The role of leptin in the transition from fetus to neonate

A. Mostyn1*, D. H. Keisler2, R. Webb3, T. Stephenson1 and M. E. Symonds1

1Academic Division of Child Health, School of Human Development, University Hospital, Nottingham NG7 2UH, UK
2Department of Animal Sciences, University of Missouri, Columbia, Missouri 65211–5300, USA
3Division of Agriculture and Horticulture, School of Biosciences, University of Nottingham, Sutton Bonington Campus, Loughborough LE12 5RD, UK

Leptin is a 16 kDa hormone which has been shown to have a major physiological role in the control of energy balance. Leptin is produced primarily in white adipose tissue, although there is evidence for its production in brown adipose tissue (BAT) and the placenta. BAT is critically important for the initiation of non-shivering thermogenesis in the newborn through the BAT-specific uncoupling protein (UCP), UCP1. This factor is particularly important in lambs in which levels of UCP1 peak at birth, concomitant with a rapid decline in plasma leptin levels. Our studies have examined the effect of acute and chronic administration of leptin to neonatal lambs, investigating effects on colonic temperature, UCP1 and thermogenic potential of BAT. Administration of leptin in sequential physiological doses of 10, 100 and 100 µg to neonatal lambs caused a modest increase in colonic temperature which was not observed in weight-matched vehicle-treated controls. This increase in colonic temperature was not mediated by an increase in either abundance or thermogenic potential of UCP1, as previously shown in adult rodents. UCP1 mRNA levels were 30 % lower in leptin-treated lambs, which is also contradictory to findings in adult rodents. Leptin treatment resulted in a dose-dependent rise in plasma leptin, with levels at the end of the study being almost twenty times greater in leptin-treated animals. To determine whether these findings in neonatal lambs were transient due to the complex milieu of hormones present after birth, we examined the effect of chronic leptin treatment over 6 d. Pairs of lambs were treated daily, from the second to seventh day of life with 100 µg leptin or vehicle. Colonic temperatures of leptin- and vehicle-treated animals remained similar throughout the study. UCP1 abundance was significantly lower in the leptin-treated animals, suggesting that the drop in UCP1 mRNA seen in the previous study had been translated to protein levels. In conclusion, the decline in plasma leptin levels at birth may be a signal to initiate enteral feeding. In lambs, the rapid loss of UCP1 mRNA, which occurs within the first few days of life, appears to be accelerated by leptin administration, possibly stimulating the development of white adipose tissue and generation of body heat through mechanisms other than non-shivering thermogenesis by UCP1 in BAT.

Leptin: Brown adipose tissue: Neonate: Uncoupling protein

Since the discovery of leptin in 1994 (Zhang et al. 1994) there has been a great deal of interest in its role in metabolic regulation and the possibility of using leptin for promoting weight loss. Evidence from human studies suggests that there are dynamic changes in leptin over the period of transition from fetus to neonate (Matsuda et al. 1999; Fig. 1).

Leptin and adipose tissue

Leptin is a 16 kDa protein and a member of the cytokine superfamily (Madej et al. 1995). It is produced mainly in white adipose tissue, although there is evidence for its production in brown adipose tissue (BAT; Cinti et al. 1997; Dessolin et al. 1997), the placenta (Hassink et al. 1997; Hoggard et al. 1997a, 2000) and also the stomach (Bado...
Leptin is also thought to act in an autocrine and paracrine manner, stimulating the hypothalamus and other peripheral tissues such as the kidney, placenta, and brown adipose tissue (BAT). Leptin acts through a family of receptors named leptin receptors (OB-R). There are multiple isoforms of OB-R: OB-Ra (the most widely expressed form), OB-Rb, OB-Rc, OB-Rd, and OB-Re. OB-Ra functions as a transmembrane receptor, while OB-Rb is a soluble binding protein. The expression of these receptors is tissue-specific, with OB-Ra being expressed in the ventromedial nucleus, arcuate nucleus, and paraventricular nucleus of the hypothalamus, which are critically important at parturition and for the onset of puberty, reproduction (Messinis et al., 1999), appetite and energy regulation (Friedman et al., 1998), and the distribution and relative abundance of OB-R in a multi-species antibody (Imagawa et al., 1998). These changes in body temperature were linked to an increased abundance of UCP1 in BAT (Scarpace et al., 1999), which is about 147 d in the sheep. Leptin mRNA levels are closely correlated with fetal weight. The slope of the relationship between leptin mRNA abundance and fetal weight is steeper at about 90 d of gestation compared with 125–140 d of gestation (Yuen et al., 1999). This finding suggests that production of leptin mRNA is modulated by the increase in size and number of adipocytes, which occurs during late gestation in the ovine fetus (Lonnqvist et al., 1997), but is also sensitive to the rapid increase in body weight at this period. The increase in leptin mRNA may also be attributed to the rise in circulating corticosteroids during late gestation, since glucocorticoids have been shown to stimulate leptin expression both in vitro and in vivo (De Vos et al., 1995; Mostyn et al., 2001). OB-R mRNA is present in a variety of murine fetal tissues (Hoggard et al., 1997a, 2000), although its physiological relevance is as yet unknown.

It has been suggested that leptin may act as a growth factor in the fetus, directing growth and development via central or peripheral actions (Hassink et al., 2000; Steppan & Swick, 1999; Udagawa et al., 2000). Many studies have measured plasma leptin concentrations in newborn infants; however, the results from these studies have been highly inconsistent, as shown in Table 1. These contrasting findings may be due to a number of confounding factors, including geographical location, maternal and social differences, as well as the clinical status of the infant at the time of blood sampling. Also, there are known to be sensitivity problems with the radioimmunoassay kit used (Linco Multi-Species; Linco Research Inc., St Charles, MO, USA), with regard to the detection of low-range values, and cross-reactivity between non-specific plasma proteins and the ‘multi-species’ antibody (Imagawa et al., 1998; Delavaud et al., 2000).

Leptin and the fetus

Leptin mRNA is detectable in fetal adipose tissue of sheep by about 90 d of gestation, with levels increasing up to term (Yuen et al., 1999), which is about 147 d in the sheep. Leptin mRNA levels are closely correlated with fetal weight. The slope of the relationship between leptin mRNA abundance and fetal weight is steeper at about 90 d of gestation compared with 125–140 d of gestation (Yuen et al., 1999). This finding suggests that production of leptin mRNA is modulated by the increase in size and number of adipocytes, which occurs during late gestation in the ovine fetus (Lonnqvist et al., 1997), but is also sensitive to the rapid increase in body weight at this period. The increase in leptin mRNA may also be attributed to the rise in circulating corticosteroids during late gestation, since glucocorticoids have been shown to stimulate leptin expression both in vitro and in vivo (De Vos et al., 1995; Mostyn et al., 2001). OB-R mRNA is present in a variety of murine fetal tissues (Hoggard et al., 1997a, 2000), although its physiological relevance is as yet unknown.

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**Fig. 1.** Western blot of leptin receptor protein in ovine tissues. Protein (30 µg) was loaded onto each lane. Samples were as follows: 1, hypothalamus; 2, adrenal; 3, kidney; 4, lung; 5, testis; Br, brain; BA, brown adipose tissue (plasma membranes). Major bands were observed at about 100 and 200 kDa, as determined by molecular-weight markers.
Results from human clinical studies suggest that leptin values remain low during early gestation, are detectable by about 35 weeks of gestation, and increase towards term in response to the increased abundance of adipose tissue (Cinaz et al. 1999; Matsuda et al. 1999). Leptin levels peak around birth in the infant, then rapidly decline by day 3 of postnatal life (Hytinantti et al. 1999; Schubring et al. 1999). There is also evidence that leptin is expressed in rodent adipose tissue at birth (Dessolin et al. 1997) and may play a role in energy regulation of the neonate (Yuen et al. 2000). These postnatal changes are likely to occur in response to the dramatic alterations in energy balance experienced by the neonate during the transition to enteral feeding, since fasting has been shown to reduce circulating leptin levels (Ahima et al. 1996). Initially there may be some delay before the mother’s milk is produced and colostrum secreted during the first few days has a low energy content. There is evidence that leptin levels are higher in female infants and lambs compared with the corresponding males (Mostyn et al. 1999), as leptin production is inhibited by testosterone (Behre et al. 1997). Leptin is also present in the placenta (Hassink et al. 1997; Hoggard et al. 1997a, 2000; Ashworth et al. 2000). This additional source may increase both fetal and maternal circulating concentrations of leptin (Dandrea et al. 2000), and has been shown to be nutritionally sensitive (Wilson et al. 2000).

### The uncoupling proteins and leptin

UCP1 is the UCP responsible for non-shivering thermogenesis in the neonate (Cannon & Nedergaard, 1985). UCP1 acts by ‘uncoupling’ normal respiration and allowing the protons produced by the respiratory chain to flow back into the mitochondrial matrix rather than through ATPase. The chemical energy from the proton motive force is dissipated as heat by the animal (Nedergaard & Cannon, 1992). The ontogeny of UCP1 mRNA in BAT is very similar to that of leptin (Fig. 1). In the ovine fetus UCP1 mRNA appears at about 110 d of gestation, and levels remain low, increasing towards term, since non-shivering thermogenesis does not occur in utero under normal circumstances (Symonds et al. 1995). In man and other large mammals UCP1 mRNA disappears within a few days after birth (for example, see Clarke et al. 1997a). UCP1 protein disappears in the first months after life, and is not expressed during adulthood except under extreme pathological conditions, e.g. phaeochromocytoma, a tumour of the adrenal gland which produces high circulating concentrations of catecholamines (Ricquier et al. 1982; Lean et al. 1986a,b). In rodents UCP1 can be reactivated by a variety of factors, including cold exposure (Denjean et al. 1999) and cafeteria-diet feeding (Denjean et al. 1999; Rippe et al. 2000).

When leptin is administered in physiological doses (e.g. 1 mg) it has been shown to stimulate UCP1 expression in the adult rodent (Scarpace et al. 1997), by increasing sympathetic activity and noradrenaline turnover in BAT (Collins et al. 1996; Haynes et al. 1997). However, these studies are not suitable for comparison with large mammals or neonates.

UCP1 belongs to a family of UCP, other members including UCP3, which is found selectively in adipose tissue and muscle (Vidal-Puig et al. 1997), and UCP2 which is expressed in a large number of tissues (Fleury et al. 1997). Both UCP2 and UCP3 are thought to have roles in energy regulation, and leptin has been shown to regulate their abundance (Scarpacce et al. 1998). UCP3 is not expressed during fetal life in rodents, but mRNA levels surge at birth (Carmona et al. 1998). The factors responsible for this post-natal rise are unknown. UCP2 and UCP3 mRNA have been shown to be present in piglet muscle (Damon et al. 2000), a

### Table 1. Summary of the studies investigating fetal and neonatal leptin concentrations in human subjects

<table>
<thead>
<tr>
<th>Country of study</th>
<th>Gestation</th>
<th>Cord leptin (ng/ml)</th>
<th>Neonatal leptin (ng/ml)</th>
<th>Main finding</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finland</td>
<td>Term</td>
<td>9·7 (median)</td>
<td>4·8</td>
<td>Leptin concentrations correlate with adiposity in female but not male newborns</td>
<td>Hytinantti et al. (1999)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Term</td>
<td>7·3 (median)</td>
<td>1·9</td>
<td>Cord leptin correlates with adipose tissue mass</td>
<td>Marchini et al. (1998)</td>
</tr>
<tr>
<td>UK</td>
<td>Term</td>
<td>5·9</td>
<td>2·7</td>
<td>Fetal leptin levels increase towards term</td>
<td>Geary et al. (1999)</td>
</tr>
<tr>
<td>Germany</td>
<td>Term</td>
<td>3·6</td>
<td>0·4</td>
<td>Cord leptin correlates with adiposity and levels decline after birth</td>
<td>Schubring et al. (1999)</td>
</tr>
<tr>
<td>Turkey</td>
<td>Term</td>
<td>2·29</td>
<td>0·52</td>
<td>Plasma leptin levels correlate with adiposity and are related to nutritional status</td>
<td>Cinaz et al. (1999)</td>
</tr>
<tr>
<td>USA</td>
<td>Term</td>
<td>4·1</td>
<td>3·5</td>
<td>Cord leptin levels are correlated with adiposity with no gender differences</td>
<td>Shkeshwatt et al. (1998)</td>
</tr>
<tr>
<td>USA</td>
<td>Term</td>
<td>4·2 (median)</td>
<td>2·9</td>
<td>Cord leptin levels are correlated with birth weight and are reduced in premature infants</td>
<td>Tarquini et al. (1999)</td>
</tr>
<tr>
<td>Japan</td>
<td>Term</td>
<td>19·6</td>
<td>1·9</td>
<td>Leptin concentrations are reduced after birth</td>
<td>Matsuda et al. (1999)</td>
</tr>
<tr>
<td>Japan</td>
<td>Artery: 9·8</td>
<td>1·2</td>
<td>1·9</td>
<td>Leptin levels are higher in umbilical veins than arteries; leptin concentrations fall rapidly after birth</td>
<td>Yura et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>Vein: 12·9</td>
<td></td>
<td>1·8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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species that does not express UCP1. It has therefore been suggested that UCP2 and UCP3 are involved in producing heat by non-shivering thermogenesis in muscle.

Rodent models of over- and underexpression of UCP3 have shown contrasting effects. Mice which overexpress human UCP3 in skeletal muscle have been shown to be hyperphagic, consuming about 40% more than wild-type mice from 4 to 12 weeks of age, but were leaner (Clapham et al. 2000). Fat mass in the UCP3-overexpression group was also significantly lower than wild type (P < 0.05), suggesting increased fat turnover and metabolism in the mice overexpressing UCP3. However, lack of UCP3 expression is not associated with obesity, nor a reduced ability to maintain body temperature during cold exposure (Vidal-Puig et al. 2000). Problems of interpreting findings from transgenic mice have been further compounded by the contrasting effects on obesity seen in UCP1-ablated mice.

The first study on UCP1-ablated mice (Lowell et al. 1993) found the animals became moderately hypothermic (i.e. body temperature about 35°C) during cold exposure (i.e. 2 h at 5°C) and developed obesity, although UCP1 protein was still detectable at very low levels. A more recent study (Enerback et al. 1997) found that mice lacking UCP1 became extremely hypothermic (i.e. body temperature decreased by 10°C to about 27°C during cold exposure (at 4°C). These mice did not become obese; the compensation for loss of UCP1 in this case has been attributed to an increase in UCP2 mRNA in BAT (Enerback et al. 1997).

Effect of acute leptin treatment on neonatal lambs

Given the rapid decline in plasma leptin concentrations after birth (Fig. 1), we investigated the role of acute leptin administration during the early neonatal period in a precocial species with thermoregulatory and hormonal responses at birth similar to those in human subjects, i.e. lambs. Lambs (1-d-old) were treated sequentially with 10, 100 and 1000 µg leptin or vehicle (sterile water) while colonic temperature was measured continuously. Blood samples were taken throughout the study to allow measurement of plasma leptin. Administration of leptin in sequential doses of 10, 100 and 1000 µg promoted maintenance of colonic temperature, which was not observed in weight-matched vehicle-treated controls (Fig. 3; Mostyn et al. 2000a).

As a consequence, colonic temperature was significantly lower (P < 0.05) in controls compared with leptin-treated animals at the end of the study. All lambs in both groups shivered, but leptin-treated lambs shivered for half as much time as controls. Lamb body and perirenal adipose tissue weights were similar between groups (Mostyn et al. 2000a). In contrast, abundance of UCP1 mRNA, when expressed as a ratio of r18S, was lower in six of eight leptin-treated lambs compared with controls. On average, UCP1 mRNA expression was 30% lower in the leptin-treated group (Bispham et al. 1999). Despite this decline in UCP1 mRNA expression there was no difference between groups in UCP1 protein abundance, or the thermogenic potential, as assessed by the guanosine diphosphate-binding assay (Mostyn et al. 1999). This outcome was as expected, since the half-life of UCP1 is 7 d (Clarke et al. 1997a).

There was no difference in plasma leptin concentrations at the start of the study (Fig. 4), although leptin concentrations were significantly higher in female lambs compared with male lambs (P < 0.05; Mostyn et al. 1999). Leptin administration resulted in a significant (P < 0.01) dose-dependent increase in plasma leptin concentrations, irrespective of gender.

These findings show that administration of leptin to 1-d-old lambs causes maintenance of colonic temperature, despite a reduction in UCP1 mRNA and no change in thermogenic potential. The loss of UCP1 mRNA suggests that leptin may be one of the factors involved in initiating the rapid loss of UCP1 after birth. These results are therefore contradictory to those of adult rodent studies (Scarpace et al. 1997) which used higher doses of...
leptin and possibly observed pharmacological effects (Scarpace et al. 1997).

**Effect of chronic leptin administration to neonatal lambs**

In order to determine whether the earlier findings in neonatal lambs were transient due in part to the complex milieu of hormones present after birth, we decided to carry out a longer-term study. Pairs of 1-d-old lambs were treated daily with either 100 µg leptin or vehicle for 6 d (days 2–7 of life; Mostyn et al. 2000b). Colonic temperature and blood samples were taken daily before treatment. There was no difference in colonic temperature between the two groups on any day (Fig. 5), but leptin-treated animals were better able to maintain body temperature between days 1 and 2 when the vehicle group exhibited a significant decline in colonic temperature ($P < 0.05$).

Despite this maintenance of colonic temperature, the leptin-treated group had significantly lower UCP1 abundance in BAT than controls ($P < 0.05$; Fig. 6), but similar thermogenic potential, as measured by guanosine diphosphate binding, after 6 d of treatment (Mostyn et al. 2000b). Body weight, BAT weight and growth rates were similar between groups.

Chronic leptin administration to neonatal lambs therefore causes loss of UCP1 protein, with no change in thermogenic potential or temperature. This loss of UCP1 may be compensated for by modification of expression of one or more of the other UCP, although this possibility has not yet been investigated.

**Future perspectives**

Leptin has the potential to play a role in the transition from fetal to neonatal life, although its exact function remains unknown. Leptin concentrations decline rapidly after birth, as the infant moves from a state of passive nutrient uptake to one of active enteral feeding. Leptin levels are known to decrease in response to starvation (Ahima et al. 1996), and this decline may be one way of facilitating the infant’s intake of milk. As the infant or lamb commences feeding and increases food intake, fat deposition will occur, since less energy is needed for maintaining body temperature. The neonate will therefore have less requirement for non-shivering thermogenesis in BAT, since heat production from dietary-induced and shivering thermogenesis in muscle plus increased insulation act to maintain body temperature (Symonds et al. 1989a,b). It is hypothesised that with increasing age plasma leptin increases in response to feeding and at the same time promotes loss of UCP1. Concurrently, abundance of UCP2 and UCP3 may be increased, the activity of which could be stimulated during periods of nutritional stress (e.g. starvation; Ahima et al. 1996). This process will enable the neonate to maintain a BMR and prevent hypothermia despite the loss of UCP1. More studies are required to fully elucidate the role of leptin in the fetus and neonate. The emergence of sheep transgenic models (McCreath et al. 2000) in which under- and over-expression of UCP can be demonstrated are likely to provide more information regarding the effect of leptin on thermogenesis at birth. Both acute and chronic leptin treatment reduce UCP1; whether a lack of leptin at birth will allow UCP1 to function for longer than the usual first 2 weeks of life remains to be established. The potential therapeutic use of leptin to promote thermoregulation and postnatal adaptation remains an intriguing possibility.

**Acknowledgements**

A. M. was funded by a University of Nottingham Scholarship.

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**Fig. 5.** Effect of chronic leptin treatment (100 µg/d) on colonic temperature in pairs of 1-d-old lambs treated daily with either leptin (●) or vehicle (sterile water; ○) for 6 d (days 2–7 of life). Values are means with their standard errors represented by vertical bars. There was a significant decline in temperature in vehicle-treated lambs between days 1 and 2 that was not observed in leptin-treated lambs: $*P < 0.05$. (From Mostyn et al. 2000b.)

**Fig. 6.** Uncoupling protein (UCP)-1 abundance in chronic leptin-treated (100 µg/d for 6 d; □) and vehicle-treated (sterile water; ○) neonatal lambs. Values are means with their standard errors represented by vertical bars. L, leptin-treated; V, vehicle-treated; -ve liver mitochondria; R, reference sample from 4-h-old lamb. Mean value was significantly different from that of vehicle-treated lambs: $*P < 0.05$. 

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