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Original Research Paper

Title: Relationship between in vitro growth of bovine oocytes and steroidogenesis of granulosa cells cultured in medium supplemented with bone morphogenetic protein-4 and follicle stimulating hormone

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Abstract

Bone morphogenetic protein-4 (BMP-4) and FSH play important regulatory roles in follicular growth and steroidogenesis in vivo. The purpose of this study was to investigate the effects of BMP-4 and FSH on in vitro growth (IVG) and steroidogenesis of bovine oocyte-cumulus-granulosa complexes (OCGCs). We cultured OCGCs collected from early antral follicles (0.5-1 mm) in medium without BMP-4 and FSH for 4 days and investigated the appearance of OCGCs and their steroidogenesis. During the first 4 days of IVG, morphologically normal OCGCs produced more estradiol-17β (E₂), but less progesterone (P₄). Morphologically normal OCGCs were subjected to an additional culture in medium supplemented with BMP-4 (0, 10, and 50 ng/mL) and FSH (0 and 0.5 ng/mL) until day 12. We examined the viability and steroidogenesis of OCGCs after 8 and 12 days of culture. Oocyte growth, characteristics of granulosa cells, and the maturational competence of oocytes were also investigated. On day 8, the viability of OCGCs cultured without FSH was higher in the 10 ng/mL BMP-4 group than in the 50 ng/mL BMP-4 group (P<0.05). No significant difference was observed in the viability of groups cultured with FSH, regardless of the addition of BMP-4, and FSH improved the viability of 50 ng/mL BMP-4 group similar to 10 ng/mL BMP-4 group. The total number of granulosa cells was larger in 10 ng/mL BMP-4 group cultured with FSH than in 50 ng/mL BMP-4 group cultured with FSH on day 8 (P<0.05). E₂ production decreased from days 8 to 12, and P₄ production increased throughout IVG culture, regardless of the addition of BMP-4 and FSH (P<0.05). No significant differences in E₂
production were observed between groups from days 4 to 8, regardless of whether BMP-4 was added without FSH; however, E₂ production in the group cultured with 50 ng/mL BMP-4 was suppressed by FSH. BMP-4 suppressed E₂ production from days 8 to 12, regardless of whether FSH was added. The group cultured with 10 ng/mL BMP-4 without FSH showed the lowest P₄ production among all groups for all culture periods. OCGCs that produced mature oocytes tended to secrete more E₂ and less P₄ than OCGCs that produced immature oocytes. In conclusion, until day 8 of the IVG culture, P₄ production by OCGCs was suppressed by the addition of 10 ng/mL BMP-4 in the absence of FSH, without inhibiting E₂ production. These conditions appear to mimic growing follicles until day 8 and mimic degenerating follicles from days 8 to 12 of culture.

Keywords: BMP-4; Early antral follicle; FSH; In vitro growth; Maturational competence; Steroidogenesis.
1. Introduction

A large number of primordial follicles exist in mammalian ovaries, and granulosa cells multiply and oocytes become developmentally competent as they grow. However, most follicles degenerate during follicular growth, and only a small proportion of follicles develop sufficiently to undergo ovulation [1, 2]. If it is possible to develop a culture system that enables early stage oocytes or follicles to grow to the ovulatory stage, more embryos may be produced and an experimental model may also be established to investigate the mechanisms underlying follicular recruitment, selection, and ovulation. In mice, tissue culture of neonatal ovaries combined with in vitro growth (IVG) culture of oocyte-cumulus-granulosa complexes (OCGCs) allows pups to be produced from primordial follicles in vitro [3, 4]. However, in cattle, no studies have currently reported the production of calves from follicles at stages earlier than preantral follicles. Previous studies described bovine calves derived from IVG oocytes that originated from OCGCs in early antral follicles [5, 6, 7]; however, their developmental competence to transferable embryos was lower than the competence of in vivo matured oocytes [5-13].

The primary roles of follicular cells are to support the growth and maturation of oocytes, as well as the production of sex steroid hormones by granulosa cells. Therefore, in order to mimic in vivo follicular growth via an in vitro culture system, the growth of oocytes and production of sex steroid hormones by granulosa cells both need to be investigated. A previous study that combined histological observations with the measurement of sex steroid hormones in follicular fluid revealed
that estradiol-17β (E$_2$) concentrations in growing follicles increased as the follicles grew, with a peak at estrus in cattle, and the degeneration of follicles led to increases in progesterone (P$_4$) concentrations [14]. Furthermore, E$_2$ concentrations in dominant follicles increased concomitantly with follicular development and the E$_2$/P$_4$ ratio also increased; however, subordinate follicles showed low E$_2$/P$_4$ ratios [14, 15]. These findings indicate that a culture system of OCGCs that produces more E$_2$ and less P$_4$ is needed to mimic in vivo dominant follicular development. In conventional IVG, serum has typically been added to culture media to promote cell growth and survival [5, 6, 7]. However, granulosa cells cultured in media containing serum luteinize, compromise E$_2$ production, and begin to produce P$_4$ [16, 17]. Previous studies attempted to culture OCGCs in serum-free media [18, 19]; however, the oocytes derived from serum-free cultures had low maturational competence and low fertilizability. Thus, a culture system for OCGCs that produces oocytes with high developmental competence and inhibits the luteinization of granulosa cells under culture conditions containing serum needs to be developed. As shown in our previous study, the addition of bone morphogenetic protein-4 (BMP-4) to the growth medium inhibited the luteinization of granulosa cells [20].

BMP-4 is produced by theca cells in bovine follicles, and its receptor is primarily expressed in oocytes and granulosa cells [21]. An in situ hybridization analysis of rat ovaries revealed that the expression level of BMP-4 increases during follicular growth [22]. Based on previous studies of cultured granulosa cells without oocytes, BMP-4 promotes E$_2$ production by
inhibiting apoptosis [23] and promoting aromatase (P450arom) activity in cattle [21]. In addition, P4 production is inhibited by the suppression of steroidogenic acute regulatory protein (StAR) in cattle [24] and sheep [25] and cholesterol side chain cleaving (P450scc) in sheep [25] at the messenger RNA (mRNA) and protein levels. Moreover, BMP-4 promotes the FSH-mediated activation of E2 production, which is increased in the presence of oocytes [26]. On the other hand, P4 production was inhibited in a manner independent of the presence of oocytes in an in vitro study of rat granulosa cells [26]. Therefore, the addition of BMP-4, which compensates for the lack of theca cells, and FSH to the medium of IVG for bovine OCGCs may promote oocyte growth by promoting E2 production and inhibiting P4 production. According to our recent report, the addition of BMP-4 (10 ng/mL) to an IVG culture suppressed P4 production and did not affect oocyte growth, nuclear maturation, or fertilization, but impaired subsequent embryonic development and, at a higher concentration (50 ng/mL), even compromised the viability of OCGCs by suppressing the proliferation of granulosa cells [20]. In that study [20], we cultured OCGCs in medium that contained high concentrations of E2 (1 μg/mL) to increase the E2/P4 ratio similar to a dominant follicle; therefore, we were unable to correctly investigate the effects of BMP-4 and FSH on the steroidogenesis of granulosa cells. In the present study, we added BMP-4 and FSH to the growth medium without the addition of E2 and examined the production of sex steroid hormones from individually cultured OCGCs. We also retrospectively analyzed the correlation between the steroidogenesis of OCGCs during the IVG culture and the nuclear maturation of the corresponding
2. Materials and Methods

2.1. Chemicals

All chemicals used in this study were purchased from Sigma-Aldrich (St. Louis, MO, USA), unless indicated otherwise.

2.2. Collection of OCGCs and the IVG culture

Bovine ovaries obtained from a local abattoir were stored in plastic bags at 20°C and transported to the laboratory within 6-10 h of their collection. After the ovaries were washed three times with physiological saline, slices of ovarian cortex tissues (< 1 mm thickness) were prepared using a surgical blade (no. 11) and stored in tissue culture medium 199 (TCM-199; Thermo Fisher Scientific, Roskilde, Denmark) supplemented with 0.1% polyvinyl alcohol, 25 mM 2-[4-(2-Hydroxyethyl)-1-piperazinyl] ethanesulfonic acid (HEPES), 10 mM sodium bicarbonate, and 50 μg/mL gentamicin sulfate (isolation medium, pH 7.4) at 37 °C, as described elsewhere [8]. Under a stereomicroscope, early antral follicles (0.5 to 1 mm in diameter) were dissected from sliced ovarian tissues using a surgical blade (no. 20) and fine forceps in a 90-mm petri dish that had a 1-mm² scale on its bottom (FLAT Co., Ltd., Chiba, Japan). OCGCs were isolated from early antral follicles using a pair of fine forceps and subjected to IVG as previously described [27]. The growth
medium was HEPES-buffered TCM-199 supplemented with 0.91 mM sodium pyruvate, 5% (v/v) fetal calf serum (FCS; Invitrogen), 4 mM hypoxanthine, 4% (w/v) polyvinylpyrrolidone (MW 360,000), 50 μg/mL ascorbic acid 2-glucoside (Wako Pure Chemical Industries, Ltd., Osaka, Japan), 55 μg/mL cysteine, 50 μg/mL gentamicin sulfate, and 10 ng/mL androstenedione (A₄) as a precursor for E₂ [11]. OCGCs with oocytes surrounded by a cumulus investment and an attached mural granulosa-cell layer (Fig. 1) were cultured individually in a 96-well culture plate (Primaria 353872, Corning Life Sciences, Tewksbury, MA, USA) with 200 μL of growth medium at 39 °C for 12 days in humidified air with 5% CO₂. At the onset of the IVG culture, OCGCs were photographed under an inverted microscope (CK 40, Olympus, Tokyo, Japan) with an attached CCD camera (Moticam 2000, Shimadzu Rika Corporation, Tokyo, Japan). The diameters of the oocytes were assessed using software (Motic Images Plus 2.2s, Shimadzu). Every 4 days of the IVG culture, half (100 μL) of the growth medium was replaced with the same amount of fresh medium. Spent media collected at 4, 8, and 12 days of culture were stored at -30 °C until steroid hormone assays were conducted.

2.3. Evaluation of OCGC morphology

After 4 days of IVG culture, the morphological appearance of OCGCs was examined (Fig. 1). OCGCs with an evenly granulated ooplasm that were completely enclosed by several layers of healthy cumulus and granulosa cells were defined as normal. When OCGCs had oocytes with an abnormal appearance and/or oocytes were denuded by scattering cumulus and granulosa cells,
OCGCs were defined as abnormal.

2.4 Evaluation of the characteristics of granulosa cells

The total number, viability, and diameter of granulosa cells after growth culture from morphologically normal OCGCs on days 8 and 12 were assessed using an acridine orange/propidium iodide cell viability kit together with a cell counter (F23001 and L2000, respectively; Logos Biosystems, Gyunggi, Republic of Korea) as previously described [20]. The culture medium in the well of each viable OCGC was removed and replaced with 80 μL of Dulbecco’s PBS without calcium and magnesium (DPBS) supplemented with 0.125% trypsin and 0.05% EDTA to prepare the granulosa cells for counting. After 10 min of trypsinization and pipetting several times, 20 μL of FCS were added to stop the digestion. Denuded oocyte was removed from the well and discarded.

2.5 Evaluation of nuclear status of oocyte after IVG and IVM

After 12 days of IVG culture, oocytes surrounded by several layers of cumulus cells were collected from morphologically normal OCGCs by aspiration using a fine glass pipette. Immediately after IVG, some of the oocytes were denuded from cumulus cells by individually pipetting, and fixed in 10 μL of DPBS containing 60% (v/v) methanol in each well of micro-well plates (Mini Trays 163118, NUNC, Roskilde, Denmark) for 30 min. After fixation, oocytes were stained with 5 μg/mL Hoechst 33342 in 10 μL of DPBS in each well of the micro-well plate at 37 °C.
for 15 min in the dark, as described elsewhere [28]. The nuclear status was then evaluated under an inverted fluorescence microscope (ECLIPSE TE300, Nikon, Tokyo, Japan) using a UV filter (excitation 334–365 nm) to confirm meiotic arrest. Oocytes with a nuclear envelope were defined as being in the germinal vesicle stage. Other oocytes were submitted to individual IVM as previously described [29]. Oocytes surrounded by several layers of cumulus cells were washed with IVM medium, which consisted of HEPES-buffered TCM-199 supplemented with 0.2 mM sodium pyruvate, 20 μg/mL FSH, 1 μg/mL E2, 10% FCS, and 50 μg/mL gentamicin sulfate. IVM of oocytes was performed in each well of micro-well plates filled with 6 mL of IVM medium at 39 °C under 5% CO2 in air for 22 h. After IVM, oocytes were denuded from cumulus cells by individually pipetting, photographed, and their diameters measured. Oocytes were mounted individually on a slide glass and fixed with a mixture of acetic acid and ethanol (1:3) for 6 h. After fixation, oocytes were stained with 1% (w/v) aceto-orcein and the status of their nuclei was examined under a phase contrast microscope, as described elsewhere [30]. Oocytes that reached metaphase II and had a polar body were defined as mature; oocytes with other nuclear statuses were defined as immature.

2.6. E2 and P4 assays

Spent media (100 μL) from IVG cultures were assayed to determine the E2 and P4 concentrations using a competitive double antibody enzyme immunoassay, as previously described
Samples were subjected to 2- to 2000-fold serial dilutions with assay buffer (145 mM NaCl, 40 mM Na₂HPO₄, and 0.1% BSA (w/v), pH 7.2). Diluted samples (20 μL) were incubated with the primary antisera and HRP-labeled hormone (100 μL each) in the wells of a 96-well microplate (Costar 3590, Corning, NY, USA) coated with the secondary antiserum for 16–18 h at 4 °C. The primary antisera used for the E₂ and P₄ assays were anti-estradiol-17β-6-CMO-BSA (QF-121, Teikoku Hormone Mfg. Co. Ltd., Kanagawa, Japan) and anti-progesterone-3-CMO-BSA (7720-0504, Biogenesis, Poole, England), respectively. Goat anti-rabbit serum (270335, Seikagaku, Tokyo, Japan) was used as the secondary antiserum. After washing all wells four times with 300 μL of washing buffer (0.05% Tween 80), 150 μL of TMB solution (5 mM citric acid, 50 mM Na₂HPO₄, 500 mM UHP, 1 mM TMB, and 2% DMSO) were added to each well and incubated at 37 °C for 40 min. The absorbance of the solution in the wells was measured at 450 nm using a microplate reader (Model 550, Bio-Rad Laboratories, Tokyo, Japan) after stopping the chromogenic reaction with 50 μL of 4 N H₂SO₄. All samples were assayed in triplicate. Assay sensitivities were 7.1 pg/well for E₂ and 11.2 pg/well for P₄. The inter- and intra-assay coefficients of variation were 15.8 and 4.0% for E₂ and 17.5 and 3.9% for P₄, respectively.

2.7. Experimental design

2.7.1. Morphology and steroidogenic capacity of OCGCs

OCGCs were cultured in growth medium without BMP-4 or FSH for 4 days to select
healthy OCGCs that exhibited steroidogenic activity similar to developing follicles in vivo (Fig. 2). The correlation between the morphological normality of OCGCs and the production of steroid hormones was evaluated by measuring the concentrations of E₂ and P₄ in spent media. OCGCs defined as normal were subjected to subsequent experiments.

2.7.2. Effects of BMP-4 and FSH on the viability of OCGCs, the characteristics of granulosa cells, growth and maturation of oocytes, and steroidogenesis

Normal OCGCs were randomly divided into six groups after 4 days of IVG culture to evaluate the effects of BMP-4 and FSH on the functions of OCGCs. We cultured OCGCs for an additional 8 days (a total of 12 days of IVG culture) in growth medium supplemented with different concentrations of BMP-4 (0, 10, or 50 ng/mL; HZ-1045, Humanzyme, Chicago, IL, USA) and FSH (0 or 0.5 ng/mL) (Fig. 2). The concentrations of BMP-4 and FSH were determined according to previous studies in which granulosa cells were cultured in vitro [23, 25, 32]. In these studies, 10 and 50 ng/mL BMP-4 promoted cell viability [23] and suppressed P₄ production [25], whereas 0.5 ng/mL FSH enhanced the expression of the P450arom mRNA and E₂ production [32]. After 8 and 12 days of IVG culture, the viability of OCGCs was defined by the normality of their morphological appearance (Fig. 1); i.e., morphologically normal OCGCs were defined as having survived, whereas morphologically abnormal OCGCs were defined as dead. In addition, antrum formation in the granulosa cell layer was noted on day 12 of the IVG culture [6]. On day 12 of the IVG culture, 233 oocytes that were judged as having survived were subjected to IVM and nuclear maturation was
examined (5 to 20 oocytes/replicate). However, 12 oocytes were accidentally collapsed during the pipetting procedures for denudation from cumulus cells. Other oocytes that were not subjected to IVM were used to evaluate meiotic arrest immediately after the IVG culture. In vivo-derived oocytes collected from antral follicles of 2-8 mm in diameter were also subjected to IVM and served as in vivo controls. Oocyte growth was evaluated as the difference in oocyte volume calculated based on diameters [33] before the IVG culture and after IVM.

The concentrations of E$_2$ and P$_4$ in spent media collected on days 8 and 12 of the IVG culture were measured to evaluate the steroidogenesis of OCGCs that survived for the 12 days of IVG culture. Steroid hormone production during each period (days 4 to 8 and days 8 to 12) was calculated using the following formula:

$$\text{Steroid hormone production (ng)} = 0.2 \, (\text{mL}) \times \text{Concentration at the end of the period (ng/mL)}$$

$$- 0.1 \, (\text{mL}) \times \text{Concentration at the start of the period (ng/mL)}$$

Three hundred forty-eight OCGCs were cultured to evaluate the characteristics of the granulosa cells, and the total number, viability, and diameter of granulosa cells from OCGCs that had survived on day 8 (90 OCGCs) and day 12 (93 OCGCs) were assessed. OCGCs were divided based on whether an antrum had formed or not and whether OCGCs produced mature or immature oocytes to evaluate the relationship between OCGC characteristics and steroidogenesis. The relationships between these factors and steroidogenesis (the production of E$_2$ and P$_4$ and the E$_2$/P$_4$ ratio) were then retrospectively examined.
2.8. Statistical analysis

All statistical analyses were performed using software (JMP version 10, SAS Institute, Cary, NC, USA and StatView 4.51, Abacus Concepts, Inc., Calabasas, CA, USA). Differences in steroid hormone production from OCGCs which had normal or abnormal appearance were analyzed using Student’s $t$-test. The effects of BMP-4 and FSH on the viability of OCGCs and the nuclear maturation of IVG oocytes were analyzed using a chi-square test. The differences in oocyte volumes between experimental groups cultured with the same FSH concentrations were analyzed using Tukey-Kramer’s HSD test. Volumes of oocytes cultured with the same BMP-4 concentrations were analyzed using Student’s $t$-test. Oocyte volumes measured before and after IVG were compared using Dunnett’s test. The volume before IVG served as a control. The differences in the production of steroid hormones and the characteristics of granulosa cells between experimental groups within the same culture period were compared using a one-way ANOVA followed by Tukey-Kramer’s HSD test. The differences in steroid production and the characteristics of granulosa cells between days 4 to 8 and days 8 to 12 of culture were analyzed using Student’s $t$-test. In the retrospective analysis, the relationship between antrum formation and steroid production was analyzed using Student’s $t$-test. The characteristics of OCGCs (oocyte volume and steroid production) between OCGCs that produced mature and immature oocytes were compared using Student’s $t$-test. The difference in antrum formation between OCGCs that
produced mature and immature oocytes was analyzed using a chi-square test.

3. Results

3.1. Morphology and steroidogenic capacity of OCGCs

Nine hundred eight OCGCs (8 to 60 OCGCs/replicate) were cultured in growth medium without the addition of BMP-4 or FSH. After 4 days of IVG culture in the absence of both BMP-4 and FSH, 93.7% (851/908) of OCGCs had a normal appearance. E₂ and P₄ levels were then measured in culture media collected from 475 OCGCs with a normal appearance and 10 OCGCs with an abnormal appearance. As shown in Fig. 3, OCGCs with a normal appearance produced more E₂ (P < 0.01) and less P₄ (P < 0.01) than abnormal OCGCs.

3.2. Effects of BMP-4 and FSH on the viability of OCGCs, the characteristics of granulosa cells, growth and maturation of oocytes, and steroidogenesis

Eight hundred fifty-one OCGCs were cultured in media containing BMP-4 (0, 10, or 50 ng/mL) and FSH (0 or 0.5 ng/mL), and 718 OCGCs were cultured until day 12; the remaining 133 OCGCs were cultured until day 8 to evaluate the characteristics of granulosa cells. The viabilities of OCGCs on days 8 and 12 of IVG culture are shown in Table 1. After 8 days of culture, the group cultured with 10 ng/mL BMP-4 in the absence of FSH showed higher viability than the group cultured with 50 ng/mL BMP-4 in the absence of FSH (P < 0.05). In the presence of 50 ng/mL
BMP-4, the group cultured with 0.5 ng/mL FSH showed higher viability than the group cultured without FSH on days 8 (P < 0.05). The viability of the group cultured with 10 ng/mL BMP-4 and 0.5 ng/mL FSH was similar between days 8 and 12; however, the viability of other groups decreased from days 8 to 12. As shown in Fig. 4, on day 8, the group cultured with 10 ng/mL BMP-4 and 0.5 ng/mL FSH showed the highest total number of granulosa cells (approximately 68,000 cells), which was larger than that in the group cultured with 50 ng/mL BMP-4 and 0.5 ng/mL FSH (approximately 42,500 cells, P < 0.05). Also, the number was slightly larger than the group cultured with 10 ng/mL BMP-4 in the absence of FSH (approximately 47,000 cells, P = 0.06). On day 12, no significant differences were observed in the total number of granulosa cells between the experimental groups. The total numbers of granulosa cells observed on days 8 and 12 were similar in the same experimental groups. The viability of granulosa cells on day 8 was approximately 100% in all experimental groups. On day 12, viability was greater than 90% in all groups and small differences were observed between the experimental groups. The highest viability was observed for cells cultured with 50 ng/mL BMP-4 in the absence of FSH (98.9%), and the lowest viability was observed for cells cultured with 50 ng/mL BMP-4 and FSH (92.5%). The addition of FSH to the groups cultured with 10 ng/mL BMP-4 (0 ng/mL FSH, 11.5 µm; 0.5 ng/mL FSH, 12.4 µm; P < 0.01) and 50 ng/mL BMP-4 (0 ng/mL FSH, 11.1 µm; 0.5 ng/mL FSH, 12.0 µm; P = 0.05) increased the diameters of granulosa cells measured on day 8; however, no significant differences were observed between experimental groups on day 12.
The mean volumes of oocytes in all groups before the IVG culture were similar; therefore, the mean values of all groups were used as controls prior to the IVG culture. As shown in Fig. 5, the mean volumes of oocytes in all groups were larger after IVG culture than before IVG (P < 0.05). In addition, the mean volumes of oocytes were similar in the groups cultured with 0 and 10 ng/mL BMP-4 regardless of whether FSH was added following IVM. However, in the groups cultured with 50 ng/mL BMP-4, oocyte volumes were larger in the group cultured without FSH than in the group cultured in the presence of FSH (P < 0.05).

Two hundred thirty-three oocytes were studied to evaluate effects of BMP-4 and FSH on nuclear maturation. Immediately after IVG, before IVM culture, all oocytes were arrested at the stage of the germinal vesicle. The results are summarized in Table 2. After the IVM culture, only oocytes derived from OCGCs cultured with 50 ng/mL BMP-4 in the absence of FSH showed a maturation rate similar to oocytes grown in vivo, whereas oocytes derived from other cultures had lower rates of nuclear maturation compared to the in vivo control (P < 0.05).

E2 and P4 production were evaluated in 364 cultures with BMP-4 (0, 10, or 50 ng/mL) and FSH (0 or 0.5 ng/mL), and results are shown in Fig. 6. E2 was produced at a lower level from days 8 to 12 than from days 4 to 8, whereas P4 production increased in all groups during culture (P < 0.05). From days 4 to 8, E2 production did not significantly differ between the groups cultured without FSH, regardless of the presence or absence of BMP-4. In the presence of FSH, production decreased in the group cultured with 50 ng/mL BMP-4 (P < 0.01). Additionally, the addition of
FSH to the groups cultured with 0 and 10 ng/mL of BMP-4 increased P₄ production from days 4 to 8 (P < 0.05). Between days 8 and 12, the addition of BMP-4 decreased E₂ production, regardless of whether FSH was added (P < 0.05). FSH decreased E₂ production in the group cultured with 50 ng/mL BMP-4 (P < 0.01). The group cultured with 10 ng/mL BMP-4 in the absence of FSH exhibited the lowest production of P₄, regardless of the culture period.

After 12 days of culture, 364 OCGCs were evaluated for antrum formation, which was observed in 96 OCGCs. As shown in Table 3, OCGCs with antra on day 12 produced larger amounts of E₂ from days 4 to 8 (P < 0.01) and smaller amounts of P₄ in both periods than OCGCs without an antrum (P < 0.01). As shown in Table 4, oocytes that achieved nuclear maturation had larger diameters than oocytes without nuclear maturation (P < 0.01) after the IVM culture. In addition, OCGCs that produced mature oocytes generated slightly larger amounts of E₂ (P = 0.10) and less P₄ (P = 0.09) between days 4 and 8 than OCGCs that produced immature oocytes. Although no significant differences were observed in the mean values obtained for E₂ and P₄ production from days 8 to 12, the E₂/P₄ ratio varied markedly. E₂ and P₄ production varied in OCGCs that generated mature oocytes throughout the duration of the IVG culture. Some of the oocytes that achieved nuclear maturation showed markedly high E₂/P₄ ratios. No obvious relationship was observed between the nuclear maturation of IVG oocytes and antrum formation in the granulosa cell layer.
4. Discussion

In the present study, OCGCs that had a normal appearance 4 days after the initiation of the IVG culture produced a large amount of $E_2$ and less $P_4$ during the initial period of the IVG culture.

During the *in vivo* development of a dominant follicle, the $E_2$ concentration increases as follicles grow [14, 15]. Thus, we only used healthy OCGCs in subsequent experiments to evaluate the effects of BMP-4 and FSH on steroidogenesis and oocyte maturation.

On day 8 of the IVG culture, the viability of the group cultured with 10 ng/mL BMP-4 was higher than the group cultured with 50 ng/mL BMP-4 ($P < 0.05$) when OCGCs were cultured without FSH. The low viability of OCGCs cultured with 50 ng/mL BMP-4 may stem from a decrease in granulosa cell numbers, as we reported previously [20]. Actually, the lowest number of granulosa cells was observed on day 8 in the group cultured with 50 ng/mL BMP-4 (approximately 41,000 cells/well) among all groups tested (approximately 47,000 cells/well) in the absence of FSH, although the values were not significantly different. On the other hand, when 0.5 ng/mL FSH was added to growth medium, the viability of OCGCs in the group cultured with 50 ng/mL BMP-4 improved on days 8 and 12. In the present study, we only examined OCGCs that had survived; therefore, we could not find the increase of granulosa cell number. We speculate that the result may be attributed to the increased proliferation of granulosa cells by the addition of 0.5 ng/mL FSH from days 4 to 8 [34], and was particularly apparent in the group cultured with 10 ng/mL BMP-4 and FSH, which showed the highest viability on day 12 (approximately 68,000 cells/well).
Between days 4 and 8 of the IVG culture, the addition of 10 ng/mL BMP-4 and 0.5 ng/mL FSH did not affect E₂ production by OCGCs; however, this supplementation regime decreased P₄ production compared to cultures with 0.5 ng/mL FSH in the absence of BMP-4. On the other hand, no significant differences were noted between the number of granulosa cells in both groups; therefore, under the present culture conditions containing serum, 10 ng/mL BMP-4 may inhibit P₄ production by granulosa cells by suppressing StAR [24, 25] and P450scc [25] at the mRNA and protein levels. However, P450arom may not be enhanced, because previous studies showed that P450arom activity is increased in granulosa cells cultured without serum [21, 34]. A study that cultured granulosa cells for 6 days in the presence of serum showed that the expression of the P450arom gene was suppressed, but not StAR and P450scc [17]. These findings indicate that the luteinization of granulosa cells induced by serum counteracts the stimulatory effects of BMP-4 on E₂ production. Our results demonstrated that this supplementation regime permitted OCGCs to partially mimic developing follicles, which secrete E₂ as follicles develop and the E₂/P₄ ratio increases [15]. However, 0.5 ng/mL FSH increased P₄ production from days 4 to 8 and particularly from days 8 to 12. Previous studies reported that in vivo-grown large luteal cells (38.4 μm in diameter) originated from granulosa cells and in vitro-luteinized granulosa cells (38.4 μm) are larger than granulosa cells in pre-ovulatory follicles (10.6 μm) [35, 36]. Under our culture conditions, the mean diameter of granulosa cells on day 8 increased with the addition of FSH to medium containing 10 ng/mL BMP-4 (0 ng/mL FSH, 11.5 μm vs. 0.5 ng/mL FSH, 12.4 μm; P < 0.01) or 50 ng/mL
BMP-4 (0 ng/mL FSH, 11.1 µm vs. 0.5 ng/mL FSH, 12.0 µm; P = 0.05). FSH appears to have enhanced the luteinization of granulosa cells under the present IVG conditions, as has been reported previously [37]. On day 12 of the IVG culture, no significant differences were observed in the diameters of granulosa cells between experimental groups; however, the group cultured with 50 ng/mL BMP-4 in the absence of FSH showed a larger diameter (12.2 µm) than the same group on day 8 of the IVG culture (11.1 µm, P < 0.05). These results indicate that the anti-luteinizing effects of BMP-4 were lost when the culture period was extended.

A previous study that cultured granulosa cells for 6 days in serum-free media demonstrated that E₂ and P₄ production increased as the culture period was extended [38]. According to our results, the production of E₂ from cultured OCGCs was maintained at least until day 8, even when the medium contained serum. However, granulosa cells are apparently unable to stably produce E₂ for the 12 days of IVG culture. High densities of granulosa cells have been shown to inhibit E₂ secretion and P₄ expression and also to increase P₄ secretion and the levels of mRNA encoding progestogenic enzymes, such as StAR and P450sc5c [39]. We previously reported that the number of granulosa cells peaked on day 12 of the IVG culture and then decreased [40]. These findings indicate that luteinization progresses as the density of granulosa cells increases.

OCGCs cultured with 50 ng/mL BMP-4 in the absence of FSH showed the lowest viability; however, the surviving oocytes derived from these OCGCs had the largest volumes and highest levels of meiotic competence. The meiotic competence of bovine oocytes grown in vivo
increases as oocytes [41, 42] and follicles [43] grow. The administration of exogenous BMP-4 during IVG (50 ng/mL) [20] and IVM (100 ng/mL) [44, 45] did not affect oocyte nuclear maturation in previous studies. Thus, BMP-4 does not directly promote oocyte nuclear maturation. However, OCGCs, which can produce oocytes with higher maturational competences, may survive in the presence of higher concentrations of BMP-4 in the absence of FSH, and the highest viability of granulosa cells was also observed on day 12 (98.9%). Based on these results, we speculate that OCGCs producing oocytes with high intrinsic developmental competence may survive in the presence of high concentrations of BMP-4. In further studies, the relationship between oocyte competence and the function of granulosa cells needs to be examined.

In addition, FSH did not promote the nuclear maturation of oocytes in the present study. A previous study that cultured bovine OCGCs for 14 days with a higher concentration of FSH (3.5 mg/mL) showed that no oocytes progressed to the metaphase II stage and 73.3% of oocytes degenerated after IVM [46]. According to another study, the addition of 10 μg/mL FSH improved cumulus expansion, whereas the proportion of oocytes at metaphase II after IVM did not significantly differ from cultures that did not include FSH [47]. These findings and the present results suggest that FSH does not affect the maturational competence of bovine oocytes, although FSH improves granulosa cell proliferation [34] and cumulus expansion [47].

In the present study, OCGCs that formed antra produced more E₂ and less P₄ than OCGCs without an antrum. As reported in the study by Endo et al. [48], OCGCs that formed antra
exhibited similar levels of gene expression to healthy follicles that grew in vivo. Thus, antrum formation in the granulosa cell layer is related to the steroidogenesis of OCGCs. On the other hand, we were unable to detect a relationship between oocyte maturation and antrum formation in the granulosa cell layer, as has been described in a previous study [48]; however, OCGCs that produced mature oocytes produced slightly more E2 and less P4 during the IVG culture than OCGCs that produced immature oocytes. Furthermore, some of the OCGCs that produced mature oocytes secreted extremely large quantities of E2. In the present study, we added A4 to medium instead of the E2 used in the previous study [20], and did not observe any effects of BMP-4 on nuclear maturation. These results suggest that the ability to produce E2 by granulosa cells has an important effect on the acquisition of oocyte ability. In future studies, we need to investigate the relationships between the maturational competence of oocytes, the steroidogenesis of granulosa cells and antrum formation, and the expression dynamics of growth factors and their receptors, such as BMP-4, in more detail.

5. Conclusions

Based on the results of the present study, BMP-4 inhibits the luteinization of granulosa cells and FSH enhances the proliferation of granulosa cells, viability of OCGCs and the luteinization of granulosa cells. Moreover, cultured OCGCs with antra that produce a large amount of E2 and less P4 are similar to follicles that are grown in vivo. However, E2 production increased until day 8.
of the culture and then decreased. In conclusion, an IVG culture with 10 ng/mL BMP-4 in the absence of FSH partially mimics in vivo steroidogenesis and the development of growing follicles until day 8 of culture. The same conditions also mimic the steroidogenesis of degenerating follicles from days 8 to 12 of the culture, particularly in the presence of FSH. The addition of serum to the growth medium may have enhanced the luteinization of granulosa cells in the present study; however, oocytes derived from serum-free cultures had low maturational competence and low fertilizability in previous studies [18, 19]. In further studies, we should develop an IVG system that does not use serum but enhances oocyte competence, or a system that inhibits the luteinization of granulosa cells even when the growth medium contains serum.

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Figure Legends

Fig. 1. Oocyte-cumulus-granulosa complexes (OCGCs) before and after day 4 of the growth culture. The left panel shows an OCGC before the growth culture. OCGCs with oocytes surrounded by a cumulus investment and an attached mural granulosa cell layer were subjected to the growth culture. The white arrow head indicates the cumulus investment. The black arrow head indicates the mural granulosa cell layer. The central panel shows an OCGC with an evenly granulated ooplasm enclosed by several layers of healthy granulosa cells. The right panel shows an OCGC that has an abnormal appearance with a degenerated oocyte. Scale bars indicate 100 µm.

Fig. 2. Schematic of experimental design

Firstly, oocyte-granulosa cell complexes (OCGCs) were cultured in growth medium without bone morphogenetic protein-4 (BMP-4) and FSH for 4 days. Morphologically normal OCGCs were cultured for an additional 8 days in growth medium supplemented with different concentrations of BMP-4 (0, 10, or 50 ng/mL) and FSH (0 or 0.5 ng/mL). On day 12 of the IVG culture, oocytes judged as having survived were subjected to IVM. The assessments described in the schematic were conducted at days 0, 4, 8, and 12 and after IVM.

Fig. 3. Steroidogenesis of oocyte-cumulus-granulosa-complexes (OCGCs) on day 4 of the growth culture.
** Asterisks indicate significant differences between normal and abnormal OCGCs (P < 0.01).

Numbers in parentheses indicate the number of OCGCs evaluated.

Error bars indicate the SEM.

Fig. 4. Effects of bone morphogenetic protein-4 (BMP-4) and FSH on the number, viability, and diameter of granulosa cells at different culture periods.

Different letters indicate significant differences between OCGCs cultured without FSH in the same culture period (P < 0.05).

Different letters indicate significant differences between OCGCs cultured with FSH in the same culture period (P < 0.05).

* Asterisks indicate significant differences between OCGCs cultured with the same BMP-4 concentration in the same culture period (P < 0.05).

Error bars indicate the SEM.

Fig. 5. Effects of bone morphogenetic protein-4 (BMP-4) and FSH on the oocyte volume after the growth culture.

Lines on the boxes delineate the 25th, 50th, and 75th percentiles, whereas the whiskers depict the 10th and 90th percentiles.

Values above boxes indicate the mean diameters (μm) of oocytes.
Values under boxes indicate the numbers of oocytes examined and the number of replicates are shown in parentheses.

* An asterisk indicates a significant difference between groups cultured with and without FSH in the presence of the same BMP-4 concentration (P < 0.05).

† A dagger indicates a significant difference between the values measured before and after IVG in all groups (P < 0.05).

Fig. 6. Effects of bone morphogenetic protein-4 (BMP-4) and FSH on steroidogenesis in oocyte-cumulus-granulosa complexes (OCGCs) at different culture periods.

In all experimental groups, E\textsubscript{2} was produced at a lower level between days 8 and 12 than between days 4 and 8 (P < 0.05); P\textsubscript{4} was produced at a higher level between days 8 and 12 than between days 4 and 8 (P < 0.05).

\textsuperscript{a,b} Different letters indicate significant differences between OCGCs cultured without FSH in the same culture period (P < 0.05).

\textsuperscript{x,y} Different letters indicate significant differences between OCGCs cultured with FSH in the same culture period (P < 0.05).

\textsuperscript{*,**} Asterisks indicate significant differences between OCGCs cultured with the same BMP-4 concentration in the same culture period (*P < 0.05; **P < 0.01).

Error bars indicate the SEM.
Fig. 1
Fig. 2

Assessments

- Oocyte volume
- Morphology of OCGCs $E_2 \cdot P_4$ production
- Viability of OCGCs Characteristics of granulosa cells $E_2 \cdot P_4$ production
- Oocyte volume Nuclear status of oocytes

Timeline:
- 0
- 4
- 8
- 12 days
- 22 h

Events:
- Cultured without BMP-4 and FSH
- Cultured with 0, 10 and 50 ng/mL BMP-4 and 0, 0.5 ng/mL FSH
- IVM
- IVG
Fig. 3
Fig. 4

Day 8

Total cell number ($10^7$ cells/well)

Day 12

Viability (%)

Diameter ($\mu$m)

FSH 0 0.5 0 0.5 0 0.5

BMP-4 0 10 50 0 0.5 0 0.5

(ng/mL) (ng/mL) (17) (11) (14) (12) (17) (19) (14) (19) (19) (14) (13) (14)
Fig. 5

Volume of oocytes ($\times 10^3 \, \mu m^3$)

<table>
<thead>
<tr>
<th>FSH</th>
<th>BMP-4</th>
<th>Before IVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>233 (23)</td>
</tr>
<tr>
<td>0.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

| 112.5 | 47 (5) |
| 113.3 | 46 (4) |
| 112.9 | 44 (3) |
| 114.1 | 31 (4) |
| 110.1 | 33 (3) |

97.0 $\mu m$

* †
Fig. 6

Days 4 to 8

Days 8 to 12

 Estradiol-17β (ng/well)

 Progesterone (ng/well)

FSH

BMP-4

(68) (82) (48) (45) (55) (66)

(68) (82) (48) (45) (55) (66)

(ng/mL)

(ng/mL)
Table 1. Effects of bone morphogenetic protein-4 (BMP-4) and FSH on the viability of oocyte-cumulus-granulosa complexes (OCGCs) during the growth culture.

<table>
<thead>
<tr>
<th>Experimental groups</th>
<th>Day 8</th>
<th>Day 12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of oocytes (replicates)</td>
<td>% of viable OCGCs</td>
</tr>
<tr>
<td>BMP-4 (ng/mL)</td>
<td>FSH (ng/mL)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>158 (14)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>172 (16)</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>120 (10)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>103 (8)</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>153 (10)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>145 (10)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>851* (68)</td>
</tr>
</tbody>
</table>

* One hundred and thirty-three OCGCs were used to evaluate the granulosa cell characteristics on day 8.

<sup>a,b</sup> Different superscripts indicate differences between groups in the same culture period (P < 0.05).

<sup>x,y</sup> Different superscripts indicate significant differences between days 8 and 12 in the same group (P < 0.05).

Table 2. Effects of bone morphogenetic protein-4 (BMP-4) and FSH on the nuclear maturation of oocytes after the maturational culture.

<table>
<thead>
<tr>
<th>Experimental groups</th>
<th>No. of oocytes (no. of replicates)</th>
<th>% of nuclear maturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMP-4 (ng/mL)</td>
<td>FSH (ng/mL)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>32 (4)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>47 (5)</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>46 (4)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>44 (3)</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>31 (4)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>33 (3)</td>
</tr>
<tr>
<td>Oocytes grown in vivo</td>
<td></td>
<td>79 (7)</td>
</tr>
</tbody>
</table>

<sup>a,b</sup> Different superscripts indicate significant differences within a column (P < 0.05).
Table 3. Relationship between antrum formation in the granulosa cell layer on day 12 and steroidogenesis in oocyte-cumulus-granulosa complexes (OCGCs) in different culture periods.

<table>
<thead>
<tr>
<th>Antrum formation on day 12 (n)</th>
<th>$E_2$ (ng/well) Days 4 to 8</th>
<th>$E_2$ (ng/well) Days 8 to 12</th>
<th>$P_4$ (ng/well) Days 4 to 8</th>
<th>$P_4$ (ng/well) Days 8 to 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (96)</td>
<td>$1.5 \pm 0.9^a$</td>
<td>$0.8 \pm 1.0$</td>
<td>$5.8 \pm 6.4^b$</td>
<td>$13.9 \pm 18.4^b$</td>
</tr>
<tr>
<td>No (268)</td>
<td>$1.2 \pm 1.0^b$</td>
<td>$0.7 \pm 0.8$</td>
<td>$10.9 \pm 12.4^a$</td>
<td>$42.3 \pm 58.4^a$</td>
</tr>
</tbody>
</table>

Values are presented as means ± SD.

$^a,b$ Different superscripts indicate significant differences within a column ($P < 0.01$).
Table 4. Relationship between the nuclear maturation of oocytes, oocyte growth, steroidogenesis, and antrum formation by oocyte-cumulus-granulosa complexes (OCGCs).

<table>
<thead>
<tr>
<th>Nuclear Status*</th>
<th>Diameter of oocytes (µm)</th>
<th>E₂ (ng/well)</th>
<th>P₄ (ng/well)</th>
<th>E₂/P₄ ratio (range)</th>
<th>% of antrum formation (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>before IVG</td>
<td>after IVM</td>
<td>Days 4 to 8</td>
<td>Days 8 to 12</td>
<td>Days 4 to 8</td>
</tr>
<tr>
<td>Mature (167)</td>
<td>97.3 ± 5.0</td>
<td>113.5 ± 4.9ᵃ</td>
<td>1.2 ± 0.8</td>
<td>0.5 ± 0.7</td>
<td>9.0 ± 10.7</td>
</tr>
<tr>
<td>Immature (66)</td>
<td>96.3 ± 5.1</td>
<td>110.0 ± 5.6ᵇ</td>
<td>1.0 ± 0.9</td>
<td>0.4 ± 0.7</td>
<td>12.1 ± 16.6</td>
</tr>
</tbody>
</table>

Values are presented as means ± SD.
* Oocytes at metaphase II were defined as mature.
ᵃᵇ Different superscripts indicate significant differences within a column (P < 0.01).