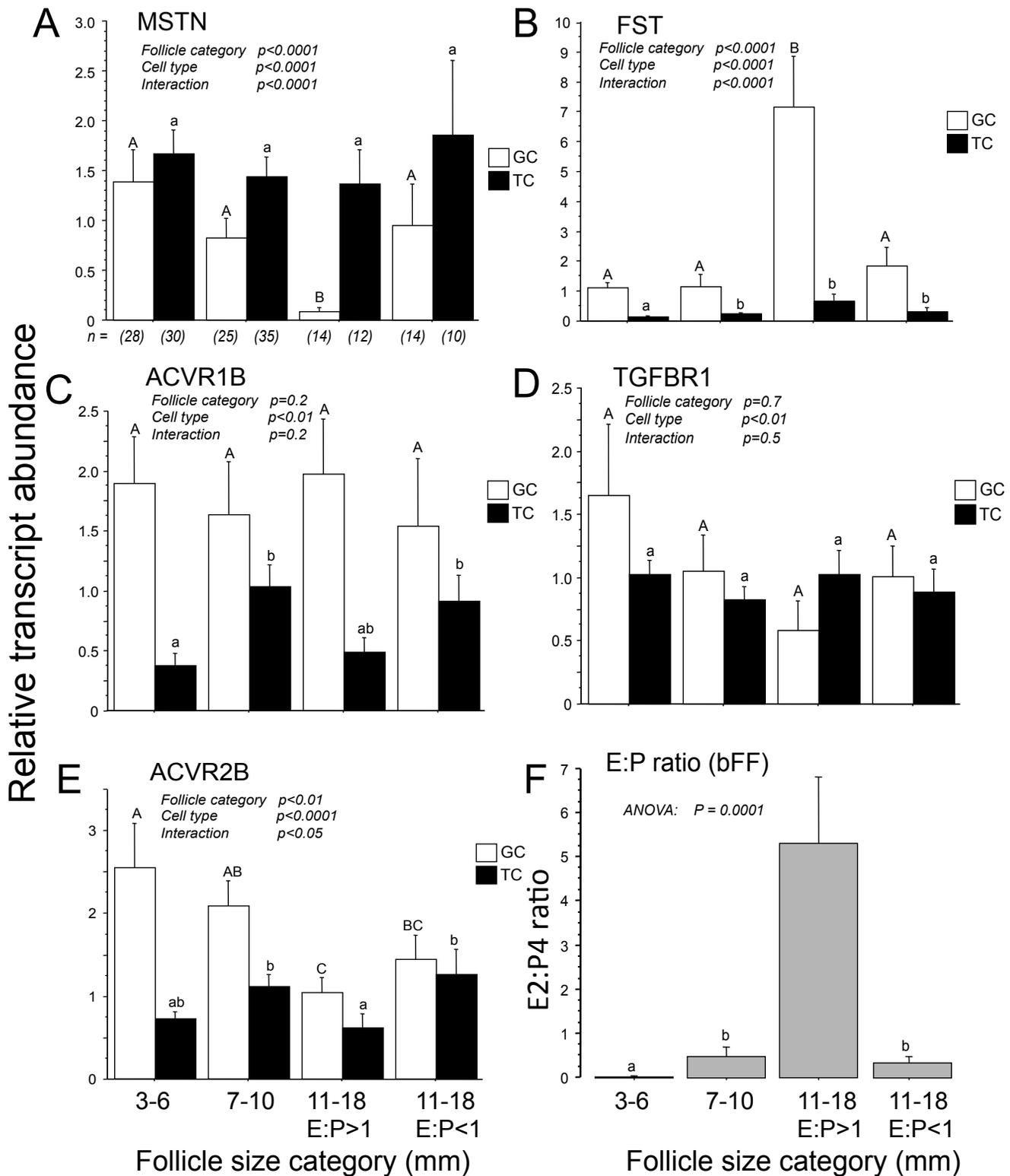


Fig. 2

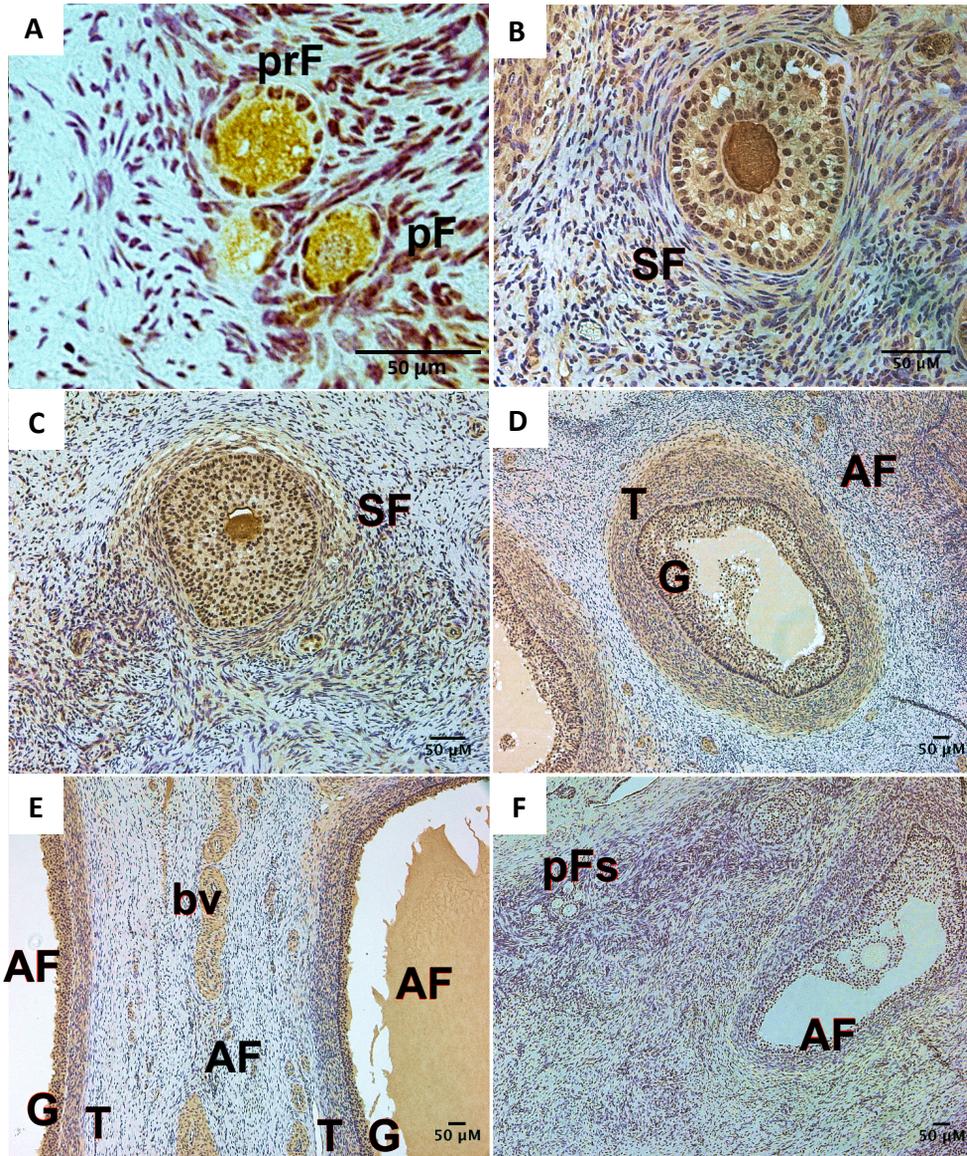


Fig. 3

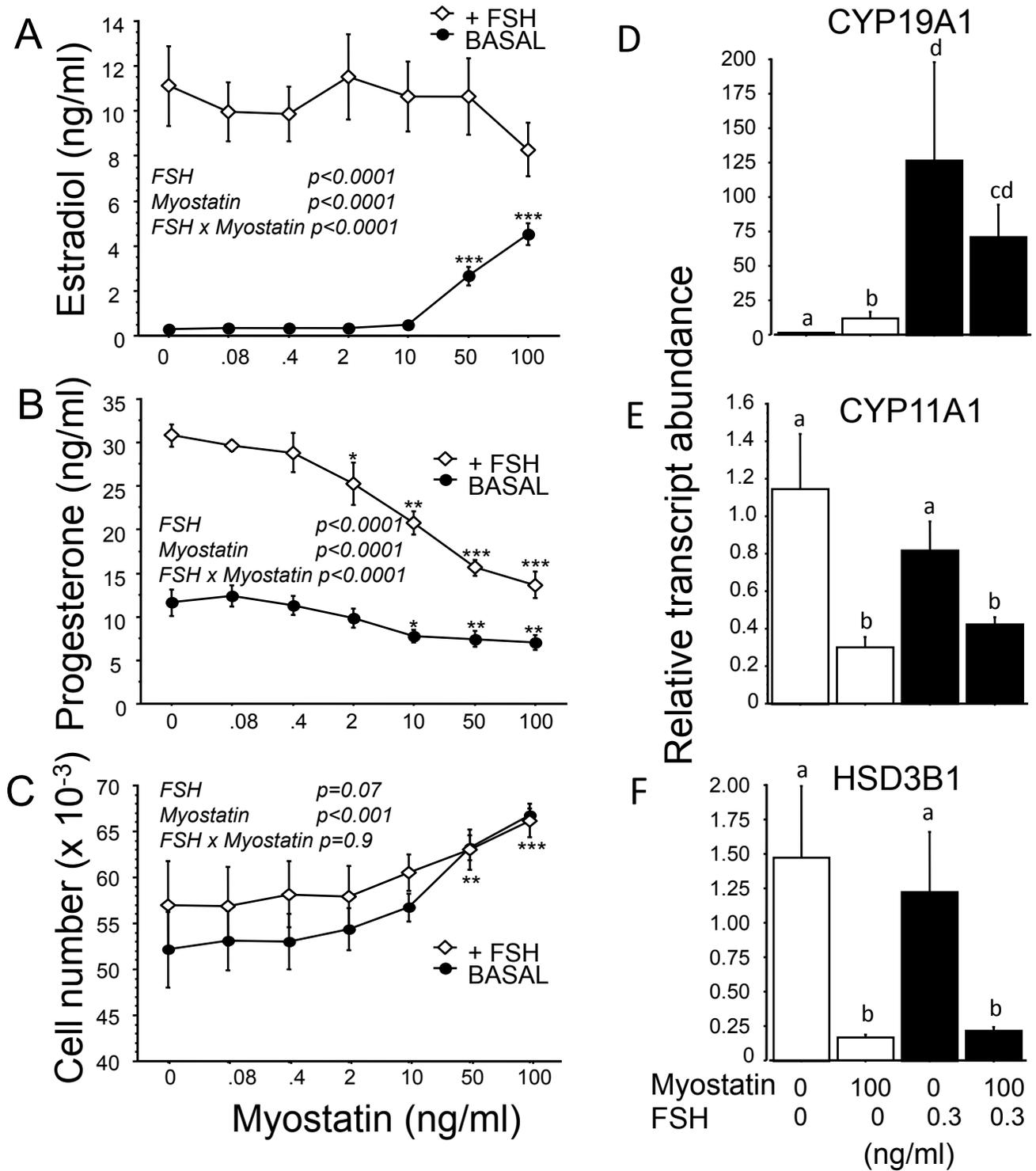


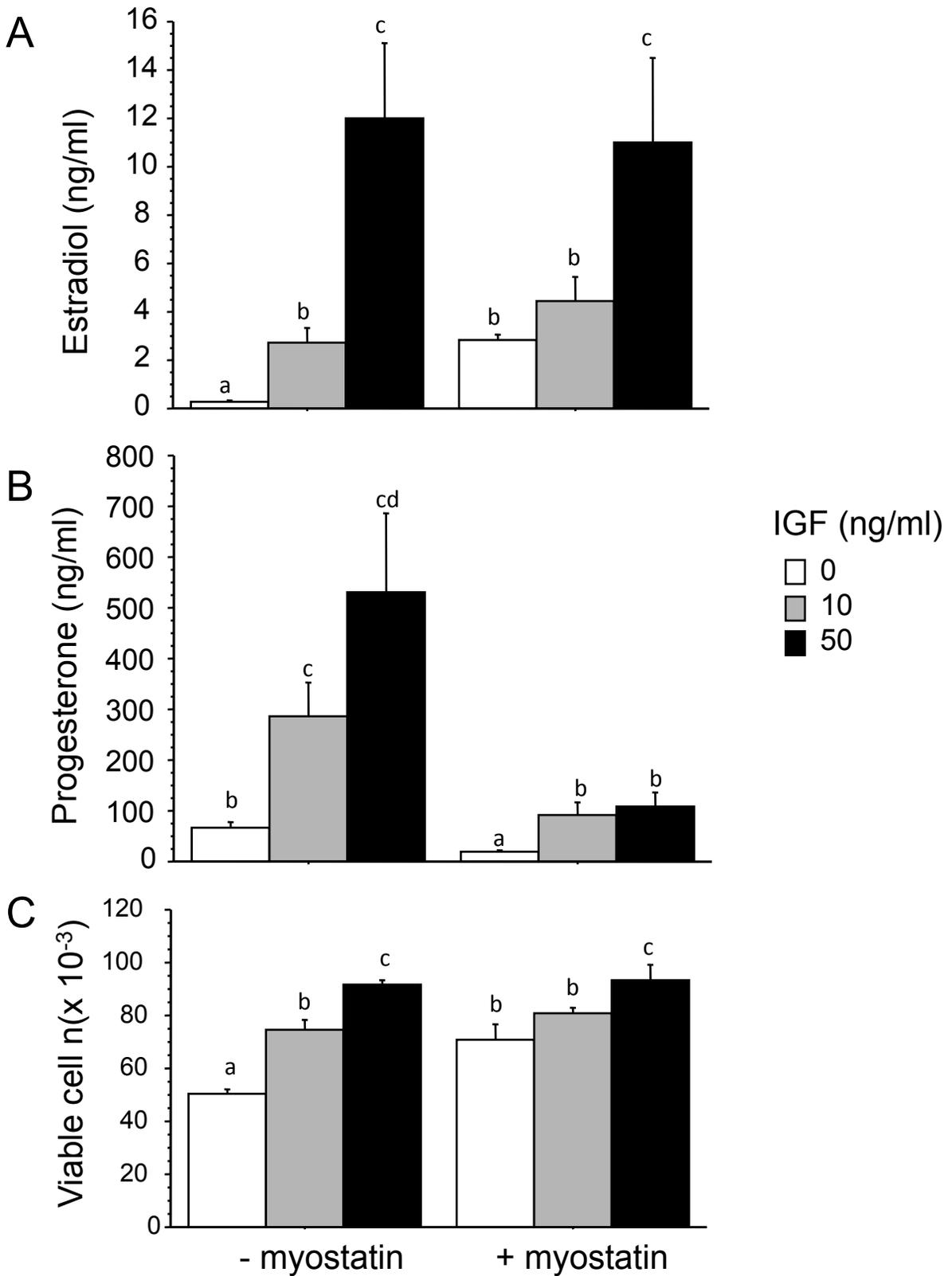
Fig. 4

Fig 5

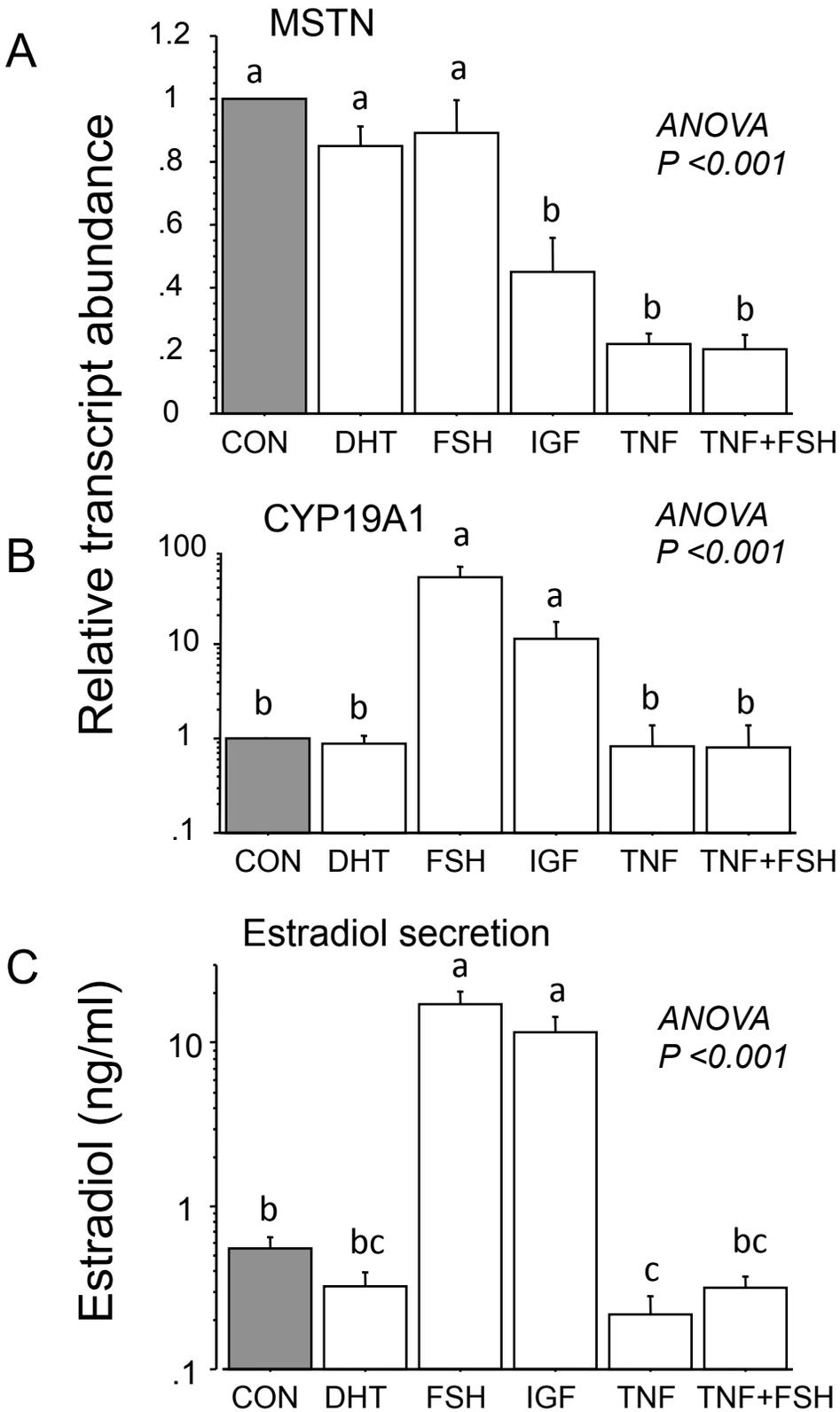


Fig. 6

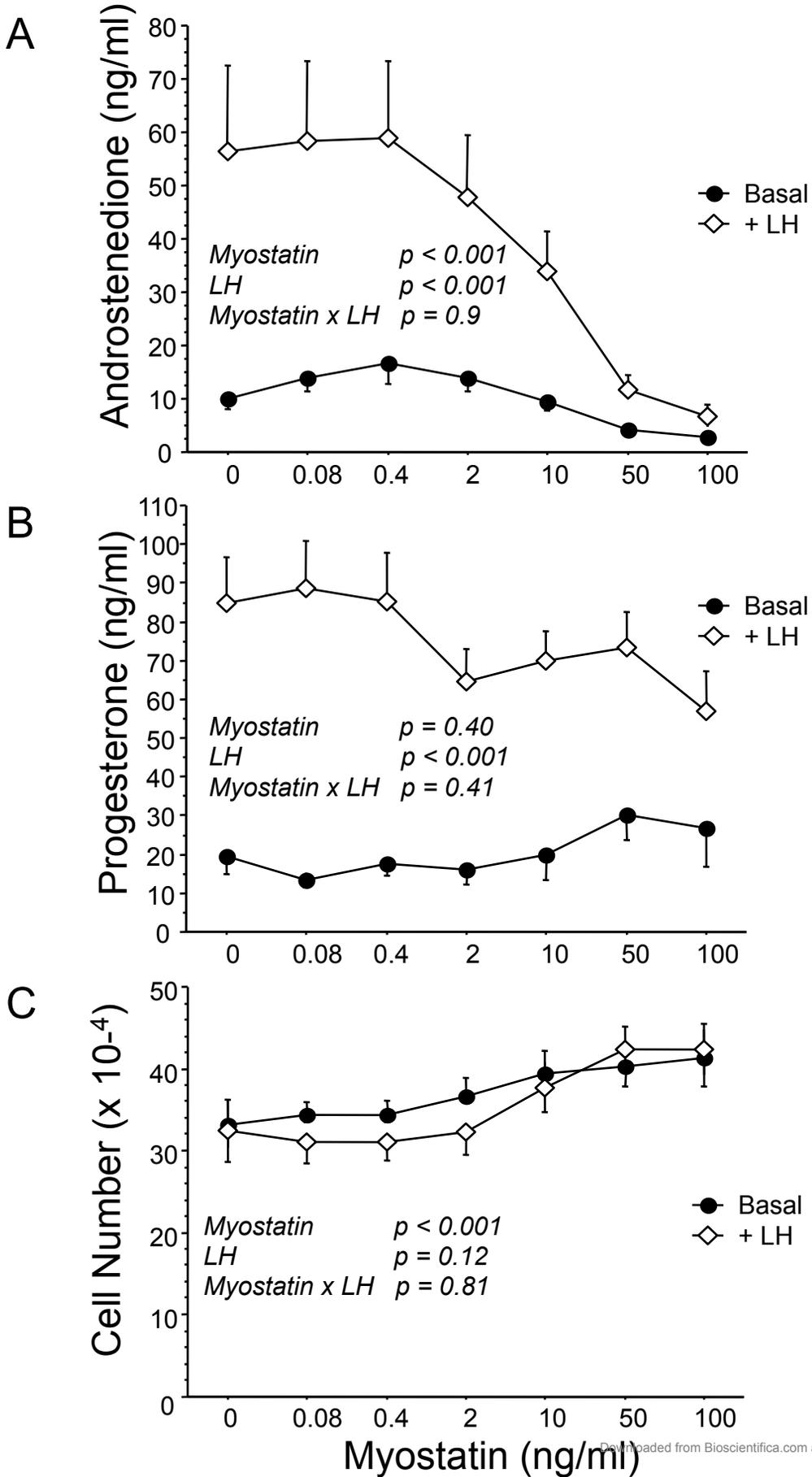


Fig. 7

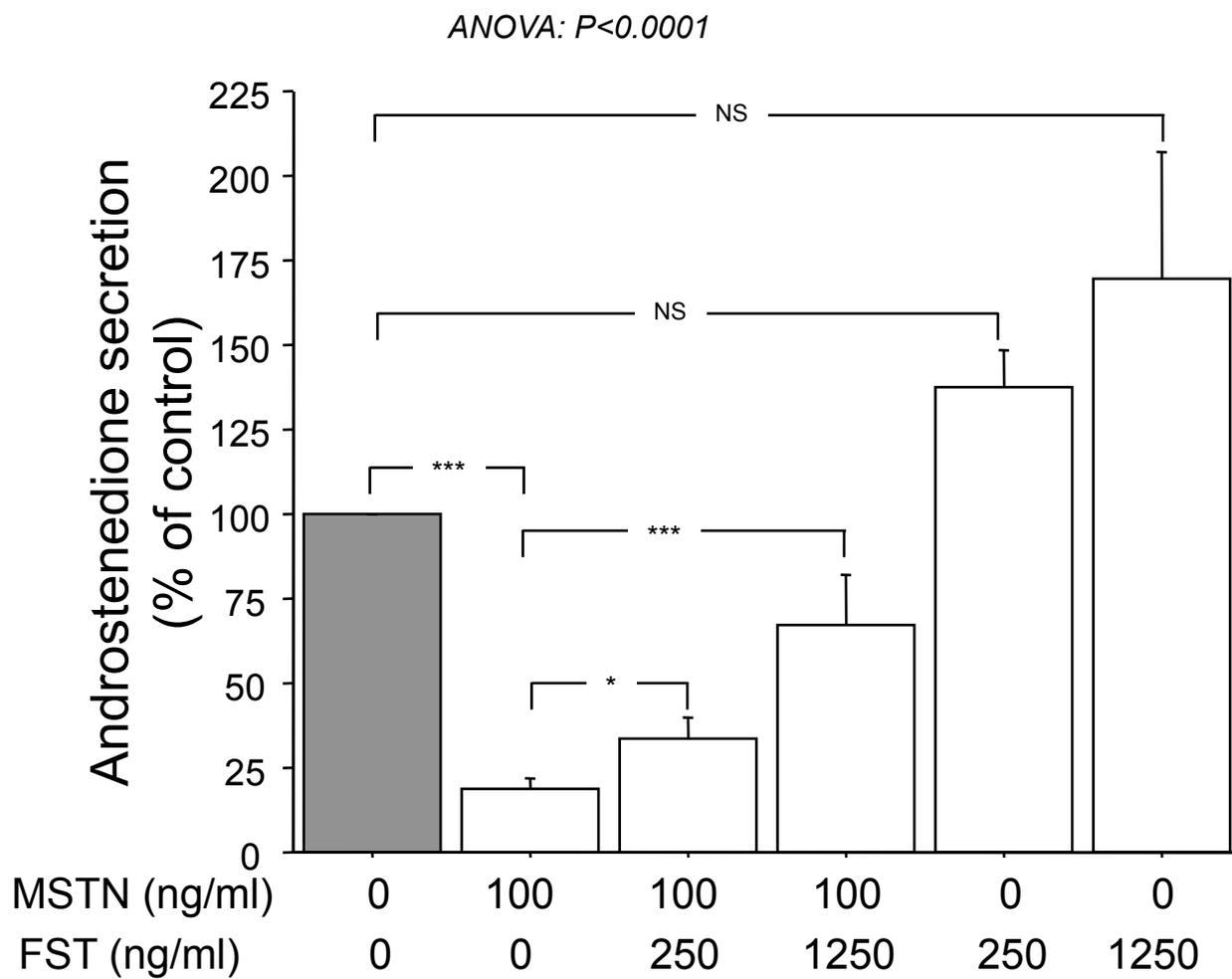


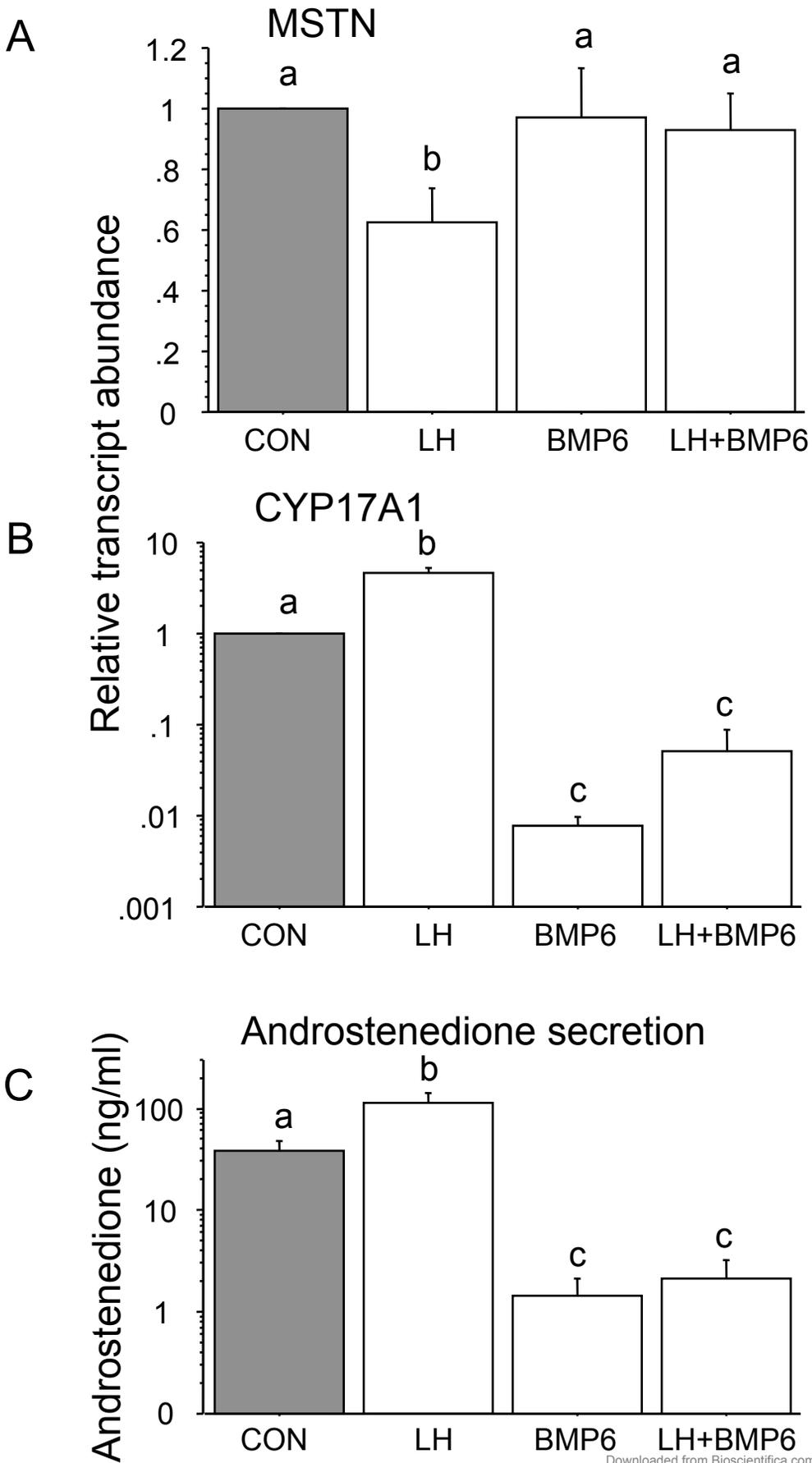
Fig. 8

Fig. 9

