Embryonic genotype and inbreeding affect preimplantation development in cattle

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Abstract

Infertility in cattle herds is a growing problem with multifactorial causes. Embryonic genotype and level of inbreeding are among the many factors that can play a role on reproductive efficiency. To investigate this issue, we produced purebred and crossbred bovine embryos by in vitro techniques from Holstein oocytes and Holstein or Brown Swiss semen and analyzed several cellular and molecular features. In the first experiment, purebred and crossbred embryos, obtained from abattoir oocytes, were analyzed for cleavage, development to morula/blastocyst stages, amino acid metabolism and gene expression of developmentally important genes. The results indicated significant differences in the percentage of compacted morulae, in the expression of three genes at the blastocyst stage (MNSOD, GP130 and FGF4) and in the utilization of serine, asparagine, methionine and tryptophan in day 6 embryos. In the second experiment, bovine oocytes were collected by ovum pick up from ten Holstein donors and fertilized with the semen of the respective Holstein sires or with Brown Swiss semen. The derived embryos were grown in vitro up to day 7, and were then transferred to synchronized recipients and recovered on day 12. We found that purebred/inbred embryos had lower blastocyst rate on days 7–8, were smaller on day 12 and had lower expression of the trophoblast gene PLAC8. Overall, these results indicate reduced and delayed development of purebred embryos compared with crossbred embryos. In conclusion, this study provides evidence that embryo genotype and high inbreeding can affect amino acid metabolism, gene expression, preimplantation development and therefore fertility in cattle.

Introduction

Several investigators have shown a clear decline in reproductive efficiency in dairy cattle over the last 50 years. Butler (1998), in particular, has reported that the first service conception rate has decreased from ~65% in 1951 to 40% in 1996 for dairy cattle of New York state. Equivalent declines in reproductive efficiency have occurred in other countries and specific studies have been published for Ireland (Roche et al. 2000), UK (Royal et al. 2000), Spain (Lopez-Gatius 2003) and Australia (Macmillan et al. 1996). Several authors have attributed this decline to the selection for increasing milk production (Butler 1998, Olori et al. 2002, Wall et al. 2005) and published large datasets show a clear inverse relationship between milk production and reproduction efficiency in dairy cattle (Dematawewa & Berger 1998, Hansen 2000). Other changes, besides increased milk production, have occurred in the dairy cattle industry over the last 50 years. For instance, the decline in the number of dairy herds and the concentration of the dairy industry in larger farms has brought about new challenges in reproductive management. Larger herds require more time for heat detection, record keeping, sorting and insemination and also different strategies from visual heat detection, such as timed artificial insemination. Such strategies can offer management advantages although conception rate is lower (Nebel & Jobst 1998). By contrast, in herds with poor estrus detection and low fertility, this choice can improve the interval to first service and overall pregnancy rate (Schmitt et al. 1996, Pursley et al. 1997), thus achieving a positive effect on reproductive management. Therefore, the size of the herd and its reproductive management can play an important role in reproductive efficiency. Finally, other factors such as season of calving, post partum diseases (Grohn & Rajala-Schultz 2000) and negative energy balance in high-producing cows are also involved in the genesis of infertility.
although to variable degree according to numerous published reports (Staples et al. 1990, Lucy et al. 1992).

In addition to all these factors, the rising inbreeding in dairy herds has also been included in the multifactorial causes of low reproductive efficiency. The coefficient of inbreeding measures the percentage of genes of an individual that are identical by descent and, over the last 30 years, this coefficient has increased from about 1 to ~5% in the Holstein breed. Estimates of the effects of inbreeding on reproduction indicate a detrimental effect on reproductive parameters such that every 1% increase in inbreeding led to 0.17 increase in service/conception, 2 days increase in the period from calving to conception (days open) and 3.3 percentage-unit decrease in conception rate (Hermas et al. 1987). As a strategy to counterbalance the rise in inbreeding in dairy breeds, crossbreeding has been proposed as a possibility to increase productive and reproductive efficiency (McAllister 2002). The economical benefits of cross-breeding have been reported in a large study in the USA, (VanRaden & Sanders 2003) and interestingly, a recent in vitro study (Boediono et al. 2003) demonstrated that crossbred embryos develop faster and at higher rate than purebred embryos, suggesting that genotype and possibly inbreeding can influence developmental competence.

In light of all these published reports, the aim of this study was to further investigate the effect of inbreeding on reproductive efficiency by focusing on a number of cellular and molecular parameters of preimplantation development in embryos of different genotype and level of inbreeding.

Results

Embryo development: experiment 1

A total number of 2274 oocytes were collected and matured in vitro, 1135 were fertilized with six different Holstein bulls and 1139 with six different Brown Swiss bulls. Oocytes collected from each batch of ovaries were divided and assigned to the crossbred or purebred group to reduce the effect of the oocyte quality. We found no difference in cleavage rate at 30 h (28.78 vs 26.41%) and in total cleavage rate (78.79 vs 74.35%), although we observed a significant difference in favor of crossbred embryos in the compaction rate on day 6 and blastocyst development on day 7 (18.93 vs 20.89%) and 8 (29.18 vs 33.18%; $P=0.07$, $\chi^2$ test). Results are summarized in Table 1.

Amino acid analysis

Overall, purebred and crossbred embryos displayed a similar amino acid profile but there was a significant difference in the utilization of serine ($P=0.0079$), asparagine ($P=0.012$), methionine ($P=0.000$) and tryptophan ($P=0.034$) between the two groups (Fig. 1). Purebred embryos contained an average of 105.87 ± 3.12 cells ($n=45$), which was not significantly different from 108.56 ± 3.06 cells ($n=44$) obtained for crossbred embryos. There was also no difference in total amino acid depletion, appearance or turnover between the two groups (Fig. 2).

Embryo development: experiment 2

A total of 39 and 40 ovum pick ups (OPUs) were performed on ten Holstein heifers to generate inbred and crossbred embryos respectively. Six hundred and eighty oocytes were fertilized with the Holstein sire of each donor heifer and 688 with four different Brown Swiss bulls chosen from those used in experiment 1. Results indicate a significantly higher cleavage rate (74.3 vs 63.4%, see Table 2) for crossbred embryos compared with inbred embryos. In addition, we found that the rate of morula compaction, calculated on the total number of oocytes (22.7 vs 25.4%, see Table 2), the blastocyst rate on day 7, calculated both on the oocytes and on the cleaved embryos (11.6 and 18.3 vs 18.5 and 24.8%), and the blastocyst rate on day 8, calculated on the oocytes (16.2 vs 22.5%), were significantly higher for crossbred embryos (Table 2).

The higher developmental rate observed on day 7 was further investigated by transferring the embryos in synchronized recipients and recovering them on day 12 (Fig. 3). A total of 43 inbred embryos and 70 crossbred embryos were transferred on day 7 in eight recipient heifers in total, four recipients for each group. Overall, 29 embryos (67.4%) and 48 embryos (68.6%) respectively were recovered on day 12 (Table 3). Although the recovery rate was similar in the two groups, we found a significantly higher rate of ovoid embryos (56.3 vs 20.6%) in the crossbred group, while in

Table 1: Experiment 1: effect of genotype on embryo development.

<table>
<thead>
<tr>
<th>Type of embryo</th>
<th>Number of oocytes</th>
<th>Number of cleaved (%)</th>
<th>Number of compacted morulae, day + 6 (% of cleaved)</th>
<th>Number of blastocysts, day + 7 (% of cleaved)</th>
<th>Number of blastocysts, day + 8 (% of cleaved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purebred</td>
<td>1135</td>
<td>898 (78.79)</td>
<td>238 (26.5)</td>
<td>170 (18.93)</td>
<td>262 (29.18)</td>
</tr>
<tr>
<td>Crossbred</td>
<td>1139</td>
<td>847 (74.35)</td>
<td>257 (30.03)</td>
<td>177 (20.89)</td>
<td>281 (33.18)</td>
</tr>
</tbody>
</table>

$\chi^2$ test. Values within columns with different letters are statistically different ($P<0.05$).
the inbred group, most of the embryos were spherical (79.4 vs 43.7%), indicating that also in the second week of development crossbred embryos developed faster and at higher rate. This observation was confirmed also by the difference in the average size of the recovered embryos: crossbred embryos mean size was 0.48 ± 0.12 × 0.40 ± 0.10 mm (length × width) compared with 0.35 ± 0.18 × 0.28 ± 0.09 mm (length × width) of inbred embryos.

**Gene expression analysis: experiment 1**

Statistical analysis using a Student’s t-test indicated that, in day 7 blastocysts, the relative expression of three genes was significantly higher in the crossbred group: MNSOD, a mitochondrial Mn-superoxide dismutase, GP130, a glycoprotein subunit of the LIF receptor and fibroblast growth factor 4 (FGF4; Fig. 4A). Also PED, the preimplantation embryo development gene, and GJA1 (also known as CX43), a connexin implicated in cellular communication, were more expressed in the crossbred group but without reaching a statistical difference. By contrast, transcripts of stress- and apoptosis-related genes, G6PDH and BAX, a glucose-6-phosphate dehydrogenase and the apoptosis regulator box-a had a tendency for higher expression in the purebred group. SLC2A5, a glucose transporter (also know as GLUT5), insulin-like growth factor 1 receptor (IGF1R) and interferon tau (IFNT) showed a similar expression in both groups.

**Gene expression analysis: experiment 2**

In day 12 embryos, we found that the genes responsible for embryo elongation, trophoblast development and fetus–maternal interaction, IFNT, CDX2 and PTGS2 (also known as COX2), had a tendency for increased expression in crossbred groups, but only PLAC8 displayed statistical significance using a Student’s t-test (Fig. 4B). On the contrary, genes involved in programmed cell death such as MSX1 and BAX were slightly more expressed in inbred embryos as previously observed in day 7 blastocyst. Expression of HSP70 was linked more to the season in which the flushing was performed than to the class of embryos: in both groups, inbred and crossbred, the expression of HSP70 was twice as high and statistically different in the summer season from that in the spring (data not shown).

**Discussion**

In this study, we have investigated the effect of genotype on embryo development, metabolic activity and gene expression. First of all, we monitored embryo development by examining morphological parameters. In experiment 1, we observed that crossbred embryos derived from oocytes of slaughtered donors had a tendency to cleave faster than purebred embryos. Interestingly, several studies performed on different species have demonstrated that the time of first cleavage is positively correlated with the developmental competence of the embryos (van Soom et al. 1997, Fenwick et al. 2002) and it was demonstrated that bovine fast-cleaving embryos have a different gene expression that reflects their higher quality compared with late-cleaving embryos (Gutierrez-Adan et al. 2004). Another determining step for embryo development before blastocyst formation is the compaction of the morula on day 6. In experiment 1, we found that crossbred embryos have a significantly higher rate of compaction compared with purebred and inbred embryos, strongly indicating a greater competence/quality of this group. This finding was confirmed in experiment 2 in which we observed higher blastocyst development of crossbred embryos. Remarkably, this trend was confirmed by the data on embryo development at day 12, where we demonstrated that crossbred embryos undergo elongation at a higher rate compared with inbred embryos. Elongation is a crucial step for bovine embryo development since most embryonic losses occur between blastulation and elongation (Diskin & Sreenan 1980) and embryos more advanced on day 12 establish pregnancies at significantly higher rate than smaller embryos (Lazzari et al. 2002). Therefore, our observations, starting from the
early cleavage stage to elongation, indicate a higher developmental capacity and most likely a higher ability to establish pregnancies for crossbred embryos. This detrimental effect of inbreeding on embryo development reminds, to some extent, the fact that in the mouse, most outbred stocks and some inbred strains display a compromised in vitro embryo development that is normally not observed in hybrids (Scott & Whittingham 1996). All together, these findings further confirm that embryo genotype can play a significant role during early embryo development and also highlight the importance of the preservation of rare and endangered breeds to maintain the species gene pool as wide as possible.

The level of amino acids utilized by purebred and crossbred embryos were found to be similar to that previously observed in bovine blastocysts (Gopichandran & Leese 2003). Although the overall depletion, appearance and turnover of amino acids were not significantly different between purebred and crossbred embryos, there was a significant difference in the utilization of serine, asparagine, methionine and tryptophan. This suggests that purebred embryos have a different amino acid requirement from crossbred embryos. To the best of our knowledge, this is the first report of genotype affecting the amino acid utilization of bovine embryos.

Regarding gene expression, we examined a panel of genes indicative of embryo quality, developmental competence, metabolism and stress reactivity. Among them, MNSOD is a mitochondrial Mn-superoxide dismutase that indicates mitochondrial activity and also has a role in detoxification of reactive oxygen species, cellular differentiation and embryo compaction. As recently demonstrated (Lonergan et al, 2003), the level of MNSOD expression is higher in in vivo-produced embryos in respect to those produced in vitro. Therefore, the higher level of expression found in the crossbred group suggests greater mitochondrial activity and improved quality compared with the purebred group. Two other genes significantly up-regulated in the crossbred group are GP130 and FGF4. In bovine embryos, both genes start to be expressed at the time of morula compaction and the expression is maintained during blastulation. In the mouse, Fgf4 is also expressed at the morula to blastocyst stage and is required for normal development since Fgf4 null embryos undergo implantation but do not develop substantially thereafter (Feldman et al, 1995). Published bovine data indicate that embryos with low developmental potential, such as nuclear transfer embryos, have lower or absent FGF4 expression, therefore suggesting an important role for this gene. (Daniels et al, 2000). GP130 is a LIF and interleukin 6 receptor subunit, and even if it is not clear whether the LIF–LIF receptor system has, in ruminant embryos, the same role in implantation known in the mouse, it was demonstrated that addition of LIF to the culture of ovine blastocysts significantly improves pregnancy rate after transfer in recipients ewes (Fry et al, 1992). In summary, a higher expression of FGF4 and GP130 can indicate, as mentioned above for MNSOD, a higher developmental and implantation competence of the crossbred group. Another examined gene was PED. Interestingly, in vivo-cultured embryos and early-cleaving embryos show high expression of PED (Fair et al, 2004), and these observations applied to our results suggest that crossbred group have both higher quality and greater developmental potential. GJA1 also displayed an increased expression in the crossbred group, and like PED, a higher level of expression has

### Table 2: Experiment 2: effect of genotype on embryo development.

<table>
<thead>
<tr>
<th>Type of embryo</th>
<th>Number of OPUs</th>
<th>Number of oocytes</th>
<th>Number of cleaved (%)</th>
<th>Number of compacted morulae, day + 6 (%) of oocytes</th>
<th>Number of blastocysts, day + 7 (%) of oocytes</th>
<th>Number of blastocysts, day + 8 (%) of oocytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbred</td>
<td>39</td>
<td>680</td>
<td>431 (63.4)a</td>
<td>98 (14.4)a</td>
<td>79 (11.6)a</td>
<td>110 (16.2)a</td>
</tr>
<tr>
<td>Crossbred</td>
<td>40</td>
<td>688</td>
<td>511 (74.3)b</td>
<td>138 (20.1)b</td>
<td>127 (18.5)b</td>
<td>155 (22.5)b</td>
</tr>
</tbody>
</table>

χ² test. Values within columns with different letters are statistically different (P<0.05).
been found in faster-developing embryos (Gutierrez-Adan et al. 2004), indicating that this gene is associated with embryo quality.Remarkably, GJA1, which is involved in gap junctional intracellular communication and compaction, was higher in crossbred embryos which displayed an increased rate of compaction compared with purebred embryos. The genes related to stress and apoptosis tended to display increased expression in the purebred embryos, although the difference was not significant. BAX is a proapoptotic gene previously suggested to be a marker of blastocyst quality with the level of expression being lower in good-quality embryos. G6PDH was defined as sentinel for oxidative stress (Lonergan et al. 2003), and in this study, the expression is higher in the inbred group. G6PDH is an enzyme indispensable for maintaining the cellular redox state and the high level suggests a stressful condition for the embryo.

The same higher developmental competence in terms of gene expression was also observed comparing ovoid day 12 crossbred and inbred embryos. The expression of IFNT, a trophoblastic-specific gene (Degrelle et al. 2005) strictly involved in embryo–endometrial interaction and pregnancy signalling (Spencer et al. 2008) and also other elongation- and implantation-related genes, such as PLAC8, CDX2 and PTGS2, displayed increased expression in crossbred ovoid embryos. Recently, it was demonstrated that these three latter genes are more expressed in biopsies of blastocysts, resulting in the delivery of a calf, compared with those resulting in resorption (El-Sayed et al. 2006). In the same work, it was observed that genes linked to programmed cell death such as MSX1 were up-regulated in embryos, resulting in no pregnancy. Our data indicated that MSX1 was more expressed in the inbred group and, as previously observed in day 7 embryos, BAX expression was also slightly higher. Interestingly, we found that HSP70 expression was significantly higher in both groups in the summer season compared with the spring, indicating a high level of stress induced by environmental conditions. This casual observation demonstrates that the temperature to which the embryos are exposed plays an important role in the expression of stress-related genes and should be always taken into account in an experimental design.

A final particular aspect to be considered about experiment 2 is that the data refer to embryos with extreme inbreeding levels, inbred–purebred, that are not commonly found in bovine herds. Therefore, a more accurate evaluation of the embryonic effects of different levels of inbreeding, within the Holstein breed for example, is needed to identify the threshold level that can negatively affect the developmental characteristics of preimplantation bovine embryos. These data, when available, could be integrated with recent findings on candidate genes and pathways affecting fertilization rate and early embryo development (Khatib et al. 2009, Wang et al. 2009). Ultimately, all this information would be of practical use in the design of selection breeding programmes.

In conclusion, this study demonstrates, using a panel of cellular, metabolic and molecular parameters, that embryo genotype and high inbreeding affect embryonic development in the first 2 weeks after fertilization, a period that represents the crucial developmental window bringing to the establishment of pregnancy in cattle.

Finally, this study was conducted on purebred Holstein Friesian and crossbred Holstein Friesian–Brown Swiss embryos; therefore, more research is needed to further investigate the embryonic consequences of inbreeding and crossbreeding in other cattle breeds.

Table 3 Development and size of day 12 inbred and crossbred embryos after in vivo culture.

<table>
<thead>
<tr>
<th></th>
<th>Number of embryos transferred on day +7</th>
<th>Number of embryos recovered on day +12</th>
<th>Recovery rate (%)</th>
<th>Number of ovoid embryos</th>
<th>Percentage of recovered</th>
<th>Number of spheric embryos</th>
<th>Percentage of recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbred</td>
<td>43</td>
<td>29</td>
<td>67.4</td>
<td>7</td>
<td>20.6(^{a})</td>
<td>27</td>
<td>79.4(^{a})</td>
</tr>
<tr>
<td>Crossbred</td>
<td>70</td>
<td>48</td>
<td>68.6</td>
<td>27</td>
<td>56.3(^{b})</td>
<td>21</td>
<td>43.7(^{b})</td>
</tr>
</tbody>
</table>

\(^{\chi^2}\) test. Values within columns with different letters are statistically different (\(^{P}<0.05\)).
Materials and Methods

In this study, we compared groups of in vitro-produced embryos of two different origins: purebred embryos produced by fertilizing Holstein oocytes with Holstein semen and crossbred embryos obtained by fertilizing Holstein oocytes with Brown Swiss semen. The study was carried out in two separate experiments using either oocytes collected at the abattoir from slaughtered donors (experiment 1) or oocytes recovered by OPU from live donors (experiment 2). Different Holstein and Brown Swiss bulls were used for each replicate. For experiment 2, the bull sire of each heifer was chosen for IVF in order to produce highly inbred embryos. All the derived embryos were observed during in vitro development, evaluating the time of first cleavage, compaction at day 6 and blastocyst rate at days 7 and 8. In addition, part of the blastocysts derived from experiment 1 were analyzed for the pattern of expression of transcripts implicated in pre- and post-implantation periods, embryo metabolism, apoptosis and oxidative stress and the others were used for the evaluation of amino acid turnover. Embryo viability during the second week of development was investigated by transferring blastocysts derived from experiment 2, inbred and crossbred, in synchronized recipients on day 7 of the cycle. These embryos were nonsurgically recovered 5 days later, on day 12, to evaluate their size, gene expression pattern and stage of development.

Experiment 1

Oocyte collection, maturation, fertilization and embryo culture. All chemicals were purchased from Sigma–Aldrich, unless otherwise indicated.

Ovaries of Holstein cows were collected immediately after slaughter and transported to the laboratory in Dulbecco’s PBS with antibiotics. Oocytes recovered by aspiration were selected for uniform, non-expanded and non-atretic cumulus morphology, and were matured for 20–24 h at 38.5°C in 5% CO2 and 5% O2 in TCM199 supplemented with 10% FCS, gonadotropins (FSH and LH, 0.05 IU each; Pergovet, Serono), insulin, transferrin, sodium selenite (ITS), Long-IGF1 (100 ng/ml) and Long-EGF (50 ng/ml).

After maturation, oocytes were assigned to one of the two following groups: 1) purebred, 2) crossbred. Group 1 oocytes were fertilized with semen of Brown Swiss bulls and group 2 oocytes were fertilized with semen of Holstein bulls for a total of six replicates. After thawing, the semen was separated on a Percoll gradient and resuspended in synthetic oviduct fluid (SOF) medium (Tervit et al. 1972), HEPES buffered and supplemented with fatty acid-free BSA (6 mg/ml), modified Eagle medium (MEM) amino acids, 1 µg/ml heparin, 20 µM penicillin, 1 µM epinephrine and 10 µM hypotaurine. Matured oocytes were coincubated with the semen for 18–20 h at 38.5°C in 5% CO2 and 5% O2.

Zygotes were cultured in groups of 50–80 embryos in 400 µl of m-SOF (modified SOF) medium supplemented with MEM amino acids and BSA (4 mg/ml) until day 8, performing 50% changes of medium at day 4 and 6 at the same atmosphere as above. Each group was evaluated 30 h post fertilization to assess the first embryonic cleavage. Cleavage rate, compaction at day 6 and blastocyst rate at days 7 and 8 were recorded.

Experiment 2

Oocyte recovery by OPU, maturation, fertilization and embryo culture. Ten Holstein heifers were used as oocyte donors by OPU. Oocyte collection was performed by transvaginal ultrasound-guided follicular aspiration (Galli et al. 2001). Briefly, all ovarian follicles ranging from 3 to 15 mm size were aspirated using a 17 G, 55 cm long, single-lumen cannula with a 19 G long spinal needle mounted at the tip connected to an aspiration pump. Collected oocytes were in vitro matured as previously described in experiment 1. Each oocyte batch was fertilized either with the semen of the heifer’s sire (inbred group) or with Brown Swiss semen (crossbred group), giving rise to purebred–inbred embryos or crossbred embryos. Development was assessed observing cleavage rate, compaction at day 6 and blastocysts formation at days 7 and 8 as in experiment 1.

To evaluate embryo development in the second week post fertilization, pools of day 7 in vitro–grown inbred or crossbred blastocysts were nonsurgically transferred in synchronized recipients on day 7 of the cycle (Bowen et al. 1978). On day 12, the embryos were collected with a Dissi catheter (Minitub, Tiefenbach, Germany) by flushing the uterine horns using Dulbecco PBS supplemented with 1% FCS. The fluid was recovered in glass bottles and the embryos were allowed to settle. The supernatant was aspirated, the embryos were collected from the bottom and placed in HEPES-buffered SOF. Length and width of all recovered embryos were measured under a stereomicroscope, with the aid of a calibrated ruler (Lazzari et al. 2002). After multiple washings in PBS supplemented with 1 mg/ml of polyvinyl alcohol, embryos were collected in RNAase DNAse free tubes and snap-frozen for PCR analysis.

Amino acid analysis

Forty-five purebred and 43 crossbred, day 6, compacted morula were washed twice in SOF medium containing a complete mixture of amino acids (Tay et al. 1997) and cultured individually in 6 µl drops of this medium for 16 h. Embryo-free control drops of medium were also included in each dish to allow for any non-specific amino acid degradation. After incubation, the embryos were removed from the drops, fixed for 24 h in acetic acid: ethanol (1:3) mixture and stained with Lacto to count the number of cells. The spent medium was stored at –80°C prior to amino acid analysis. The concentration of amino acids was determined by reverse-phase HPLC using a modification of a previously described method (Stokes et al. 2007). The spent medium (2 µl) was diluted with 23 µl HPLC-grade water and amino acid analysis was performed on an automated Agilent 1100 HPLC fitted with a Gemini 3 µm 50×4.6 mm C18 column (Phenomenex, Macclesfield, UK) and an Agilent fluorescence detector. Equal volumes of diluted samples and o-phthalaldehyde were mixed and 5 µl of the solution was loaded onto the column. An elution gradient was established at a flow rate of 2.5 ml/min. Solvent A consisted of 80% 83 mM sodium acetate (pH 5.9), 18.5% methanol and 1.5% tetrahydrofuran. Solvent B consisted of 80% methanol and 20% sodium acetate (pH 5.9). Using this method, it was not possible to detect cysteine and proline.
an indication of the effects of embryo genotype and level of inbreeding on embryo quality, developmental competence and response to stress: MNSOD, SLC2A5, IGF1R, IFNT, G6PDH, BAX, GJA1 (Gutierrez-Adan et al. 2004), GP130 (Eckert & Niemann 1998), FGF4 (Daniels et al. 2000) and PED (Fair et al. 2004). Primers are listed in Table 4. Genes examined in day 12 embryos included trophoblast-specific genes and proapoptotic genes: IFNT and BAX (Gutierrez-Adan et al. 2004), PTGS2, PLAC8, MSX1 (El-Sayed et al. 2006) and CDX2 (Degrelle et al. 2005).

Statistical analysis

Embryos development data were analyzed with χ² test, while statistical differences in genes expression were determined with Student’s t-test.

All amino acid data were analyzed to determine whether they were normally distributed using the Anderson–Darling normality test. Differences between amino acid appearance/depletion and turnover between purebred and crossbred embryos were determined using Student’s t-test or Mann Whitney U test.

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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