Effect of bovine oviductal extracellular vesicles on embryo development and quality in vitro

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Abstract

The aim of this study was to evaluate the effect of extracellular vesicles (EV) from oviductal fluid (OF), either from the ampulla or isthmus, on the development and quality of in vitro-cultured bovine embryos. Zygotes were cultured in synthetic oviduct fluid (SOF + 3 mg/mL BSA) without calf serum (C− group), in the presence of 3 x 10^4 EV/mL from ampullary or isthmic OF at either 1 x 10^4 g (10K) or 1 x 10^5 g (100K), and compared with SOF + 5% FCS (C+ group). OF-EV size and concentration were assessed by electron microscopy and nanotracking analysis system. Embryo development was recorded on Days 7–9, and blastocyst quality was assessed through cryotolerance and gene expression analysis. Lower blastocyst yield was observed on Day 7 in the C− and OF-EV groups (12.0–14.3%) compared with C+ (20.6%); however, these differences were compensated at Days 8 and 9 (Day 9: 28.5–30.8%). Importantly, the survival rate of blastocysts produced with isthmic 100K OF-EV was higher than that of C+ and C− group at 72h after vitrification and warming (80.1 vs. 34.5 and 50.5% respectively, P < 0.05). In terms of gene expression, blastocysts produced in the presence of 100K isthmic OF-EV upregulated the water channel AQP3 and DNMT3A and SNRPN transcripts compared with the C+, with the expression in C− being intermediate. The lipid receptor LDLR was downregulated in C+ compared with all other groups. In conclusion, the addition of oviductal fluid extracellular vesicles from isthmus, to in vitro culture of bovine embryos in the absence of serum improves the development and quality of the embryos produced.


Introduction

Despite considerable improvements in assisted reproductive technologies in the last several decades, conditions of in vitro embryo production are far from the physiological (Lonergan & Fair 2008). The in vitro deficiencies are reflected in lower embryo developmental rates and quality of the blastocysts produced when compared to their in vivo counterparts (Lonergan 2007), evidenced by lower cryotolerance (Rizos et al. 2008), altered inner cell mass/trophectoderm cell ratio (Plourde et al. 2012), altered gene expression patterns (Niemann & Wrenzycki 2000) and lower pregnancy rates of transferred embryos (Pontes et al. 2009). Biological complements added to culture media, such as serum and serum albumin, improve embryo developmental rates. However, it has been shown that serum exhibits a biphasic effect, increasing the number of transferable embryos but reducing their quality reflected in short-term (Rizos et al. 2003) and/or long-term effects such as large offspring syndrome (Lazzari et al. 2002).

The oviduct is a dynamic organ where fertilization and early embryo development takes place. Regulatory mechanisms modulate the fluidic milieu composition to allow sperm capacitation, transport and fertilization of the mature oocyte in the ampulla and early embryonic development in the isthmus (Leese et al. 2007, Rodriguez-Martinez 2007). It has been shown that the oviductal environment can support embryonic growth up to the blastocyst stage and produce better-quality embryos across a wide range of species after trans-species transfer (Rizos et al. 2010). Moreover, the use in vitro of oviductal epithelial cells (OEC) allows the study of mechanisms involved in sperm storage in the oviduct (Abe & Hoshi 1997) and the embryotrophic effects on early embryo development and quality (Cordova et al. 2014). Thus, the use of in vitro models can provide evidence on physiological embryo–maternal interactions, mechanisms that are difficult to study in vivo.

The OF is generated by transudation from plasma into the oviductal lumen supplemented with secreted substances from OEC (Menezo & Guerin 1997).
Secretions present in the OF affect oocyte and sperm function (Killian 2011, Mondéjar et al. 2013) and comprise proteins, such as glycodehins and lactoferrin, involved in gamete interaction (Ghersevich et al. 2015), oviductin, osteopontins and the complement protein C3 important for early embryo development (Tse et al. 2008), and oviductal glycoprotein 1 (OVGP1) important for sperm–zona pellucida binding (Coy et al. 2012). The use of pure bovine OF during in vitro maturation of porcine oocytes prior to fertilization improves embryo development and quality, protecting them against adverse impacts of mtDNA transcription/replication and apoptosis induced by the culture environment (Lloyd et al. 2009). In contrast in cattle, OF treatment of matured oocytes had no effect on fertilization parameters, cleavage rate, blastocyst yield or morphology. However, several gene transcripts related to embryo quality were upregulated in blastocysts (Cebrían-Serrano et al. 2013). When bovine zygotes were cultured in vitro with low concentrations of OF (1.25% and 0.625%), it was demonstrated that OF had a positive effect on the development and quality of the produced blastocysts (Lopera-Vasquez et al. 2015).

Extracellular vesicles (EVs) play an important role in intercellular communication and the regulation of physiological and pathological processes (for review, see Yanez-Mo et al. 2015). They contain and may transfer different bioactive molecules (proteins, mRNAs, miRNAs (Simons & Raposo 2009, Silveira et al. 2012) and lipids (Raposo & Stoorvogel 2013)). EV nomenclature commonly relates to EV size and origin, and includes exosomes (30–200 nm) of endosomal origin and microvesicles (MV) (100–1000 nm), those EV that bud from the plasma membrane. These major vesicle subtypes are commonly enriched by differential centrifugation (Théry et al. 2006). Smaller vesicles are typically isolated by sedimentation at 100,000–200,000 g (100–200 K) (Théry et al. 2009), whereas MVs are typically reported to be enriched at 10,000–20,000 g (10–20 K) (Witwer et al. 2013).

EVs have been identified in vivo in all body fluids studied including amniotic fluid, urine and blood (Simpson et al. 2008). Regarding reproduction, EVs have been reported in follicular fluid (Silveira et al. 2012), uterine fluid (Burns et al. 2014) endometrial environment (Ng et al. 2013) and seminal plasma (Piehl et al. 2013). Saadeldin and coworkers (Saadeldin et al. 2014) showed that the addition of exosomes isolated from the conditioned medium of parthenogenetic embryos increased the developmental competence of cloned embryos. Recently, we provided evidence that EV derived from media conditioned by bovine oviduct epithelial cells (BOEC) improves blastocyst quality and induces cryoprotection in in vitro culture to the same extent as classical co-culture with fresh BOEC monolayers (Lopera-Vasquez et al. 2016). Thus, the aim of the present study was to isolate EV from bovine OF and evaluate their effect on early embryonic development and quality of the blastocysts in vitro. This may contribute to the improvement of assisted reproduction technologies in mammals and humans as well as providing new insights on early embryo–maternal communication.

Materials and methods

Unless otherwise stated, all chemicals were purchased from Sigma Aldrich Química S.A.

Extracellular vesicle isolation

Ipsilateral oviducts from slaughtered heifers at the early or mid-luteal phase of the estrous cycle (based on corpus luteum morphology) were transported to the laboratory on ice. All oviducts were washed twice in PBS, and trimmed free of tissue on a cooled surface. The ampulla and isthmus was washed through the ampullary–isthmic junction, identified where the oviduct diameter first exhibited a marked reduction in size. Each oviductal region (ampulla and isthmus) was washed with 5 mL of PBS (4°C). After a first centrifugation for BOEC elimination (400 g), EV were pelleted under two sequential centrifugation (g) forces: (i) 10,000 g (10K) and (ii) 100,000 g (100K) following the procedures of Théry and coworkers (Théry et al. 2006) with minor modifications. Briefly, after BOEC removal, the OF was centrifuged at 10 K for 60 min at 4°C. Then, the supernatant was removed and centrifuged again at 100 K for 60 min at 4°C and the resultant pellet was recovered (Avanti J30i, Beckman Coulter). The EV recovered at 10 K and 100 K g-forces were washed in PBS and pelleted again under the previous conditions.

EV characterization

Nanoparticle tracking analysis (NTA)

A representative part (100 μL) of the resultant pellet (≈400 μL obtained vesicles) was used to determine the size and number of EV by NTA with Nanosight LM10 and NTA 2.3 Software (Nanosight, Wiltshire, UK). EV concentration was standardized, and samples were frozen for embryo culture.

Transmission electron microscopy (EM)

For negative staining of exosomes, ionized carbon and collodion-coated copper EM grids were floated on a sample drop, washed and stained with 2% uranyl acetate (in double-distilled water) for 1 min and visualized in a JEM-1010 (JEOL, Tokyo, Japan) transmission EM.

Western blot

EV preparations were lysed in non-reducing Laemmli loading buffer and resolved in a 4–25% gradient SDS-PAGE gel (Biorad). Proteins were transferred to a PVDF membrane (Biorad), blocked with 10% skimmed milk and incubated
with the following primary antibodies: anti-CD 9 mAb VJ1/20, anti-ERM 90:3 pAb and anti-TSG101 mab (Abcam) (Lopera-Vásquez et al. 2016) followed by peroxidase-coupled secondary antibodies and revealed by chemiluminescence with an ImageQuant LAS4000 biomolecular imager (GE LifeSciences).

**In vitro embryo production**

Oocyte collection and in vitro maturation

Immature cumulus oocyte complexes (COCs) were obtained by aspirating follicles (2–8 mm) from the ovaries of postpubertal heifers and cows collected at slaughter. Class 1 and 2 COCs were matured for 24 h in 500 µL of maturation media (TCM 199 supplemented with 10% (v/v) fetal calf serum (FCS) and 10 ng/mL epidermal growth factor) in a four-well dish, in groups of 50 COCs per well at 38.5°C under an atmosphere of 5% CO₂ in air, with maximum humidity.

Sperm preparation and in vitro fertilization

Frozen semen from a previously tested Asturian Valley bull (ASEAVA, Asturias, Spain) was thawed at 37°C in a water bath for 1 min and centrifuged for 10 min at 280 g through a gradient of 1 mL of 40% and 1 mL of 80% Bovipure according to the manufacturer’s specification (Nidacon Laboratories AB, Göthenborg, Sweden). The sperm pellet was isolated and washed in 3 mL of Boviwash (Nidacon) by centrifugation at 280 g for 5 min. The pellet was re-suspended in the remaining 300 µL of Boviwash. Sperm concentration was determined and adjusted to a final concentration of 1 × 10⁶ sperm/mL for IVF. Gametes were co-incubated for 18–22 h in 500 µL of fertilization media (Tyrode’s medium with 25 mM bicarbonate, 22 mM Na lactate, 1 mM Na-pyruvate, and 6 mg/mL fatty acid-free BSA supplemented with 10 mg/mL heparin sodium salt, Calbiochem) in a four-well dish, in groups of 50 COCs per well under an atmosphere of 5% CO₂ in air, with maximum humidity at 38.5°C.

**Assessment of embryo development and quality**

Embryo development

Cleavage rate was recorded at Day 2 (48 h p.i.), and cumulative blastocyst yield was recorded at Days 7, 8 and 9 p.i. under a stereomicroscope.

Embryo quality

Blastocyst vitrification

The ability of the blastocyst to withstand cryopreservation was used as a quality indicator. Days 7 and 8 blastocysts were vitrified in holding medium (HM) (TCM199 supplemented with 20% (v/v) FCS) and cryoprotectants, following the procedures of Rizos and coworkers (Rizos et al. 2002), in a two-step protocol using the Cryoloop device (Hampton Research, Aliso Viejo, CA, USA). First step: HM with 7.5% ethylene glycol, 7.5% dimethyl sulfoxide and second-step final solution: HM with 16.5% ethylene glycol, 16.5% dimethyl sulfoxide and 5% FCS (F2442 – Sigma).

Table 1 Details of primers used for qRT-PCR.

<table>
<thead>
<tr>
<th>Gene</th>
<th>Primer sequence (5′–3′)</th>
<th>Fragment size (bp)</th>
<th>Gene bank accession no.</th>
</tr>
</thead>
</table>
| H2A.Z  | Forward: ACGACGACTAGCCATGTGACGTG  
Reverse: CACCCACGGAAATTGACCTTG | 212 | NM_016750 |
| AQP3   | Forward: CCGTGTGTTTCTCCTCACTCA  
Reverse: CAGAGGGGGTAGTTGGGAAG | 299 | NM_001079794.1 |
| AQP11  | Forward: GGCTTCGATACCACTCGTCTG  
Reverse: TGAATGAAATGCGCCAAGG | 102 | NM_001110069.1 |
| ATP1A1 | Forward: GCCGACACGAGAAGCA | 158 | NM_001076798.1 |
| LDLR   | Forward: CAAAACCCCGCATTCCCAACCA  
Reverse: GAGGCATACCCCGTCAAG | 194 | NM_001166530 |
| LDHA   | Forward: TTCTTAAGGAAAGAATGTC  
Reverse: TTTCACTGCGAGAACAA | 310 | NM_174099.2 |
| DNMT3A | Forward: CGTGGTGTTGAAGACTTGGGC  
Reverse: CAGAAAGGGGGCGCTCATTAC | 318 | AY271299 |
| IGF2R  | Forward: GCTGGCGGTGCTCGAAAGGAAAG  
Reverse: AGGCCCTCTGTGCGTGGTACCT | 201 | NM_174352.2 |
| GRB10  | Forward: GAGAAGGAGGAGAGAACAAAGG  
Reverse: CTGGCACCACGTAACCATCTC | 291 | XM_010803961.1 |
| SNRPN  | Forward: AACAGCACGTACAGAAGG | 144 | NM_001079797.1 |
0.5 M sucrose. The blastocysts were warmed in two steps in HM with 0.25 M and 0.15 M sucrose and then cultured in 25 µL droplets of SOF with 5% FCS. Survival was defined as re-expansion of the blastocoel and its maintenance for 24, 48 and 72 h.

**Gene expression analysis**

Poly(A) RNA was extracted from five pools of 10 blastocysts from each experimental group using the Dynabeads mRNA Direct Extraction Kit (Dynal Biotech, Oslo, Norway) with minor modifications (Bermejo-Álvarez et al. 2008). Immediately after extraction, the RT reaction was carried out following the manufacturer’s instructions (Bioline, Ecogen, Madrid, Spain) using poly(T) primer, random primers and MMLV reverse transcriptase enzyme. The quantification of all mRNA transcripts was carried out by qPCR with two repetitions for all genes of interest. qPCR was performed by adding a 2 µL aliquot of each cDNA sample to the PCR mix containing the specific primers. All primers were designed using Primer-BLAST software to span exon-exon boundaries when possible (http://www.ncbi.nlm.nih.gov/tools/primer-blast/). Primer sequences and the approximate sizes of the amplified fragments of all transcripts are shown in Table 1. For quantification, qPCR was performed as described previously (Bermejo-Alvarez et al. 2010); PCR conditions were tested to achieve efficiencies close to 1. The comparative cycle threshold (CT) method was used to quantify expression levels. Values were normalized to the endogenous control, H2AFZ. Fluorescence was acquired in each cycle to determine the threshold cycle or the cycle during the log-linear phase of the reaction at which fluorescence increased above background for each sample. Within this region of the amplification curve, a difference of one cycle is equivalent to a doubling of the amplified PCR product. According to the comparative CT method, the ΔCT value was determined by subtracting the H2AFZ CT value for each sample from each gene CT value of the sample. The calculation of ΔΔCT involved using the highest treatment ΔCT value, i.e., the treatment with the lowest target expression, as an arbitrary constant to subtract from all other ΔCT sample values. Fold changes in the relative gene expression of the target were determined using the formula 2−ΔΔCT.

**Experimental design**

The developmental capacity of bovine zygotes and the quality of the produced blastocysts cultured in vitro with EV from

**Table 2** Concentration OF-EV isolated from OF at different cycle phases at different g-forces (10–100K).

<table>
<thead>
<tr>
<th>Cycle Phase</th>
<th>Centrifugal Force (g)</th>
<th>n</th>
<th>Concentration*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early (Day 1–4)</td>
<td>10K</td>
<td>5</td>
<td>2.8±1.2*</td>
</tr>
<tr>
<td></td>
<td>100K</td>
<td>5</td>
<td>9.28±4.1</td>
</tr>
<tr>
<td>Medium (Day 4–8)</td>
<td>10K</td>
<td>5</td>
<td>1.25±0.3*</td>
</tr>
<tr>
<td></td>
<td>100K</td>
<td>5</td>
<td>3.98±0.5*</td>
</tr>
</tbody>
</table>

n: Number of oviductal samples used in nanoparticle analysis system (Nanosight). K: Represents 1 × 103.

*EV particles/mL ± s.d. a,b,c Values in the same column with different superscripts differ significantly (P < 0.05).

Figure 1 Experimental design.

Figure 2 Electron microscope images and NTA analyses of OF-EV isolated at 10K (A and C) and 100K (B and D) g-forces. Western blot analysis of OF-EV with EV markers (E).
OF-EV from the ampulla and isthmus isolated at 10 K and 100 K and diluted in SOF supplemented with 3 mg/mL BSA (C−) under adjusted concentration of 3 × 10^5 EV/mL. A group of SOF supplemented with 5% fetal calf serum was included (C+). Embryo development was assessed on Days 7, 8 and 9. To assess blastocyst quality a representative number of Days 7–8 blastocysts from each group were either vitrified/warmed, and survival rate was recorded every 24 h up to 72 h after warming or frozen in LN2 in groups of 10 and stored at −80°C for gene expression analysis. A total of 11 replicates were carried out.

Statistical analysis

Results of EV concentration, cleavage rate, blastocyst yield, survival after vitrification/warming and relative mRNA abundance for candidate genes were analyzed using one-way ANOVA (P < 0.05). All analyses were performed with the SigmaStat software package (Jandel Scientific, San Rafael, CA, USA).

Results

Oviductal fluid contains extracellular vesicles

Extracellular vesicles were enriched from OF by ultracentrifugation at two different centrifugal forces (10 K and 100 K). Transmission electron microscopy revealed a larger (with some vesicles larger than 500 nm) and more scarce vesicle population in the 10 K pellet, whereas the 100 K pellet was mainly composed of smaller vesicles of less than 200 nm of diameter (Fig. 2A and B respectively). Nanosight analyses confirmed a broader size distribution in the 10 K pellet, encompassing vesicles larger than 500 nm, whereas the 100 K pellet revealed a more homogeneous and smaller distribution (Fig. 2C and D respectively). These vesicles expressed some of the classical markers described for exosomes (ERM, TSG101 and tetraspanin CD9 proteins) (Lopera-Vásquez et al. 2016) (Fig. 2E). Regarding vesicle number, the 100 K pellet contained more vesicles than the 10 K pellet, this difference being more evident in the early phase of the estrous cycle (Table 2). Because the early embryo is still in the oviduct during the early luteal phase, we thereafter focused on this early phase isolating OF from either the isthmus or the ampulla section of the oviduct for the present experiment. These analyses revealed that in the ampulla, vesicles were more or less equally divided in the 10 K and the 100 K pellet, whereas the isthmus had a higher concentration of smaller vesicles mainly recovered in the 100 K pellet (Table 3).

Extracellular vesicles isolated from isthmus OF have a positive effect on the quality of in vitro-produced bovine embryos

Addition of OF-derived EV to in vitro embryo culture resulted in no differences in terms of cleavage rates (range: 88.0–89.6%) and blastocysts yield at Day 8 (range: 24.6–26.9%) and Day 9 (range: 28.5–30.8%), as shown in Table 4. As previously reported, the blastocyst yield at Day 7 in the C+ group was significantly higher (20.6%) compared with the rest of the groups (range: 12.0–14.3%) (P < 0.05).

Interestingly, the survival rate at 24 h after vitrification/warming of blastocysts produced with 100 K OF-EV from isthmus was significantly higher than C+, C− and ampulla-10 K groups (91.3% vs 48.3%; 71.0%; 62.2% respectively, P < 0.05). At 48 and 72 h, these differences were increased with a survival rate of isthmus-100 K group of 80–89%. The survival rate of the blastocysts from isthmus-10 K group was also significantly higher than that in C+ at all time points (Table 5).

Table 3 Concentration OF-EV isolated from the ampulla and the isthmus at different g-forces (10–100 K).

<table>
<thead>
<tr>
<th>Centrifugal force (g)</th>
<th>n</th>
<th>Concentration*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ampulla</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 K</td>
<td>3</td>
<td>9.0 ± 3.4ab</td>
</tr>
<tr>
<td>100 K</td>
<td>3</td>
<td>10.5 ± 3.1b</td>
</tr>
<tr>
<td>Isthmus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 K</td>
<td>3</td>
<td>3.6 ± 2.5ac</td>
</tr>
<tr>
<td>100 K</td>
<td>3</td>
<td>7.5 ± 0.2ab</td>
</tr>
</tbody>
</table>

n: Number of oviductal samples used in nanoparticle analysis system (Nanosight). K: Represents 1 × 10^3.

*EV Particles/mL ± s.d. a,b,c: Values in the same column with different superscripts differ significantly (P < 0.05).

Table 4 Effect of in vitro embryo culture with OF-EV (ampulla–isthmus) isolated at different g-forces (10–100 K × g) on development in vitro.

<table>
<thead>
<tr>
<th>Centrifugal force (g)</th>
<th>n</th>
<th>Cleavage*</th>
<th>Blastoocyte yield*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (C+)</td>
<td>490</td>
<td>432 (88.5 ± 2.2)</td>
<td>99 (20.6 ± 2.1)b</td>
</tr>
<tr>
<td>Control (C−)</td>
<td>566</td>
<td>498 (88.1 ± 1.3)</td>
<td>75 (13.4 ± 1.8)b</td>
</tr>
<tr>
<td>Ampulla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 K</td>
<td>514</td>
<td>460 (89.6 ± 1.3)</td>
<td>62 (12.0 ± 1.6)b</td>
</tr>
<tr>
<td>100 K</td>
<td>462</td>
<td>406 (88.0 ± 1.1)</td>
<td>63 (13.8 ± 1.9)b</td>
</tr>
<tr>
<td>Isthmus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 K</td>
<td>557</td>
<td>494 (88.6 ± 1.5)</td>
<td>75 (13.7 ± 1.1)b</td>
</tr>
<tr>
<td>100 K</td>
<td>549</td>
<td>488 (89.1 ± 1.2)</td>
<td>68 (14.3 ± 3.0)b</td>
</tr>
</tbody>
</table>

K: Represents 1 × 10^3.

*Results presented as n (% ± s.e.) where n represents total number of presumptive zygotes placed in culture. a,b,c: Values in the same column with different superscripts differ significantly (P < 0.05).
Table 5  Survival rate after vitrification and warming of D7–8 blastocyst cultured with OF-EV (ampulla–isthmus) isolated at different g-forces (10–100 K x g).

<table>
<thead>
<tr>
<th>Centrifugal force (g)</th>
<th>n</th>
<th>4h</th>
<th>24h</th>
<th>48h</th>
<th>72h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (C+)</td>
<td>80</td>
<td>65 (80.4 ± 5.2)</td>
<td>43 (48.3 ± 9.1)a</td>
<td>37 (41.3 ± 7.0)a</td>
<td>31 (34.5 ± 8.0)a</td>
</tr>
<tr>
<td>Control (C−)</td>
<td>105</td>
<td>92 (87.6 ± 4.3)</td>
<td>77 (71.0 ± 6.6)ab</td>
<td>64 (58.0 ± 7.7)ab</td>
<td>56 (50.5 ± 8.1)ab</td>
</tr>
<tr>
<td>Ampulla 10 K</td>
<td>88</td>
<td>78 (85.9 ± 4.6)</td>
<td>61 (62.2 ± 10.4)ab</td>
<td>52 (50.8 ± 11.5)ab</td>
<td>48 (46.3 ± 11.2)ab</td>
</tr>
<tr>
<td>100 K</td>
<td>64</td>
<td>59 (89.9 ± 3.6)</td>
<td>50 (73.5 ± 7.4)abc</td>
<td>49 (71.9 ± 7.7)bc</td>
<td>45 (66.8 ± 7.6)bc</td>
</tr>
<tr>
<td>Isthmus 10 K</td>
<td>119</td>
<td>114 (96.6 ± 1.8)</td>
<td>100 (83.6 ± 4.7)bc</td>
<td>93 (78.6 ± 3.3)bc</td>
<td>86 (70.5 ± 4.4)bc</td>
</tr>
<tr>
<td>100 K</td>
<td>97</td>
<td>93 (96.7 ± 1.6)</td>
<td>87 (91.3 ± 3.8)c</td>
<td>84 (89.3 ± 4.3)c</td>
<td>79 (80.1 ± 3.9)c</td>
</tr>
</tbody>
</table>

n: Total number of presumptive zygotes placed in culture. K: Represents 1 × 10⁴.

*Data are presented as n (% ± s.e.). a,b,c Different superscripts indicate significant differences for each gene (P < 0.05).

The expression levels of three genes related to membrane trafficking (AQP3, AQPI1 and ATP1A1), two genes related to metabolism (LDLR and LDHA) and four genes involved in epigenetics (DNMT3A, IGF2R, GRB10 and SNRPN) were determined in blastocysts cultured in the presence (C+) or absence (C−) of FCS or supplemented with EV from OF from the isthmus enriched either at 10 K (Isthmus 10 K) or 100 K (Isthmus 100 K) (Figs 3 and 4). The addition of 100 K isthmus EV induced a significant upregulation of the water channel AQP3, DNMT3A and SNRPN genes compared with the group supplemented with serum (C−), whereas blastocysts cultured with BSA (C−) showed intermediate but not significantly different levels. The lipid receptor LDLR was significantly downregulated in C+ compared with the rest of the groups. The remaining genes analyzed displayed no differences among groups.

Discussion

In this study, we report that the in vitro culture of bovine embryos with OF-EV from the isthmus, in the absence of serum improves the quality of the produced embryos. We found that embryo development was not affected by the presence of OF-EV, but the quality of the produced embryos in terms of cryotolerance and the expression of genes related to metabolism and epigenetics were improved. To our knowledge, this is the first attempt at isolating and characterizing EV from the ampullary and isthmic OF and evaluating their effect during in vitro culture.

The first stages of early bovine embryo development occur in the oviduct, where the embryo spends around 4 days (Hackett et al. 1993). The OF comprises the secretions of BOEC and the transudation into the oviduct lumen of blood plasma (Ellington 1991). To date, the effect of bovine OF in vitro has been evidenced in porcine- and bovine-matured oocytes in terms of ZP modulation and embryo quality (Coy et al. 2008, Lloyd et al. 2009, Cebrian-Serrano et al. 2013); and during in vitro culture of bovine zygotes with a positive effect on embryo development and quality (Lopera-Vasquez et al. 2015).

The EVs are membrane vesicles secreted by most cell types that are nowadays considered mechanisms of intercellular communication (Yanez-Mo et al. 2015). Different EV populations associate different morphological characteristics and RNA profiles (Lötvall et al. 2014). The analyses by NTA of the size
and concentration of EV from maternal reproductive tract show that they are heterogeneous. Human follicular fluid EV are polydisperse, including MV and exosome-sized EV, with an average of ≈220 nm and a mean concentration of ≈2.7 × 10^6 EV/mL (Tannetta et al. 2014). In ovine uterine fluid, EVs showed a mean size of ≈148 nm in a ≈200 × 10^9 EV/mL (Burns et al. 2014). Our samples also presented polydispersed populations. NTA analyses revealed a broadly distributed population in the 10K pellet and a more narrow and smaller-sized distribution in the 100K pellet, even though the mean size of both samples was not significantly different irrespective the g force used for isolation. Moreover, the concentration of small vesicles was greatly increased in the early phase of the cycle, and predominant at the isthmus, whereas in the ampulla, vesicles were more or less equally divided in the 10K and the 100K pellet. This may be explained by the fact that the isthmus is the part of the oviduct where the embryo develops in vivo, up to ≥16 cell stage, before entering the uterus and that the vesicles are responsible for the interaction between the oviduct and the early embryo.

The role of EV present in the reproductive tract is a recent field of research. Silveira and coworkers (Silveira et al. 2012) isolated MV and exosomes of equine ovarian follicular fluid and evidenced the presence of proteins and miRNAs that were present in the follicular cells, suggesting EVs play an important role in cell-to-cell communication within the mammalian ovarian follicle (Silveira et al. 2012). Sohel and coworkers (Sohel et al. 2013) demonstrated a miRNA transport mediated by exosome and non-exosome structures in bovine follicular microenvironment, associating the extracellular miRNA with the growth status of the oocyte (Sohel et al. 2013). Using an in vitro model, Ng and coworkers (Ng et al. 2013) identified and examined the presence and role of EV of the uterine cavity. The miRNA present in the uterine EV allowed a bioinformatic identification of pathways possibly influenced after the EV uptake by trophectoderm or endometrial epithelium at the time of implantation or after sperm transfer during the transit across the uterus (Ng et al. 2013). Burns and coworkers (Burns et al. 2014) evidenced the presence of EV in the uterine fluid of pregnant and cyclic ewes. The differences identified in the molecular contents determined by the pregnancy status suggested different EV sources (endometrium conceptus), supporting the idea that EV in the uterine fluid plays a relevant role in the establishment and maintenance of pregnancy (Burns et al. 2014). The same group clearly demonstrated the function of EVs from conceptus trophectoderm and uterine epithelia in conceptus elongation and conceptus–endometrial interactions during early pregnancy in sheep (Burns et al. 2016). Al-Dossary and coworkers (Al-Dossary et al. 2013) revealed the expression and secretion via oviductal exosomes of plasma membrane Ca^{2+}-ATPase 4a (PMCA4a–Ca^{2+} homeostasis) in the female reproductive tissues and luminal fluids during estrous, and their uptake by sperm with a possible role in sperm viability during storage in the oviduct, capacitation and acrosome reaction (Al-Dossary et al. 2013).

In spite of the recent efforts made to elucidate the function of EVs during reproductive events, the role of bovine OF-EV in early embryo development is still unknown. Our results show for the first time that EV can be isolated from the isthmus of the bovine oviduct at the early luteal phase and can be used successfully during in vitro culture with developmental rates similar to serum-containing media. In a similar in vitro system, we recently demonstrated a positive effect of EV secreted by BOEC monolayer on the developmental capacity of bovine zygotes and the quality of the produced embryos in vitro (Lopera-Vásquez et al. 2016). Data from this study, in which we assessed different EV doses (as low as 7.5 × 10^4), showed no significant differences, indicating that we may be probably working at saturating conditions in this in vitro conditions. In addition, we could also demonstrate that some of the deleterious effects of serum were reduced by the presence of EVs extracted from BOEC cultures in vitro (Lopera-Vásquez et al. 2016). Here, the quality of the blastocysts cultured with isthmus-100K OF-EV was higher than that of blastocysts produced in semi-defined media with serum or BSA in terms of cryotolerance. This effect may be possibly due to cell–cell communication mechanisms related to the dialog between the oviduct and the early embryo. Thus, it is not surprising that the positive effect is mostly observed with the small vesicle population recovered from the isthmus, the part of the oviduct where in vivo the early embryo develop up to ≥16 cell stage. Interestingly, the number of small vesicles greatly increases in the early phase of the oestrous cycle, when most likely an oviduct–embryo interaction takes place. Thus, the OF complexity is associated with the dynamic nature of oviductal epithelial cell populations at different stages of estrous cycle (Yániz et al. 2000). This is in agreement with a recent study from our group (Maillo et al. 2016) that identified 2287 genes differentially expressed between ampulla and isthmus in pregnant animals after characterization of the bovine oviductal transcriptome on Day 3 between cyclic and pregnant heifers.

A plausible molecular explanation for the increased survival rates after vitrification in the isthmic OF-EV is the upregulation of the water channel AQP3. However, the difference with the C− group was not significant, suggesting an additional role of serum in the regulation of this gene. In a previous study, we also detected a significant upregulation of AQP3 in blastocysts cultured in the presence of oviductal fluid, which also exhibited higher cryotolerance than those cultured in the presence of serum (Lopera-Vásquez et al. 2015). Aquaporins selectively conduct water molecules allowing the
her rapid movement of water through the membrane and thereby facilitating survival after freezing and thawing. In particular, the artificial expression of AQP3 in mouse oocytes (Edashige et al. 2003) improved survival after cryopreservation and AQP3 has been proposed as a major water and cryoprotectant transporter in bovine morulae (Jin et al. 2011). In contrast, two other genes related with membrane trafficking, another aquaporin (AQP11) and the Na/k-ATPase α1-subunit (ATP1A1), essential for blastocyst expansion in mice (Barcroft et al. 2004), did not differ between groups. We also analyzed the expression of a lipid receptor (LDLR) and a glycolytic enzyme (LDHA) that has been related with anaerobic glycolysis in bovine cumulus cells (Bermejo-Alvarez et al. 2010). LDHA did not display significant differences between groups, but LDLR was significantly downregulated in the presence of serum compared with the other groups. This result is in agreement with our previous findings in bovine embryos (Lopera-Vasquez et al. 2015) and may be the consequence of higher amount of lipids in the serum supplemented media. In this perspective, LDLR has been reported to be downregulated in embryos derived from obese mice, and it was proposed as a regulator of lipid uptake in blastocysts (Bermejo-Alvarez et al. 2012).

Finally, the de novo DNA methyltransferase DNMT3A and the imprinted gene SNRPN were downregulated in the group supplemented with serum compared with isthmic 100 K OF-EV. However, the imprinted gene IGF2R and the putatively imprinted gene GRB10 did not reveal significant differences, although did show a similar trend. Altered expression patterns of imprinted genes may be indicative of imprinting disorders. Imprinting disorders caused by artificial reproductive techniques are known to cause phenotypic alterations in the offspring such as the large offspring syndrome (Young et al. 2001). In particular, abnormal SNRPN imprinting causes Prader-Willi syndrome in humans (Özçelik et al. 1992). Similar to humans, bovine SNRPN is a paternally expressed imprinted gene (Luciferio et al. 2006), and its expression is positively linked with methylation in bovine. Thus, a reduced expression of DNMT3A may have caused a reduction in methylation and expression of SNRPN, similar to the one observed in bovine placenta derived from IVF embryos compared with AI (Suzuki et al. 2009).

In conclusion, bovine OF-EV can be isolated from the isthmus by ultracentrifugation at 100 K and used in in vitro embryo culture with a positive effect on embryo quality, reflected in cryotolerance. Regarding gene expression patterns, significant differences of important genes related with metabolism, epigenetics and water channel traffic were observed compared with the group cultured in the presence of serum. The presence of isthmus-100 K OF-EV also slightly increased the abundance of some of these genes compared with the no-serum control. These results provide evidence of the essential association of the oviducal environment and developing embryo confirming an early embryo–maternal dialog. Further studies of OF-EV characterization will elucidate possible mechanisms of communication between the mother and the embryo mediated by the EV.

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

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Oviductal extracellular vesicles in IVP


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