THEMATIC REVIEW

Competition for nutrients in pregnant adolescents: consequences for maternal, conceptus and offspring endocrine systems

Jacqueline M Wallace
Rowett Institute, University of Aberdeen, Aberdeen, UK
Correspondence should be addressed to J M Wallace: Jacqueline.Wallace@abdn.ac.uk
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Abstract
The competition for nutrients that arises when pregnancy coincides with continuing or incomplete growth in young adolescent girls increases the risk of preterm delivery and low birthweight with negative after-effects for mother and child extending beyond the perinatal period. Sheep paradigms involving nutritional management of weight and adiposity in young, biologically immature adolescents have allowed the consequences of differential maternal growth status to be explored. Although nutrient reserves at conception play a modest role, it is the dietary manipulation of the maternal growth trajectory thereafter which has the most negative impact on pregnancy outcome. Overnourishing adolescents to promote rapid maternal growth is particularly detrimental as placential growth, uteroplacental blood flows and fetal nutrient delivery are perturbed leading to a high incidence of fetal growth restriction and premature delivery of low birthweight lambs, whereas in undernourished adolescents further maternal growth is prevented, and depletion of the maternal body results in a small reduction in birthweight independent of placental size. Maternal and placental endocrine systems are differentially altered in both paradigms with downstream effects on fetal endocrine systems, organ development and body composition. Approaches to reverse these effects have been explored, predominantly targeting placental growth or function. After birth, growth-restricted offspring born to overnourished adolescents and fed to appetite have an altered metabolic phenotype which persists into adulthood, whereas offspring of undernourished adolescents are largely unaffected. This body of work using ovine paradigms has public health implications for nutritional advice offered to young adolescents before and during pregnancy, and their offspring thereafter.

Introduction
Adolescent fertility rate as measured by births per 1000 females aged 15–19 years has steadily declined in virtually all countries across the globe from 1960 to present day (https://data.worldbank.org/indicator/sp.ado.tfrt). Nevertheless, pregnancy during adolescence still accounts for an estimated 11% of all births worldwide.
with more than 95% of these occurring in developing countries (https://www.who.int/en/news-room/fact-sheets/detail/adolescent-pregnancy). The antecedents of early childbearing are diverse and in the developed world include social disadvantage, low educational attainment, dysfunctional family structures, ethnicity and an intergenerational history of early childbirth, as well as a propensity for risky, aggressive and delinquent behaviours (Meade et al. 2008, Gaudie et al. 2010). In contrast, in developing countries, early marriage and childbearing are often the cultural norm particularly in communities where access to education for girls is limited and the supporting health infrastructure is weak (Das et al. 2017). Irrespective of geographical location there is commonality in the hazards associated with early childbearing, and systematic reviews, multi-country surveys and population-based studies consistently report a higher risk of premature delivery, low birthweight and neonatal morbidity and mortality in adolescent pregnancies (Salihu et al. 2006, Gibbs et al. 2012, Malabarey et al. 2012, Kozuki et al. 2013, Ganchimeg et al. 2014, De Azevedo et al. 2015). Relative to adult women, pregnancy at any age during adolescence is associated with a greater possibility of experiencing anaemia, eclampsia, puerperal endometritis and systemic infections, while heightened risk of preterm delivery, low birthweight and neonatal mortality is most pronounced in very young girls (≤15 years of age and/or within 2 years of first menses) who are biologically immature (Ganchimeg et al. 2014, Weng et al. 2014, Torvie et al. 2015, Neal et al. 2018). A short cervix, small uterine volume and immature pelvis leading to cephalopelvic disproportion are more common in younger mothers and may predispose them to early delivery and complications such as obstetric fistula and other maternal near-miss events (Moerman 1982, Stevens-Simon et al. 2000, Gadelha Da Costa et al. 2004, Tebeu et al. 2012, Ganchimeg et al. 2014, Oliveira et al. 2014). Maternal mortality is thankfully rare, but in low resource settings the adjusted risk of mortality is four times higher for very young mothers than for both older adolescents and adult women (Conde-Aguedelo et al. 2005).

Maternal–fetal competition for nutrients

Greater prevalence of adverse perinatal outcomes in very young adolescent mothers may additionally reflect that a significant proportion are either still growing or have the potential to grow at the time of conception setting up a maternal–fetal competition for nutrients. Although the peak in growth velocity characteristic of adolescence is reached before menarche, girls continue to grow thereafter and on average gain a further 7 cm in height before linear growth ceases (Roche & Davila 1972). In the US-based Camden Adolescent Pregnancy and Nutrition Project, approximately 50% of young adolescents (≤16 years) continued to grow as indicated by increases in knee height over a 6-month period from mid-pregnancy to 4–6 weeks post-partum. This drive to maternal tissue growth as reflected by higher gestational weight gains, increased fat stores and greater post-partum weight retention was associated with a three-fold higher risk of small-for-gestational-age birth and lower average birthweights than in both non-growing adolescents of equivalent age and mature women (Scholl et al. 1994, 1997). A similar alteration in nutritional priorities leading to smaller babies has been observed in young (<15 years) ‘still-growing’ Peruvian girls: in this instance adolescent growth was defined as continuing or complete based on their height at delivery relative to parental height (Frisancho et al. 1985). When pregnant adolescents are undernourished, it is likely that both mother and fetus are compromised and in partial support there is evidence from rural Bangladesh that pregnant adolescents (average age 16.3 years) cease linear growth and deplete their fat stores compared with non-pregnant adolescents of equivalent gynaecological age (Rah et al. 2008). Perinatal outcomes were not reported, but the effects on maternal growth were most pronounced in the girls who became pregnant at an earlier age. In contrast, in a UK-based study involving older adolescents (average age 17.8 years), continuing maternal growth measured as a change in knee height of >2 mm between 13- and 29-weeks gestation did not limit fetal growth relative to non-growing adolescents but in this instance both macronutrient and micronutrients intakes generally exceeded recommended levels (Jones et al. 2010). Together these studies suggest that the competition for nutrients that arises between the maternal body and gravid uterus when pregnancy coincides with adolescence is specific to very young girls and is likely to be moderated by maternal nutritional status and dietary intake.

Consequences for mother and child beyond the perinatal period

The negative impact of adolescent pregnancy for mother and infant extends beyond the perinatal period. For adolescent mothers themselves longer-term health
outcomes include poorer mental health scores and a two-fold higher rate of suicide (Webb et al. 2011, Aitken et al. 2016), more premature deaths due to cervical and lung cancer (Otterblad-Olausson et al. 2004, Webb et al. 2011) and a three-fold higher risk of diabetes-related mortality (Vandenheede et al. 2012). A young age at first birth is also associated with a higher prevalence of hypertension and osteoporosis in postmenopausal women (Cho et al. 2012, Park et al. 2016), and with poor physical performance and greater risk scores for cardiovascular disease in later life (Pirkle et al. 2014, Rosendaal et al. 2017). In contrast, women with an early first birth have a reduced risk of breast cancer, and the earlier the pregnancy, the lower the risk (Kelsey & Berstein 1996). While some of these relationships likely reflect the complex psychosocial needs and life choices of women who experience early childbirth, others could have a physiological basis originating close to the initial pregnancy. For example, women who give birth during adolescence in the developed world are prone to greater weight retention and adiposity than adolescents who did not experience pregnancy and older pregnant women, and this may influence their metabolic health in later life (Gunderson et al. 2009, Thame et al. 2010).

For the offspring of adolescent mothers, Demographic Health Surveys reveal evidence of low height or stunting in infancy in 9 of 18 developing countries studied (Africa, Asia, Latin America and so on; Yu et al. 2016) and similarly pooled data from five birth cohorts (Brazil, Guatemala, India, The Philippines and South Africa, n~13,000; Fall et al. 2015) reveal a 46% higher risk of stunting at 2 years of age and a greater likelihood of offspring failing to complete their secondary education. The latter study also found a relationship between young maternal age and elevated offspring fasting glucose concentrations in early adulthood (n~10,000) independent of any difference in body composition or blood pressure. In high-income countries, an association between young maternal age (particularly ≤15 years) and greater developmental issues in offspring aged 5 as assessed by school teachers has been reported (n=99,950; Falster et al. 2018) and in a smaller study (n=2643), offspring born to adolescent mothers had a lower IQ score and a higher risk of low IQ at 21 years of age (Khatun et al. 2017). Furthermore, a nationwide evaluation in Denmark (n=1,793,681) has linked early childbearing (12–19 years) with a greater risk of criminality, substance abuse and attempted suicide in offspring aged between 15 and 40 years (Mok et al. 2017).

Depending on the context, each of the aforementioned studies adjusts the data to some degree for potential confounders, for example, maternal smoking, child feeding practice, educational attainment, but residual confounding is likely to be an issue as it is unlikely that all the socioeconomic, environmental and biological/genetic influences that impact a young mother and her offspring from the peri-conception period forwards are sufficiently well documented. Animal models are of value in that specific known confounders can be controlled or removed, allowing researchers to better study the exposure of interest. This was the rationale behind the development of a sheep paradigm to explore the competition for nutrients when pregnancy coincides with continuing or incomplete growth of the young adolescent mother.

### Adolescent sheep paradigms: approach

Sheep producers generally avoid breeding young females during adolescence because relative to adults, they have an inferior reproductive performance characterised by a variable onset of puberty and short first breeding season, low ovulation rate, failure to be mated, fertilisation failure and high embryo loss (Beck et al. 1996, Kenyon et al. 2014, Edwards et al. 2016). The approach developed at the Rowett Institute bypasses many of these issues by using assisted conception procedures to synchronise breeding and establish singleton pregnancies in peripubertal adolescent ewes of equivalent age (~7.5 months), and standardised live-weight and adiposity at conception. Adult ewes of known reproductive history act as embryo donors, thus avoiding the inherently low viability of embryos arising from adolescents themselves (Quirke & Hanrahan 1977, McMillan & McDonald 1985, Morton 2008). Donor ewes in optimal body condition for breeding are superovulated using exogenous hormones, and semen from a single sire is deposited directly into the uterus to ensure fertilisation. Within each study high-quality embryos harvested from any given embryo donor are then distributed evenly across the adolescent recipient study groups: this approach minimises the impact of the main peri-conceptual factors known to influence feto-placental growth and maximises the genetic homogeneity of the resulting fetuses (Wallace et al. 1996).

Nutritional treatments normally begin immediately after embryo transfer and involve presenting the young still-growing adolescent recipient with different quantities of a nutritionally complete diet to manipulate gestational weight gain and thus her growth and body composition. In the overnourished adolescent model, this involves offering a high dietary intake throughout gestation (ad libitum intake, ~2× maintenance requirements) to promote rapid...
maternal growth and is designed to mirror pregnancy in very young but relatively well-nourished adolescent girls who continue to grow substantially while pregnant. By comparison, in the undernourished model, the adolescent dams are prevented from growing further while pregnant (low intake, ~0.7× maintenance), mimicking the situation in very young and poorly nourished adolescents who prematurely cease linear growth during pregnancy. For both models the control group involves a moderate dietary intake calculated to maintain maternal adiposity at a constant level throughout gestation (maintenance). This facilitates a small degree of maternal growth ensuring that the nutrient requirements for optimum conceptus growth are met: this is achieved by modest step-wise increases in maternal dietary intake during the final third of pregnancy.

Pregnancy outcome in rapidly growing adolescent sheep

The nutritional manipulation of gestational weight gain in young adolescent dams to prioritise their own growth leads to adverse outcomes, consistent across multiple studies (Table 1). These include an increased incidence of late miscarriage or stillbirth, reduced placental growth and a shorter gestation length prior to spontaneous delivery of lambs that are on average 30% lighter than those born to optimally fed controls (Wallace et al. 2004a). The extent of fetal compromise within individual studies is variable and closely relates to the degree of placental growth restriction observed. Live-born fetuses are categorised as markedly growth restricted if birthweight is more than two standard deviations below the mean sex-specific birthweight of fetuses in the control group. A summary analysis of contemporary trials revealed that almost half of overnourished pregnancies were in this category, and average placental and fetal weight was reduced relative to controls by ~45% (Wallace 2016). The remaining pregnancies were much less perturbed, but average placental and fetal weights were still statistically lower than those in controls (Fig. 1A and B). Although male conceptuses were larger than females, both sexes were similarly perturbed by maternal nutrition. Within the overnourished groups, maternal anthropometry reveals a greater weight gain and increase in adiposity during the first-third of gestation in pregnancies which result in marked feto-placental growth restriction vs those which

Table 1  
Key characteristics of adolescent pregnancy and offspring outcomes in the overnourished and undernourished models expressed relative to optimally nourished (maintenance-fed) controls.

<table>
<thead>
<tr>
<th>Overnourished model</th>
<th>Undernourished model</th>
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<tr>
<td>Maternal dietary intake</td>
<td>Low, 0.7× maintenance</td>
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<tr>
<td>Maternal growth</td>
<td>Prevented</td>
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<td>Maternal body composition</td>
<td>Progressive fat depletion</td>
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<td>Maternal metabolic hormones</td>
<td>Low insulin, IGF1 and leptin</td>
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<td>Maternal nutrients</td>
<td>Normal cortisol</td>
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<td>Placental growth</td>
<td>Low glucose and urea</td>
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<td>Placental hormones</td>
<td>Low NEFA</td>
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<td>Uterine blood flow</td>
<td>High NEFA</td>
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<tr>
<td>Fetal growth</td>
<td>Normal</td>
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<tr>
<td>Fetal body composition</td>
<td>High placental lactogen, P₄ and E₂</td>
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<tr>
<td>Fetal hormones and nutrients</td>
<td>Reduced by 40% at 0.6 gestation</td>
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<td>Incidence of marked FGR* (%)</td>
<td>Impaired, ~30% smaller at term</td>
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<tr>
<td>Gestation length</td>
<td>Marked brain sparing and increased relative adiposity</td>
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<tr>
<td>Colostrum yield</td>
<td>Low insulin, IGF1 and glucose</td>
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<tr>
<td>Neonatal morbidity and mortality</td>
<td>45</td>
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<tr>
<td>Offspring growth</td>
<td>~5 days shorter</td>
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<tr>
<td>Offspring metabolism</td>
<td>Inadequate in &gt;50% of mothers</td>
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<td>Offspring metabolism</td>
<td>Increased but largely preventable</td>
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<tr>
<td>Offspring body composition</td>
<td>Rapid compensatory growth but reduced adult size</td>
</tr>
<tr>
<td>Fetal hormones and nutrients</td>
<td>Persistent glucose intolerance</td>
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| *Categorised as marked FGR if birthweight is more than two standard deviations below the mean sex-specific birthweight of fetuses in the optimally nourished control group.
are less perturbed (Fig. 1D). This competition for nutrients between mother and fetus is independent of dietary protein content (Wallace et al. 2006b) and exclusive to the young adolescent in that it does not occur in identically treated primiparous adult ewes of the same genotype (Wallace et al. 2005a).

One of the most predictable features of pregnancy outcome in overnourished adolescents is a reduction in gestation length with viable lambs being born as early as day 135 (term = 145 days in controls). Within overnourished adolescents, gestation length is unrelated to maternal growth or weight gain at any stage of pregnancy and the difference in gestation length for growth-restricted vs less perturbed fetuses of both sexes is less than 1 day (Fig. 1C). This implies that it is primarily high dietary intakes that underlie premature delivery and a rapid labour relative to controls. Lambs tolerate premature delivery badly irrespective of size, but it is the smallest individuals that face the most significant challenges in the neonatal period. Colostrum yield at parturition reflects placental mass (Wallace et al. 1996, 2001) and is attenuated in overnourished dams (Wallace et al. 2006b). In the first study with this model, neonatal mortality rate was 62% (Wallace et al. 1996), but subsequently a pre-emptive neonatal care protocol involving intensive monitoring, supplementary feeding and prophylactic antibiotic usage, irrespective of size at birth, ensured that most lambs survived.

### Pregnancy outcome in undernourished adolescent sheep

Relative to the overnourished model, the perinatal outcomes associated with undernourishing pregnant adolescents are much less severe: placental size and gestation length are comparable with the control group and no fetal or neonatal deaths have been observed (Table 1). Preventing maternal growth by holding body weight at peri-conception levels progressively depletes maternal fat reserves and directly limits nutrient availability in the maternal and fetal circulations. This leads to a slowing of fetal soft tissue growth and by late gestation, and following spontaneous delivery at term, the fetus is 10–17% smaller than controls (Luther et al. 2007a,b, Wallace et al. 2012). Thus, while undernourishing adolescent mothers has a modest effect on fetal growth, it is the overnourished model...
which most closely mimics the human with respect to adverse perinatal outcomes.

Two other laboratories have tried to replicate the effects of differentially feeding adolescent sheep, with variable success. Both groups have used natural mating following a synchronised oestrus, but the timing and extent of nutritional manipulation and thereby maternal growth rate differed. Swanson et al. (2008) report a shorter gestation length and a small overall reduction in birthweight (9%) when adolescents carrying singletons or twins were overnourished beginning on day 50 of gestation, whereas when rations were restricted, gestation length was unaltered and birthweight reduced by 13% relative to controls. In contrast, Peel et al. (2012) exposed singleton-bearing adolescents to ad libitum intakes throughout pregnancy in two identical trials, and, in the trial where maternal weight and adiposity diverged earlier and to a greater extent, gestation length was reduced by 5 days independent of an effect on lamb birthweight. Placental size was either unaffected (Swanson et al. 2008) or not reported (Peel et al. 2012). It is accepted that the use of assisted conception procedures may influence how the early embryo responds to differences in maternal nutritional status or diet in the Rowett model, but it is important to emphasise that maternal nutrition is the only variable that is manipulated with all other aspects controlled. Moreover, unlike human IVF/embryo transfer, the animals used have no known reproductive defects at baseline in that they respond appropriately to oestrus synchronisation and ovulation induction and conceive in high numbers following embryo transfer. Thus, it is the ability to achieve rapid maternal growth rates in early pregnancy that is most likely the root cause of placental growth restriction and the adverse perinatal events described. Uterine immaturity is proposed as a primary driver of the placental dysfunction underlying preeclampsia, fetal growth restriction and preterm delivery in young human adolescents (Brosens et al. 2017) and the suggestion that preconditioning of the immature uterus by exposure to regular ovulatory menstrual cycles is required to prepare for appropriate trophoblast invasion has considerable merit bearing in mind that the studies reported here involve peripubertal animals.

**Maternal weight and adiposity at conception and pregnancy outcome**

In the above-mentioned studies, the emphasis was to manipulate gestational weight gain and growth status immediately after embryo transfer and accordingly the adolescent recipients were deliberately of equivalent weight and adiposity level at conception. It is well established that pre-pregnancy underweight is associated with an increased risk of preterm delivery and low birthweight in adult women relative to those with normal BMI (Han et al. 2011). Similarly, although human adolescents enter pregnancy from a range of nutritional backgrounds, the majority in the developing world are likely to be underweight with low nutrient reserves at conception, and in very young girls, this may interact with their gestational growth status to influence pregnancy outcome. This scenario has been modelled in two studies using different approaches: both involved selecting two groups of adolescent sheep of the same age but with a marked difference in weight and adiposity prior to embryo transfer. In the first study, adolescents were subsequently overnourished, undernourished or fed a control intake to drive maternal growth and gestational weight gain in contrasting directions as described earlier (Wallace et al. 2010), whereas in the second study the nutritional status of the embryo donor(s) was additionally manipulated (obese vs control); all these recipients were then overnourished throughout gestation and a contemporaneous control group was included as a reference point for optimal fetal growth (Wallace et al. 2017). Together the design of these studies uniquely allows segregation of pre-, peri and post-conception nutritional exposures to evaluate their separate and/or interdependent influences. Donor ewe obesity did not influence conception rate or the feto-placental growth trajectory of high-quality embryos following transfer into adolescent recipients, and irrespective of donor ewe nutrition and gestational intake, adolescents that were relatively light and thin at conception gave birth to lambs that were smaller than those born to adolescents who were relatively heavy and fat at conception (555 g lighter in study 1 and 665 g in study 2, P<0.05). This reduction in birthweight was mirrored by corresponding reductions in placental size but was independent of gestation length. The differences in estimated body fat at the point of embryo transfer were relatively small, but irrespective, the thin adolescent dams had high lipid levels indicative of active catabolism, and low circulating nutrient and metabolic hormone concentrations which are likely to have directly impacted the early uterine environment contributing to compromised conceptus development. Accordingly, the incidence of marked fetal growth restriction was two-fold higher in recipients that were thin vs fat at conception when all were subsequently overnourished (Wallace et al. 2017). This clearly indicates...
that maternal nutritional status at the time of conception is an important consideration in predicting pregnancy outcome in still-growing adolescents, but comparison with the control groups in both studies unequivocally demonstrates that it is the high nutritional intake to drive continued maternal growth and adiposity after conception which is most closely linked to the high incidence of fetal growth restriction in young sheep (Wallace et al. 2010, 2017). Similarly, a recent study in human adolescents (n = 600) reported that gestational weight gains above the recommended levels for individual pre-pregnancy BMI categories were associated with an increased risk of low birthweight (Sámano et al. 2018), but whether the girls (mean age 16 years) were still growing was not assessed. This increased risk of low birthweight is unique to adolescent pregnancies as gestational weight gain above recommendations in adult women reduces the risk of SGA birth (Goldstein et al. 2017).

Consequences for maternal and placental endocrine systems

Overnourished model

The consequence of different dietary-intakes for maternal hormone and nutrient status in adolescent sheep has been extensively described. Relative to controls and consistent with the oversupply of nutrients, the overnourished dams have elevated peripheral insulin, insulin-like growth factor 1 (IGF1), urea and glucose concentrations from ~day 25 to 28 of gestation facilitating an early and sustained stimulus to maternal tissue growth at a time when the nutrient requirements of the fetus are negligible (Wallace et al. 1997b, 1999, 2010). Accordingly, maternal weight gains are rapid, and body weight-specific perirenal fat deposits and peripheral leptin concentrations are enhanced by day 50 of gestation (Thomas et al. 2001, Redmer et al. 2009), with the proportion of fat in the maternal carcass per se increasing between mid and late gestation (Wallace et al. 2004a). In adult sheep, maternal insulin concentrations normally decline during the final third of gestation to promote increased fatty acid mobilisation from adipose stores and to reduce glucose utilisation by non-uterine tissues (McNeill et al. 1997). However, high insulin concentrations are maintained throughout in adolescent mothers, and metabolic challenges at ~day 97 of gestation reveal enhanced insulin insensitivity, namely greater glucose area-under-the-curve post insulin challenge, and higher glucose-stimulated insulin post glucose challenge. The high circulating glucose should in theory favour fetal growth but the reduction in placental size in these animals is a major constraint to fetal nutrient supply (see the 'Placental development' section below). Indeed, reduced placental size and the attendant decrease in placental hormone secretion may compromise several of the maternal adaptations that normally underlie successful pregnancy and lactation (Napso et al. 2018), thereby contributing to the poor perinatal outcomes characteristic of these rapidly growing adolescents. Notably, the overnourished adolescent dams are characterised by attenuated placental lactogen (also known as chorionic somatomammotropin hormone, CSH) – relative to controls, the detection of the hormone in the maternal circulation is delayed, and concentrations are reduced throughout the second two-thirds of pregnancy (Lea et al. 2007). The generation of CSH-deficient sheep pregnancies by lentiviral-mediated RNA interference in vivo has recently provided convincing evidence of a causative role for this hormone in conceptus growth. Major reductions in placental and fetal weights were evident in late gestation corresponding to the decrease in CSH mRNA and protein (Baker et al. 2016), and an equivalent study terminated at day 50 revealed that the growth of the fetus was perturbed from early in pregnancy, possibly due to deficits in the paracrine actions of the hormone within the placenta (Jeckel et al. 2018). In addition to low CSH concentrations, overnourished dams are typified by low placental reproductive steroid concentrations. This may reflect increased metabolic (hepatic) clearance due to the high dietary intakes or reduced placental steroid capacity, and there is evidence to support both scenarios (Lea et al. 2007, Redmer et al. 2012). Irrespective of the cause, progesterone and oestradiol-17ß levels are reduced relative to controls early in pregnancy and remain attenuated thereafter (Wallace et al. 1997a, 2003b, 2008a). Together low concentrations of these three lactogenic hormones, as well as reduced growth hormone concentrations (Wallace et al. 1997b) are likely to underlie the impaired early lactation robustly observed in overnourished adolescents. Moreover, the attenuated concentrations of reproductive steroids, and an early decline in progesterone particularly (Taylor 1987), most likely triggers premature and rapid delivery in these pregnancies, while the deficit in circulating oestradiol is likely to be the origin of the poor mothering abilities (Dwyer 2014) regularly observed in the adolescent dams that give birth to the most growth-perturbed lambs.

In human pregnancies, failure of maternal plasma volume expansion and altered iron homeostasis are
implicated in several adverse outcomes (Vricella 2017) and although a causative link has not been established, low placental progesterone and oestradiol concentrations have been associated with the reduced maternal plasma volume expansion observed in normotensive women with idiopathic fetal growth restriction (Salas et al. 1993, 2006). Similarly, deficits in these placental steroids may impact the renin–angiotensin–aldosterone system (Scaife & Mohaupt 2017) and hence salt and water retention in our animal model of fetal growth restriction. Although this has not been directly examined, cross-sectional studies reveal that rapid growth during the first half of pregnancy is linked to increased utilisation and hence early depletion of maternal liver iron stores, and a failure of normal blood volume expansion between mid and late pregnancy (Luther et al. 2010). The accompanying increase in haematocrit, haemoglobin and plasma protein concentrations is associated with an increase in blood viscosity by late gestation (Wallace et al. 2017), and this in turn may influence uteroplacental blood flow and fetal nutrient supply.

Plasma tri-iodothyronine and thyroxine concentrations mirror maternal nutrient intake across a range of diet levels during pregnancy and around parturition (Lemley et al. 2014) but do not significantly diverge in overnourished compared with control adolescents until the final third of gestation (Wallace et al. 1997b). This suggests that these hormones are unlikely to play a causative role in placental growth restriction although two independent human studies suggest that elevated maternal thyroid hormones negatively impact fetal growth (León et al. 2015) and associate with the risk of miscarriage and fetal distress (Yang et al. 2018). Higher plasma thyroid levels in overnourished dams may however influence colostrum IgG supply to the newborn as others have shown that supplementing a basal sheep diet with excess iodine for 4 weeks prior to parturition reduces serum IgG concentration in the neonate (McGovern et al. 2016). Maternal plasma prolactin similarly reflects dietary intake level (Lemley et al. 2014) predominately in the final third of pregnancy when circulating concentrations are elevated in overnourished dams and negatively correlated with fetal weight (Matsuzaki et al. 2006). The significance of high maternal prolactin concentrations, if any, is unknown but aligns with similar observations in different models of fetal growth restriction including hyperthermic sheep (Bell et al. 1989, Regnault et al. 1999) and protein-restricted rats (Fernandez-Twinn et al. 2003). A degree of physiological stress is arguably common to these models and could theoretically impinge on the hypothalamic–pituitary axis promoting prolactin secretion, but intriguingly maternal cortisol concentrations were either equivalent or reduced relative to controls in all these animal models (Bell et al. 1989, Wallace et al. 2000, 2005b, Fernandez-Twinn et al. 2003).

**Undernourished model**

The maternal endocrine profiles and nutrient status of undernourished adolescent dams have been less rigorously studied but relative to optimally fed controls are typified by lower peripheral insulin, IGF-1 and leptin concentrations and similar cortisol levels (Luther et al. 2007a, Wallace et al. 2010). In contrast, decreased metabolic (hepatic) clearance rates in undernourished dams are thought to underlie the elevated concentrations of placental reproductive steroids observed during the final third of pregnancy independent of any change in placental size (Luther et al. 2007b). By late pregnancy maternal glucose, urea and specific amino-acid concentrations are reduced, and greater NEFA concentrations reflect dwindling internal adipose and carcass fat stores. Although maternal liver iron stores are independent of dietary treatment, a low haematocrit and haemoglobin is consistent with mild anaemia by this stage and collectively low availability of nutrients in the maternal circulation is the principal cause of the modest reduction in fetal growth observed. This is in stark contrast to overnourished pregnancies where regardless of an oversupply of nutrients in the maternal circulation, fetal growth is directly constrained by impaired placental development and function.

**Consequences for placental development and uteroplacental blood flows: overnourished model**

The competition for nutrients in the overnourished and rapidly growing adolescent dams influences placental development from early in gestation. At day 50, cellular proliferation rates within both placental compartments are reduced (Rensick et al. 2008), and capillary vessel size within the fetal cotyledon is compromised (Redmer et al. 2009), while delayed and reduced appearance of placental lactogen and pregnancy-specific protein-B concentrations in the maternal circulation suggests impaired trophoblast cell migration (Wallace et al. 1997a, Lea et al. 2007). By mid-pregnancy, angiogenic growth factor ligand and receptor mRNA expression, as well as markers of proliferation and apoptosis within...
the placenta are perturbed (Lea et al. 2005, Redmer et al. 2005). These adaptations precede the change in placental mass which does not significantly diverge from controls until 0.72 gestation (Wallace 2011), but nonetheless they are commensurate with an altered developmental and haemodynamic trajectory. Accordingly, uterine blood flow was attenuated by ~40%, and umbilical artery Doppler indices were greater in overnourished pregnancies at mid-gestation and predictive of reduced fetal growth later in pregnancy (Wallace et al. 2008b, Carr et al. 2012). The latter is in line with observations at ~32 weeks gestation in growing vs non-growing human adolescents (Scholl et al. 1997). By ~day 133 of the ovine pregnancies, placental mass was ~45% lower than that in controls and proportionate reductions in uterine and umbilical blood flows, uteroplacental glucose and oxygen consumption and lactate production, as well as placental glucose transport, were observed (Wallace et al. 2002, 2003a).

Potential for manipulating placental function in overnourished adolescents

As restricted placental development is central to the pathology of fetal growth restriction in this model, a few approaches have attempted to manipulate the placental growth trajectory to enhance fetal growth. The first of these simply involved switching dietary intakes during specific windows of gestation and showed that normal placental development and fetal growth could be achieved by reducing maternal intakes from a high to a control level at day 50 of gestation, whereas an abrupt increase in dietary intake at this stage reduced placental and fetal growth to the same degree as in continuously overnourished dams (Wallace et al. 1999). However, fetal growth could not be rescued by radically reducing dietary intake and switching the mothers from a highly anabolic to a catabolic state during the final third of pregnancy, despite changes in placental angiogenic growth factor and receptor gene expression consistent with blood vessel re-modelling (Redmer et al. 2012). Together these studies highlight that the placenta is most sensitive to nutrition during its main proliferative growth phase. While fetal growth cannot be recovered once placental mass is reduced beyond its functional capacity, there is evidence of differential placental vascular adaptations in the late gestation placenta of continuously overnourished adolescent’s dependent on the degree of fetal growth restriction observed (Carr et al. 2016a). The second approach to manipulating the placental growth trajectory of overnourished dams has involved supplementing maternal hormones. Progesterone supplementation of overnourished dams from day 5 to 55 of gestation restored circulating hormone levels to control levels and increased lamb birthweight by 30%, but this change was independent of a corresponding change in placental size at delivery, suggesting a direct effect of progesterone on the embryonic inner cell mass (Wallace et al. 2003b). Similarly, oestrogen replacement from day 50 to day 90 of gestation failed to impact fetoplacental growth or placental vascularity as assessed in late gestation (Yunusova et al. 2011). In contrast, when adolescent mothers received exogenous growth hormone (GH) during the main placental growth phase (day 35–80), their accretion of adipose tissue was reduced, and in GH-treated overnourished dams, this alteration in nutrient partitioning priorities favoured uteroplacental and fetal growth at study end (day 81, Wallace et al. 2004b). In a second study, GH treatment of overnourished dams targeted either the placental growth phase (day 35–65) or later in pregnancy when placental growth is complete, and the nutrient demands of the fetus are high (day 95–125). Both exposures had a profound influence on maternal metabolism resulting in insulin resistance, reduced lipogenesis and three-times higher circulating glucose concentrations. However, in this study, GH treatment during early pregnancy did not have a sustained effect on placental or fetal size, whereas treatment during late pregnancy increased fetal weight by ~25% and had a large impact on fetal adiposity as measured at day 130 of pregnancy, independent of placental size (Wallace et al. 2006a). On balance GH supplementation has dramatic effects on maternal endocrinology and the partitioning of nutrients within the maternal body, but the effects on the fetus reflect an abnormally high transplacental glucose supply rather than a modified placental growth trajectory. Furthermore, while increased fetal lipid deposition and the associated increase in hepatic glycogen stores could be an important energy source and protect the newborn from hypothermia in the neonatal period, it is likely to be maladaptive in the longer term. More worryingly, a similar GH treatment regime in late pregnancy in a different model of fetal growth restriction involving placental embolisation was associated with hydencephalic brain lesions in three of five fetuses (De Boo et al. 2008). Recently an alternative approach directly targeting the uteroplacental circulation of compromised adolescent pregnancies has been evaluated. This was based on the premise that local uterine artery adenovirus (Ad.)-mediated overexpression of vascular endothelial...
growth factor (VEGF) in overnourished dams would increase uterine blood flow as demonstrated in normally developing adult pregnancies (Mehta et al. 2011). In two separate studies Ad.VEGF administration in mid-pregnancy (day 89) increased fetal growth velocity as measured by ultrasound 3 and 4 weeks after injection. At 0.9 gestation, there were fewer markedly growth-restricted fetuses (Carr et al. 2014) and at term average birthweight was increased by 20% (Carr et al. 2016b). Importantly, there were no adverse responses to the gene therapy and lambs continued to thrive and exhibit appropriate growth and body composition for their size in the early postnatal period.

Consequences for placental development and uteroplacental blood flows: undernourished model

Final placental size is unperturbed in undernourished adolescents, but the relatively low nutrient availability in these mothers does significantly impact on vascular development within the placenta. Thus, a 20% reduction in capillary area density within the maternal caruncle was observed at both mid and late gestation (Luther et al. 2007b), and closely mirrored an average reduction in uterine blood flow of 22% measured between these two stages using perivascular flow probes (Wallace 2016). These haemodynamic differences between undernourished and control groups are likely to contribute to low fetal nutrient supply, but the increasingly hypoglycaemic conditions in undernourished dams are still considered the major limitation to fetal growth in these pregnancies. In support, the reduction in capillary area density persisted when underfed mothers were switched to control intakes between mid and late gestation, but despite this fetal weight was partially restored in direct response to re-alimentation by study end (Luther et al. 2007b).

Consequences for fetal and offspring endocrine systems: overnourished model

Serial ultrasonography of multiple indices of prenatal size reveals reduced growth velocity from around day 100 of gestation forwards in fetuses of overnourished dams (Carr et al. 2012). Regression analysis using natural logarithms of data obtained from fetuses necropsied at day 130 of gestation demonstrates that individual organ weights, including those of the main endocrine organs (namely, pituitary, thyroid, adrenal glands, gonads and pancreas) were predicted by the weight of the fetus ($P=0.001$ or less), rather than the dam’s nutritional treatment. The allometric plots of the fetal brain compared with the liver, and the lungs compared with the kidneys, are illustrated and serve to emphasise the extent of brain sparing in fetuses of overnourished dams (Fig. 2A and B). The latter fetuses were further categorised as markedly growth restricted when their bodyweight was more than two standard deviations below the mean sex-specific weight of fetuses in the control group. This approach revealed that, in addition to the brain, the relative pituitary, kidney and adrenal gland weights were higher in growth-restricted compared with non-perturbed and control groups (Fig. 2C, D, E and F).

Ovine paradigms permit access to the placental and fetal circulations to examine fetal endocrine and nutrient status, nutrient uptakes and fetal metabolism. Accordingly, by late gestation and relative to normally growing controls, the growth-restricted fetuses of overnourished dams are hypoglycaemic, mildly hypoxic, have low insulin and IGF-1 concentrations and high lactate levels. Absolute umbilical (fetal) uptakes of glucose, oxygen and amino acids are reduced but are normal when expressed on a fetal weight-specific basis (Wallace et al. 2002, 2003b). Similarly, when the fetal sensitivity to insulin and glucose was examined during fetal hyperinsulinaemic–euglycaemic and hyperglycaemic–euisulinaemic clamps, normal body weight-specific responses to short-term experimental increases in insulin and/or glucose were observed (Wallace et al. 2007). These maintained mechanisms of insulin action and glucose uptake/utilisation capacity allow the fetus to protect essential metabolic functions while growth velocity slows. Surprisingly, these growth-restricted fetuses have a comparatively fat phenotype prenatally in that bodyweight-specific perirenal fat mass and carcass fat content are modestly increased compared to controls by late gestation (Matsuzaki et al. 2006), and plasma cholesterol and LDL concentrations are higher at birth (Wallace et al. 2012). Greater adiposity in these otherwise growth-restricted fetuses may be caused by exposure to higher maternal and thus fetal glucose early in gestation in overnourished dams (Redmer et al. 2009) influencing adipocyte development before placental size and hence fetal glucose supply is impaired. Definitive causation in the overnourished model is lacking, but in the undernourished model, key genes involved in adipocyte proliferation and function are expressed in fetal perirenal fat tissue at mid-gestation when they are downregulated by maternal undernutrition and the associated low
glucose supply leading to reduced fetal adiposity by late gestation (Wallace et al. 2015). Glucose is the main fetal fuel and it is notable also that anorexigenic neuropeptide expression in the fetal hypothalamus is sensitive to fetal hyperglycaemia at mid-gestation with effects persisting throughout fetal life (Adam et al. 2008, 2011). Once released from the nutritional constraint imposed by the in utero environment, growth-restricted lambs born to overnourished adolescents display rapid fractional growth rates relative to their size at birth. Growth is particularly rapid during the suckling period and the extent of growth compensation at the point of weaning (11 weeks of age) depends on the degree of prenatal growth impairment. Thus, when average birthweight is reduced by a modest 22% relative to controls, complete catch-up in terms of weight is observed by weaning (Wallace et al. 2010, 2012), but when birthweight is ~40% lower, the lambs remain lighter at weaning and continue to have modestly reduced weight and stature at study end in mid-adulthood despite being fed to appetite (109 weeks, Wallace et al. 2018). In the latter study, serial dual-energy X-ray absorptiometry (DEXA) revealed that prenatally growth-restricted lambs had lower bone mineral density than controls throughout the life-course (11, 41, 64 and 107 weeks). The small fat phenotype observed in growth-restricted fetuses in late gestation was also apparent in both sexes at weaning but not at the adolescent or early adult stages when lean tissue growth was the dominant nutrient partitioning priority. The metabolic phenotype of these lambs has also been serially documented: during the suckling period and into adolescent life, fasting insulin concentrations and insulin secretion after glucose challenge are greater in growth-restricted offspring, in line with their higher fractional growth rates and increased body fat percentage at weaning. This enhanced insulin sensitivity does not persist but the prenatally growth-restricted offspring of overnourished dams are consistently characterised across studies by higher fasting glucose concentrations and/or greater glucose area-under-the-curve after glucose challenge, indicative of glucose intolerance (Wallace et al. 2012, 2014a, 2018). During the suckling period in offspring of overnourished dams, relatively higher fasting glucose concentrations in prenatally growth-restricted vs non-perturbed lambs reflect an inverse relationship between birthweight and hepatic mRNA expression and activity of a key gluconeogenic enzyme, glucose...
6-phosphatase (Fig. 3). In the life-course study, altered glucose metabolism was evident at all ages, and by the time mature body size had been reached in mid-adulthood, the animals had experienced a prolonged period of glucose intolerance and the associated alteration in tissue glucose uptake, and hence, an obese phenotype was once again evident, particularly in females that reach peak bone mass and adult size before their male counterparts (Wallace et al. 2018). Further there is evidence that the metabolic forerunner of this adverse phenotype, namely glucose intolerance at ~12 months of age, can be ameliorated by restricting nutrient intake between adolescent and young adult life – an effect specific to females (Wallace et al. 2012). Thus, when considering any potential target of developmental programming, it is important to differentiate between the sexes when possible. For example, differences in adipose tissue development are evident in fetal life with normally growing females having a greater carcass fat percentage at mid-pregnancy, and a higher bodyweight-specific perirenal fat mass and leptin gene expression in late pregnancy than males (Fig. 4). This early dissimilarity in adiposity is likely to reflect differences in sex steroid status and is maintained postnatally: independent of birthweight at 11 weeks of age, females are characterised by greater visceral fat mass, leptin gene expression, adipocyte size and carcass fat, while males exhibit faster growth rates in line with reduced hepatic IGF-1 DNA methylation, higher IGF-1 mRNA expression and greater plasma IGF-1 concentrations (Wallace et al. 2014a,b, Carr et al. 2015). The early divergence in growth and body composition is also reflected in the brain centres involved in energy balance with females having higher hypothalamic expression of anorexigenic genes and lower expression of orexigenic genes than males (Adam et al. 2013). Furthermore, serial DEXA measurements suggest that sex differences in adiposity (females > males) and bone mineral density (males > females) are life-long (Wallace et al. 2018).

Theoretically, altered hypothalamic–pituitary–adrenal (HPA) axis function may underlie and contribute to the adverse metabolic phenotype of growth-restricted offspring. The greater bodyweight-specific adrenal gland mass (Fig. 2F) and premature activation of the fetal HPA axis leading to early delivery (Fig. 1C) in the most severely growth-restricted pregnancies are arguably commensurate with enhanced in-utero stress, although no evidence of altered cortisol concentrations in mother or fetus was found, albeit measured at a single timepoint in late gestation (Wallace et al. 2000). Similarly, when stress tests involving corticotropin-releasing hormone plus arginine...
vasopressin challenge were performed in growth-restricted vs normally grown females at three ages up to 24 months (40% birthweight differential) or in growth-restricted or normal offspring of both sexes at 6 months of age (20% birthweight differential), baseline and stimulated adrenocorticotrophin and cortisol concentrations were independent of maternal nutrition and birthweight category (Wallace et al. 2011). On this basis, nutritionally programmed alterations in the development and function of the HPA axis are unlikely to be central to the phenotype of the prenatally growth-restricted offspring described earlier.

In contrast, there is robust evidence that the developing reproductive axis is impacted by maternal nutrition, particularly in female fetuses. The resting reserve of primordial follicles that determines lifetime

Figure 4
Carcass fat percentage at day 80 of gestation (A), relative perirenal fat mass (B) and relative leptin gene expression (C) at day 90 and 130 of gestation in normally growing male and female fetuses from optimally nourished control adolescents. Inset in (C) is haematoxylin and eosin-stained sections of perirenal fat from a representative male and female fetus showing differences in unilocular cell size (JM Wallace, JS Milne, RP Aitken, unpublished observations). Hepatic IGF-1 DNA methylation percentage in male and female offspring of overnourished dams (D) and the relationship between relative hepatic IGF-1 mRNA gene expression and plasma IGF-1 concentrations in the same animals at 11 weeks of age (E). Data from Carr et al. (2015).
supply of potentially fertilisable eggs is established before birth (McNatty et al. 1995). Accordingly, in the adolescent paradigm, large reductions in primordial follicle number (up to 80% less) were measured at both mid and late gestation in fetuses from overnourished dams and reflected the attenuated placental weight, and hence, fetal nutrient supply, measured at both stages (Da Silva et al. 2002, 2003). Pituitary gonadotrophin mRNA was unaffected at mid-pregnancy but by late gestation, LHβ mRNA was higher in the most growth-restricted fetuses. This indicates reduced oestrogen feedback from the placenta and/or fetal ovary directly regulating fetal pituitary function, or alternatively a temporal delay in the maturation of the pituitary gland. Irrespective, these prenatally growth-restricted females reach puberty at an equivalent weight and age as normally grown controls, and the normality and duration of ovarian cyclicity during the first breeding season is also similar (Da Silva et al. 2001). Nevertheless, the severely diminished ovarian reserve is likely to impact ovulation rate and hence fertility as the animal ages. Although males continuously produce new spermatozoa after puberty, the number of Sertoli cells, the primary determinant of sperm production and testes size in adulthood are determined by proliferation during the fetal, neonatal and peripubertal periods (Sharpe et al. 2003). Nonetheless, the number of Sertoli cells, seminiferous cords and pituitary gonadotroph mRNA expression was not impacted by maternal nutrition when assessed at mid-gestation in our model (Da Silva et al. 2003). However, in contrast to females, male lambs with a 47% suppression in birthweight had slower absolute growth rates, delayed age at puberty, attenuated testosterone concentrations and a smaller testicular volume per unit live-weight between 28 and 35 weeks of age (Da Silva et al. 2001). As Sertoli cells set the upper limit for sperm production and continue to proliferate until puberty, it is likely that impaired fetal growth velocity and a delay in reaching an appropriate pubertal weight will impact initial sperm quality and quantity, but this has not been expressly tested.

Consequences for fetal and offspring endocrine systems: undernourished model

The phenotype of fetuses and offspring from undernourished adolescent dams has been less intensively studied. Relative to controls, the modestly growth-restricted fetuses of undernourished dams do exhibit relative brain sparing but all other organ weights are unperturbed, and while plasma glucose levels at late gestation necropsy are consistent with hypoglycaemia, there is only a tendency towards lower peripheral insulin concentrations, and IGF-1 levels are not perturbed (Luther et al. 2007a). Liver glycogen stores are depleted, and body composition analysis indicates a thin phenotype with reduced adiposity but preserved skeletal growth (Luther et al. 2007a, Wallace et al. 2015). Unlike the overnourished model, the fetal phenotype with respect to glycaemia, bodyweight and carcass fat percentage can be partially rescued by switching undernourished dams to a control intake between mid and late pregnancy. The impact of this switch is also seen within the fetal hypothalamus in that the increased expression of three orexigenic neuropeptides in response to nutrient deficit can largely be normalised after improving nutrition (Adam et al. 2015). After delivery, there was no evidence of compensatory growth in the offspring of continuously undernourished dams and likewise at 6 months of age glucose metabolism and adrenal responses to stress tests in both sexes were equivalent to the same sex control groups (Wallace et al. 2010, 2011, 2012).

Conclusion

These ovine paradigms unequivocally demonstrate that the maternal–fetal competition for nutrients that arises during pregnancy in young adolescents is sensitive to maternal nutrition. While nutrient reserves at conception play a role, it is the dietary manipulation of maternal growth and body composition thereafter which has the most negative influence on pregnancy outcome: rapid maternal growth constrains placental development and function and is more detrimental than preventing maternal growth. Maternal and placental endocrine systems and associated nutrient partitioning priorities are differentially altered in both paradigms with downstream consequences for fetal nutrient supply, organ system development, body composition and metabolism, some of which are life-long. From a public health perspective, strategies to prevent pregnancy occurring during adolescence should remain the priority, but in cultures where early marriage soon after menarche is the norm, girls with a low BMI should be counselled to gain weight and achieve a normal BMI before conception. Subsequently dietary intakes should be sufficient to maintain maternal nutrient reserves throughout pregnancy and thereby meet fetal fuel requirements in the final trimester: documenting changes in skinfold thickness as well as measuring weight gain may be a simple and effective approach and requires

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evaluation. Where pregnancies are unplanned and food readily available, biologically immature mothers should be made aware of the potential consequences of excessive gestational weight gain with respect to placental development, and additional early monitoring of placental size and uteroplacental blood flows may help identify those at risk of perinatal complications. For the offspring of young adolescent mothers, individuals with the lowest birthweight are likely to be vulnerable to impaired fertility and adverse metabolic health and should be cognisant of this when making their own life choices.

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