Implanting melatonin at lambing enhances lamb growth and maintains high fat content in milk

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Abstract

Three experiments were designed to study the effects of melatonin implantation of ewes and lambs after lambing on the growth of lambs and milk quality throughout lactation. In experiment 1, 53 lambs either did (n = 28) or did not (n = 25) receive a subcutaneous 18-mg melatonin implant at the base of the left ear. In experiment 2, 55 lambs and their mothers either did (lambs: n = 28; ewes: n = 15) or did not (lambs: n = 27; ewes: n = 16) receive a melatonin implant. Milk samples were collected at 15, 30, and 45 d after lambing. In experiment 3, 16 lambs were separated from their mothers 24 h after birth, moved to an artificial rearing unit, and either did (n = 9) or did not (n = 7) receive a melatonin implant. In the three experiments, implants were inserted 24 h after lambing, and lambs were weighed (LW) weekly until weaning (for each experiment, 7, 6, and 5 wk., respectively). Average daily gains (ADG) from birth to weaning were calculated. Melatonin treatment of lambs did not have a significant effect on LW at weaning or ADG, but lambs reared by implanted ewes in experiment 2 presented higher (P < 0.05) LW (±S.E.M.) at weaning (implanted: 13.61 ± 0.51; non-implanted: 12.09 ± 0.57 kg) and ADG (implanted: 221.00 ± 10.45; non-implanted: 189.92 ± 12.44 g/d) than did lambs reared by control ewes. At day 45 of lactation, milk fat and total solid content were higher (P < 0.05) in implanted ewes than in control ewes. Groups did not differ significantly in the protein and lactose content of their milk. In conclusion, melatonin treatment of ewes at lambing induced a high growth rate of their lambs and increased the fat content of the milk; however, the direct treatment with melatonin of the lambs at birth did not have an effect in their growth rate.

Keywords Melatonin · Milk · Lambs · Growth

Sexual seasonality, which is regulated by photoperiod, limits sheep productivity (Yeates 1949). Melatonin is the hormone that transmits the photoperiodic information to the endocrine system, which dictates the precise timing of reproduction. Subcutaneous melatonin implants are a method for artificially controlling oestrus in sheep and, because melatonin is released at night, this procedure is used to cause a short daytime-like response without suppressing endogenous secretion (O’Callaghan et al. 1991; Malpaux et al. 1997). In Mediterranean genotypes, melatonin implants increased significantly (29%) the probability of pregnancy and fecundity (lambs born/ewe) (0.25 extra lambs/treated ewe) (Palacín et al. 2011). Recent studies have shown that, melatonin implants administered between 70 d and 120 d of pregnancy reduced neonatal mortality and high survival rates at weaning, which were mediated through an increase of survival of twins and an increase in tolerance for prolonged parturiion in extensively managed sheep flocks (Flinn et al. 2020a, 2020b). Melatonin diffuses freely across the ovine placenta and blood–brain barrier (Yellon and Longo 1987; Aly et al. 2015), so maternal supplementation is readily able to deliver melatonin to the foetus before birth.

We have observed an improvement in colostrum quality if mothers receive implants at the fourth month of pregnancy (Abecia et al. 2020), and lambs reared by implanted ewes were fed more IgG than were lambs from non-implanted ewes. Furthermore, apparently, maternal melatonin in pregnancy plays an important role in the production of brown adipose tissue (BAT) and newborn thermoregulation because melatonin-deficient lambs were colder at birth and reacted abnormally to cold than did control lambs, and the effects of maternal melatonin deficiency were reduced in
lambs whose mothers had been kept at a constant photo-period in pregnancy (Seron-Ferre et al. 2015). Probably the improvement of colostrum quality from implanted ewes and the best thermoregulation of lambs born from melatonin-treated pregnant ewes were responsible for the lower mortality rates and higher growth rates that we documented in Merino lambs reared under extensive conditions in Australia (Davis et al. 2021).

Three experiments were designed to quantify the effects of melatonin implantation of lambs (experiments 1, 2 and 3) and ewes (experiment 2) immediately after lambing on the growth of lambs and the quality of milk (experiment 2) throughout lactation.

### Material and methods

#### Experiment 1

The experiment involved 53 Rasa Aragonesa lambs (29 singletons, 24 twins; 29 males, 24 females) born from 40 ewes in the first week of Nov. Lambs either did (group m; \(n = 28\); 15 males, 13 females) or did not (group c, \(n = 25\); 14 males, 11 females) receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear. A digital dynamometer recorded lamb weight at birth and weekly thereafter until weaning (7 weeks). Average daily gain (ADG) from birth to weaning was calculated.

#### Experiment 2

The experiment involved 55 Rasa Aragonesa lambs (2 singletons, 44 twins, 9 triplets; 31 males, 24 females) born from 31 ewes in the first fortnight of Oct. Twenty-four hours after lambing, ewes either did (group M, \(n = 15\)) or did not (group C, \(n = 16\)) receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear. They were moved to an artificial rearing unit, which was a 16-m² pen that had an electronic milk feeder (Delaval LKF1200). Milk was distributed through a pipeline system to individual nipples in the pen. Lambs were weighted at birth and weekly thereafter until weaning (5 weeks).

#### Experiment 3

The experiment involved 16 twin lambs (8 males, 8 females) born in the first week of Oct, which were separated from their mothers 24 h after birth after having been fed colostrum by their dams. Lambs either did (m, \(n = 9\)) or did not (c, \(n = 7\)) receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear. They were moved to an artificial rearing unit, which was a 16-m² pen that had an electronic milk feeder (Delaval LKF1200). Milk was distributed through a pipeline system to individual nipples in the pen. Lambs were weighted at birth and weekly thereafter until weaning (5 weeks).

### Results

#### Experiment 1

Treatment with melatonin or sex of the lambs did not have a significant effect on LW (±S.E.M.) at weaning (m: 14.41 ± 0.42; c: 14.9 ± 0.57 kg) (males: 14.86 ± 0.44; females: 14.4 ± 0.60 kg) or ADG until weaning (m: 221.35 ± 7.80; c: 234.96 ± 10.60 g/d) (males: 230.24 ± 8.35; females: 225.10 ± 10.64 g/d) (Fig. 1).

#### Experiment 2

Melatonin implants in lambs did not have a significant effect on LW at weaning (m: 12.69 ± 0.68; c: 12.87 ± 0.45 kg) or ADG (m: 203.35 ± 0.10; c: 204.60 ± 9.05 g/d) (Table 1); however, lambs reared by melatonin-implanted ewes
Fig. 1 Experiment 1: Mean (±S.E.M.) weekly live weight and average daily gain (g/d) of Rasa Aragonesa lambs that either did or did not receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear 24 h after birth.

Table 1 Experiment 2: Live weight (±S.E.M.) (LW) at birth and weaning (kg), and average daily gain (ADG) from birth to weaning (kg/d) of Rasa Aragonesa lambs whose mothers either did (M) or did not (C) receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear and, at the same time, the lambs either did (m) or did not (c) receive a melatonin implant.

| Treatment effect | n  | Cc (LW Birth) | Cc (LW weaning) | Cc (ADG) | Mm (LW Birth) | Mm (LW weaning) | Mm (ADG) | Treatment effect |
|------------------|----|---------------|----------------|---------|---------------|----------------|---------|-----------------|
|                  |    |               |               |         |               |               |         |                 |
|                  |    | 4.23 ± 0.20   | 3.93 ± 0.13   | 4.05 ± 0.18 | 4.23 ± 0.11  | ns             | ns      |                 |
|                  |    | 12.52 ± 0.56  | 11.61 ± 1.06  | 13.40 ± 0.75 | 13.77 ± 0.74 | ns             | *       |                 |
|                  |    | 0.197 ± 0.01  | 0.182 ± 0.01  | 0.216 ± 0.01 | 0.224 ± 0.01 | ns             | *       |                 |

ns, non-significant; * P < 0.05
presented significantly ($P < 0.05$) higher LW at weaning (M: $13.61 \pm 0.51$; C: $12.09 \pm 0.57$ kg) and ADG (M: $221.00 \pm 10.45$; $189.92 \pm 12.44$ g/d) than did lambs from C ewes. Differences between groups in LW were significant from week 3 onwards (Fig. 2). The effect of melatonin implantation of the mothers was particularly evident in male lambs (Fig. 3); male lambs reared by treated ewes presented significantly higher LW at week 2, 3, and 4 than did male lambs reared by control ewes.

The fat content of milk was significantly ($P < 0.05$) higher in M ewes than it was in C ewes at day 45 of lactation, and decreased significantly ($P < 0.05$) throughout lactation in C ewes, only (Fig. 4). Protein and lactose content of milk did not differ significantly between groups, although both increased significantly ($P < 0.05$) throughout lactation in the C group. Those differences were apparent in SNF, density, and total solids ($P < 0.05$) in the C group, only, and density in the M group between day 30 and 45. The percentage of total solids was higher ($P < 0.05$) in the M group at day 45 of lactation (Fig. 4).

The treatment and control groups did not differ significantly in the pH, conductivity, salt content, and freezing
Fig. 4 Experiment 2: Mean (±S.E.M.) fat, protein (Prot), lactose (Lac), solids not fat (SNF) percentages, and density (Den), total solids (TotSol), pH, conductivity (C), salt content (S), and freezing point (°C) of milk samples collected at days 15, 30, and 45 of lactation from Rasa Aragonesa ewes that either did (M) or did not (C) receive an 18-mg melatonin subcutaneous implant (Melovine, CEVA Salud Animal, Barcelona, Spain) at the base of the left ear 24 h after lambing (letters indicate significant differences at $P < 0.05$ among days; * indicates significant differences between groups at $P < 0.05$)
point of the milk, although the conductivity of samples collected on day 30 were significantly (P < 0.05) higher than were those collected on day 15 in both groups. The salt content of milk from C ewes increased significantly (P < 0.05) throughout lactation, and milk from M ewes increased significantly (P < 0.05) from day 15 to day 30. C ewes presented a significant (P < 0.05) reduction in the freezing point of their samples from day 30 to day 45.

**Experiment 3**

Melatonin treatment did not have a significant effect on lamb birth weight (m: 3.61 ± 0.18; c: 3.79 ± 0.28 kg), LW at weaning (m: 10.59 ± 0.85; c: 10.55 ± 0.73 kg), or ADG (m: 0.21 ± 0.01; c: 0.20 ± 0.02 kg/d). The sexes differed significantly in ADG from birth to weaning, but not in LW at birth (males: 3.93 ± 0.24; females: 3.45 ± 0.17 kg) and at weaning (males: 11.37 ± 0.66; females: 9.78 ± 0.87 kg) did not. Females (0.24 ± 0.02 kg/d) had a higher growth rate than did males (0.17 ± 0.02 kg/d) (P < 0.05).

**Discussion**

The main findings of the experiments were the effects of the melatonin treatment of dams at lambing on lamb weight and growth rate, in parallel with an increase in the fat content of the milk, especially at the end of lactation. Furthermore, the milk fat levels of treatment ewes persisted from the beginning to the end of lactation. To our knowledge, this is the first evidence of this effect in a small ruminant, particularly if exogenous melatonin is implanted at lambing. Previous studies on the effects of melatonin implants on milk production and/or offspring growth focused on implantation in the second half of pregnancy or in the middle of the milking period. El Hadi (2020) reported that melatonin implants at day 35 of lactation did not have a significant effect on milk yield and composition in Manchega and Lacaune ewes, and Abecia et al. (2005) found that a melatonin implant at mid-milking did not have a significant effect on milk yield throughout the milking period in Lacaune and Assaf dairy ewes. Yang et al. (2019) reported a higher fat content in the milk of Cashmere goats that had received an implant at day 50 of lactation than was in the milk of control goats; however, daily yields of milk, milk protein, and milk lactose were lower in the implanted goats than they were in the controls goats. Melatonin administration to does in the dry period, seven weeks before kidding, produced a galactopoietic response in the subsequent lactation and an improved daily weight gain of their suckling kids, especially, males (Avilés et al. 2019). Recently, the first observation on the effect of melatonin on the number of somatic cells in sheep milk has been reported (Cosso et al. 2021), so that the results of the present experiment may also be explained by a modulation of the immune response in the mammary gland in the implanted ewes.

In our experiments, lambs that were reared by implanted ewes had a higher growth rate than did the lambs from control ewes, which might have been due to a higher volume of milk from their implanted dams (not measured), and or the higher fat content of milk, especially at the end of lactation. A high milk fat concentration, milk energy content, and milk energy concentration contributes to faster lamb growth. The administration of exogenous melatonin coupled with the simulation of a short-day photoperiod in summer had significant effects on the milk levels of solids, protein, fat, and lactose, and on the fatty acid content of sheep milk (Molik et al. 2011). Furthermore, the higher content of total solids in the milk of M Rasa Aragonesa ewes might have contributed to the higher growth rates of the lambs because total solids are a combination of fat, protein, lactose, and minerals. In one study, a 30% reduction in overall milk solids was correlated with a 20% reduction in total milk energy production (Muir et al. 2000). Although Wang et al. (2019) reported that melatonin suppressed milk fat synthesis by inhibiting the signaling pathway via the melatonin-1 receptor in bovine mammary epithelial cells, melatonin supplementation at 1 mM significantly promoted the differentiation of bovine intramuscular preadipocytes into adipocytes in vitro, with large lipid droplets and high cellular triacylglycerol levels (Yang et al. 2017). Thus, the specific role of melatonin in the regulation of milk fat synthesis, particularly in sheep, needs to be further studied.

Although milk yield was not measured in our experiment, the significant increase in protein and lactose in the control group of ewes throughout lactation, which did not occur in the M group, might indicate lower milk production in the C group because of a dilution effect (Othmane et al. 2002). This dilution factor was cited by Bianchi et al. (2018) as an explanation for the correlation between low levels of protein and lactose in milk and high milk production in sheep. On the other hand, it has been reported that melatonin membrane receptors, MT1 and MT2, are persistently expressed in the mammary glands of dairy goats throughout lactation (Zhang et al. 2019), suggesting a direct role of melatonin in regulating mammary physiology.

The three experiments did not indicate any direct effect of implanting melatonin in the lambs whether they were reared by their dams or artificially. Evidence of treatment with melatonin in suckling lambs is limited. Implanting lambs with a single melatonin sachet subcutaneously on the back at 3-4 weeks of age (Kennaway and Gilmore 1984) did not affect growth rate, and a pinealectomy of prepubertal sheep did not affect growth rate (Brown and Forbes 1980). Aridas et al. (2018) administered melatonin by intravenous infusion or through transdermal patches to newborn lambs that had...
been subject to induced asphyxia, which reduced the pathologies caused by asphyxia. In newborn lambs, treatment with melatonin reduced the in vivo pulmonary pressor response to changes in oxygenation (Astorga et al. 2018) or presented an antiproliferative effect against pathologies such as pulmonary arterial hypertension in neonates (Rivera et al. 2020). Melatonin given to human newborns with sepsis reduced the number that died because of its highly effective antioxidant and free-radical scavenging properties (Gitto et al. 2001). Although melatonin treatment has positive effects on the newborn’s health, no evidence of an effect on growth rates has been presented. Melatonin treatment of ewes in mid- or late pregnancy has positive effects on lambs. Flinn et al. (2020a, b) reported that maternal melatonin supplementation in the second half of pregnancy improved the survival of second-born twin lambs, so that melatonin implants have potential as a simple and cost-effective strategy to reduce neonatal losses of twin lambs on farm. Our group has demonstrated an improvement in colostrum quality if ewes are implanted at the fourth month of pregnancy (Abecia et al. 2020), and higher survival and growth rates from birth to weaning of Merino lambs (Davis et al. 2021). Probably, the increased survival is mediated by the high colostrum quality, and by an increase in BAT and birth weight if maternal melatonin implants were inserted from day 100 of gestation (Sales et al. 2017).

Our experiments indicated no significant differences in the growth rates of male and female lambs, and even among artificially reared lambs, females had higher growth rates than did males. Makovický et al. (2019) observed that ewe lambs at the end of milk rearing had a higher average daily gain than did ram lambs, probably, because of differences in the feeding behaviour of males and females fed ad libitum; specifically, females tend to consume less milk per meal than do males, but consume more meals per day than do males (David et al. 2014).

The higher growth rate of lambs reared by implanted dams might have been mediated by a higher melatonin concentration in their mother’s milk, which in turn might have affected the lamb’s health. In cows and goats, milk melatonin levels reflect blood concentrations of melatonin, with a short delay (Eriksson et al. 1998), and Cohen Engler et al. (2012) speculated that melatonin that is supplied to the infant via breast milk plays a role in improving sleep and reducing colic in breast-fed human offspring (Cohen et al., 2011). The lamb can readily produce an appropriately timed melatonin rhythm by 1-6 weeks of age (Claypool et al., 1989) and, although maternal melatonin is predominant before birth, significant but low-amplitude increases in nighttime melatonin can occur within the first week (Foster et al., 1989). It is likely that the positive effect of melatonin supplementation on the differentiation of intramuscular preadipocytes into adipocytes described in cattle (Yang et al. 2017) has also been able to affect growth rate of lambs reared by implanted ewes, through an increase of fat deposition in their muscles. In any case, the absence of differences between c and m lambs from the M group of ewes in Experiment 2, and the results from Experiment 3, in which lambs did not receive milk from their mothers, did not receive extra melatonin from milk, lead us to conclude that neither exogenous or endogenous melatonin of the lambs, or melatonin from their mothers’ milk have a direct effect on growth rate.

Conclusions

In conclusion, treatment ewes with melatonin at lambing induced a high growth rate in their lambs and produced an increase in the fat content of the milk; however, the direct treatment with melatonin of the lambs at birth did not have a significant effect on their growth rate.

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Author contributions JAA conceived and designed the study. SL and FC performed the experiments. JAA wrote the first draft of the manuscript. JAA, SL and FC revised the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets in this study are available from the corresponding author on reasonable request.

Declarations

The experiment was conducted at the experimental farm of the University of Zaragoza, Spain (41°40’N), under procedures approved by the Ethics Committee for Animal Experiments at the University of Zaragoza, and in accordance with the Spanish Policy for Animal Protection RD1201/05, which meets the European Union Directive 2010/63 on the protection of animals used for experimental and other scientific purposes.

Conflict of interest The authors declare that they have no competing interests.

References

Abecia JA, Forcada F, Valares JA, Palacín I, Martín S, Martino A, Gómez MI, Palacios C (2005) Does melatonin treatment during lactation influence milk production in Lacaune and Assaf ewes? Span J Agric Res 3:396–401
Abecia JA, Garrido C, Gave M, García AI, López D, Luis S, Valares JA, Mata I (2020) Exogenous melatonin and male foetuses improve the quality of sheep colostrum. J Anim Physiol Anim Nutr 104:1305–1309
Aly H, Elmahdy H, El-Dib M, Rowisha M, Awny M, El-Gohary T, Elbatch M, Hamisa M, El-Mashad AR (2015) Melatonin use for
neuroprotection in perinatal asphyxia: a randomized controlled pilot study. J Perinatol 35:186–191

Arias JDS, Yawno T, Sutherland AE, Nitsos I, Ditchfield M, Wong FY, Hunt RW, Fahey MC, Malhotra A, Wallace EM, Jenkin G, Miller SL (2018) Systemic and transdermal melatonin administration prevents neuropathology in response to perinatal asphyxia in newborn lambs. J Pineal Res 64:e12479

Astorga CR, González-Candia A, Candia AA, Figueroa EG, Cañas D, Ebenisperger G, Reyes RV, Llanos AJ, Herrera EA (2018) Melatonin decreases pulmonary vascular remodeling and oxygen sensitivity in pulmonary hypertensive newborn lambs. Front Physiol 9:185

Avilés R, Delgadillo JA, Flores JA, Duarte G, Vielma J, Flores MJ, Petrovski K, Zarazaga LA, Hernández H (2019) Melatonin administration during the dry period stimulates subsequent milk yield and weight gain of offspring in subtropical does kidding in summer. J Dairy Sci 102:11536–11543

Bianchi AE, Macedo VP, Schafer Da Silva A, Finkler da Silveira AL (2018) Effect of the addition of protected fat from palm oil to the diet of dairy sheep. Rev Bras Zootec 47:e20160137

Brown WB, Forbes JM (1980) Diurnal variations of plasma prolactin in growing sheep under two lighting regimes and the effect of pinealectomy. J Endocrinol 84:91–99

Cohen Engler A, Hadash A, Shehadeh N, Pillar G (2012) Breastfeeding may improve nocturnal sleep and reduce infantile colic: potential role of breast milk melatonin. Eur J Pediatr 171:729–732

Cosso G, Mura MC, Pulinas L, Curone G, Vigo D, Carcangiu V, Lauridiana S (2021) Effects of melatonin treatment on milk traits, reproductive performance and immune response in Sarda dairy sheep. Ital J Anim Sci 20:632–639

David I, Bouvier F, Ricard E, Ruesche J, Weisbecker J (2014) Feeding behaviour of artificially reared Romane lambs. Animal 86:982–990

Davis R, Green JM, Abecia JA (2021) Field trials of the use of melatonin implants during pregnancy as a tool to improve lamb performances. Proceedings of the British Society of Animal Science (BSAS) 2021 Conference, 12-15 April 2021

El Hadi A (2020) The impact of shearing and hormonal treatments (melatonin or cabergoline) in lactating dairy ewes. PhD Thesis, Universidad Autonoma de Barcelona, Spain

Eriksson L, Valtonen M, Laitinen JT, Paananen M, Kaikkonen M (1998) Diurnal rhythm of melatonin in bovine milk: pharmacokinetics of exogenous melatonin in lactating cows and goats. Acta Vet Scand 39:301–310

Flinn T, Gunn JR, Kind KL, Swinbourne AM, Weaver AC, Kelly JM, Walker SK, Gatford KL, van Wettere WHE, Kleemann DO (2020a) Maternal melatonin implants improve twin merino lamb survival. J Anim Sci 98:e23a344

Flinn T, McCarthy NL, Swinbourne AM, Gatford KL, Weaver AC, McGrice HA, Kelly JM, Walker SK, Kind KL, Kleemann DO, van Wettere WHE (2020b) Supplementing merino ewes with melatonin during the last half of pregnancy improves tolerance of prolonged parturition and survival of second-born twin lambs. J Anim Sci 98:e23a372

Gitto E, Karbownik M, Reiter R, Tan DX, Cuzzocrea S, Chiurazzi P, Cordaro S, Corona G, Trimarchi G, Barberi I (2001) Effects of melatonin treatment in septic newborns. Pediatr Res 50:756–760

Kennaway DJ, Gilmore TA (1984) Effects of melatonin implants in ewe lambs. J Reprod Fertil 70:39–45

Makovický P, Gálisová Čopíková M, Margetín M, Makovický P, Nagy M (2019) Growth intensity of lambs during artificial milk rearing depending on chosen non genetic factors. Iran J Appl Anim Sci 9:257–263

Malpau B, Vigué C, Skinner DC, Thiéry JC, Chemineau P (1997) Control of the circannual rhythm of reproduction by melatonin in the ewe. Brain Res Bull 44:431–438

Molik E, Bonczar G, Żebrowska A, Miształ T, Pustkowiak H, Zięba D (2011) Effect of day length and exogenous melatonin on chemical composition of sheep milk. Arch Anim Breed 54:177–187

Muir PD, Smith NB, Wallace GJ, Fugle CJ, Bown MD (2000) Maximising lamb growth rates. Proc New Zealand Grassland Assoc 62:55–58

O’Callaghan D, Karsch FJ, Boland MP, Roche FJ (1991) Role of short days in timing the onset and duration of reproductive activity in ewes under artificial photoperiods. Biol Reprod 44:23–28

Othmane MH, Carriedo JA, de la Fuente LF, Primitivo FS (2002) Factors affecting test-day milk composition in dairy ewes, and relationships amongst various milk components. J Dairy Res 69:53–62

Palacin I, Forcada F, Abecia JA (2011) Meta-analysis of the efficacy of melatonin implants for improving reproductive performance in sheep. Span J Agric Res 9:730–743

Rivera E, Garcia-Herrera C, González-Candia A, Celentano DJ, Herrera EA (2020) Effects of melatonin on the passive mechanical response of arteries in chronic hypoxic newborn lambs. J Mech Behav Biomed Mater 11:104013

Sales F, Parraguez VH, McCoard S, Cofré E, Peralta OA, Subiabre I (2017) Fetal brown fat deposition is increased by melatonin implants in sheep. J Anim Sci 95:152–153

Seron-Ferre M, Reynolds H, Mendez NA, Mondaca M, Valenzuela F, Ebenesperger R, Valenzuela GJ, Herrera EA, Llanos AJ, Torres-Farfan C (2015) Impact of maternal melatonin suppression on amount and functionality of brown adipose tissue (BAT) in the newborn sheep. Front Endocrinol 5:232

Wang Y, Guo W, Xu H, Tang K, Zan L, Yang W (2019) Melatonin suppresses milk fat synthesis by inhibiting the mTOR signaling pathway via the MT1 receptor in bovine mammary epithelial cells. J Pineal Res 67:e12593

Yang WC, Tang KQ, Wang YN, Zhang YY, Zan LS (2017) Melatonin promotes triacylglycerol accumulation via MT2 receptor during differentiation in bovine intramuscular preadipocytes. Sci Rep 7:15080

Yang CH, Xu JH, Ren QC, Duan T, Mo F, Zhang W (2019) Melatonin promotes secondary hair follicle development of early postnatal cashmere goat and improves cashmere quantity and quality by enhancing antioxidant capacity and suppressing apoptosis. J Pineal Res 67:e12569

Yeates NTM (1949) The breeding season of the ewe with particular reference to its modification by artificial light. J Agric Sci 33:1–13

Yellon SM, Longo LD (1987) Melatonin rhythms in fetal and maternal circulation during pregnancy in sheep. Am J Physiol-Endocrinol Metabol 252:E799–E802

Zhang WL, Chen JX, Zhao YX, Zheng Z, Song YL, Wang H and Tong D (2018) The inhibitory effect of melatonin on mammary function of lactating dairy goats. Biol Reprod 100:455–467

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