Repeated maternal glucocorticoid administration and the developing liver in fetal sheep

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Abstract

Prenatal glucocorticoid exposure has been associated with a reduction in birth weight and postnatal alterations in glucose homeostasis and hypothalamic–pituitary–adrenal (HPA) axis function. The mechanisms underlying these responses are unknown, although changes in fetal hepatic development may play an important role. The fetal liver produces key regulators of fuel metabolism and of the developing HPA axis that are altered by glucocorticoids. The local availability of glucocorticoids is regulated, in part, by corticosteroid-binding protein (CBG), glucocorticoid receptors (GR) and by the enzyme 11β-hydroxysteroid dehydrogenase (11βHSD), but the effects of maternal glucocorticoid administration on the expression of these genes in the fetal liver are unknown. 11βHSD1 is the predominant form of this enzyme present in the liver and is responsible for the conversion of cortisone to cortisol. To determine if prenatal glucocorticoid exposure alters fetal hepatic regulation of CBG, 11βHSD1 and GRs, we treated pregnant ewes with betamethasone (0·5 mg/kg) intramuscularly at 104, 111 and 118 days of gestation (term 150 days). Animals were killed at 125 or 146 days of gestation. Maternal betamethasone administration did not alter mean cord plasma glucose but significantly decreased cord plasma insulin levels (P<0·05) at 125 days of gestation. At 146 days of gestation, cord plasma glucose levels were significantly increased without alterations in insulin levels following maternal betamethasone treatment (P<0·05). Maternal betamethasone administration resulted in a significant increase in fetal hepatic 11βHSD1 mRNA and protein levels at 125 days of gestation (P<0·05). CBG mRNA levels were significantly elevated over control at 125 days although levels of CBG protein were not significantly different. GR protein levels were not statistically different at either 125 or 146 days of gestation following glucocorticoid administration. These data suggest that prenatal betamethasone exposure in the ovine fetus results in alterations in cord glucose and insulin levels as well as alterations in hepatic 11βHSD1 mRNA and protein expression. These changes in 11βHSD1 increase the potential to generate local cortisol from circulating cortisone. We speculate that this could affect expression of glucocorticoid-dependent hepatic enzymes involved with the regulation of glucose production and HPA responsiveness.

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Introduction

Numerous epidemiological studies have suggested that intrauterine factors are important determinants of the risk of developing a variety of adult diseases (Osmond et al. 1993, Barker 1994, 1998, McCance et al. 1994). Low birth weight has been associated with impaired glucose tolerance and insulin resistance in adulthood (Hales et al. 1991, Phipps et al. 1993, Lithell et al. 1996, Ravelli et al. 1998). The fetal programming hypothesis has been proposed to explain these associations. Programming reflects the possibility of an intrauterine factor mediating cellular growth and development at a vulnerable time in gestation, subsequently resulting in permanent alterations in tissue and organ function that are apparent later in life (Dennison et al. 1997, Barker 1998, Dodic et al. 1999, Hill 1999, Seckl & Chapman 2000).

Alterations in hypothalamic–pituitary–adrenal (HPA) activity have been associated in adulthood with the development of insulin resistance and glucose intolerance, as well as hypertension (Phillips et al. 1998, Levitt et al. 2000). However, there are no data from human studies addressing prenatal glucocorticoid exposure with metabolic function; low birth weight has been studied as a potential surrogate for fetal glucocorticoid exposure and other intrauterine alterations. Epidemiological studies have shown that low birth weight is related to elevated levels of fasting plasma cortisol levels, elevated systolic blood
pressure, plasma glucose and triglyceride levels and insulin resistance in adult men (Phillips et al. 1998). In experimental models, prenatal exposure to synthetic glucocorticoids results in decreased birth weight (Jobe et al. 1998, Sloboda et al. 2000) as well as elevations in fetal and postnatal HPA activity in sheep (Sloboda et al. 2000, 2001) and in primates (Uno et al. 1994). The role of the HPA axis in programming future metabolic function is also pertinent to the safety of clinical prenatal glucocorticoid treatment, since glucocorticoids are administered to women at risk of preterm birth to enhance lung function in current clinical practice (Liggins & Howie 1972).

Although the mechanisms linking intrauterine growth restriction, HPA activity and metabolic function are poorly understood, studies suggest that prenatal glucocorticoids may target specific organs such as the liver and the pancreas (Lindsay et al. 1996, Nyirenda et al. 1998, Hill 1999). Glucose intolerance in adult rats exposed to maternal dexamethasone in utero has been associated with elevations in hepatic glucocorticoid receptors (GR) and glucocorticoid-sensitive enzymes involved in gluconeogenesis such as phosphoenol-pyruvate carboxykinase (PEPCK) mRNA levels (Nyirenda et al. 1998, Saegusa et al. 1999). In rats, administration of maternal carbadoxolone, an inhibitor of a placental 11β-hydroxysteroid dehydrogenase (11βHSD) thus permitting increased passage of maternal glucocorticoids to the fetus (Whorwood et al. 1993), has been shown to reduce birth weight in a manner similar to that observed with dexamethasone treatment (Price et al. 1992, Lindsay et al. 1996, Levitt et al. 1996, Nyirenda et al. 1998). Moreover, adult male offspring demonstrated altered glucose tolerance indicated by higher fasting glucose levels and elevated glucose and insulin responses to a glucose challenge. Maternal adrenalectomy prevented this effect, supporting the role of fetal exposure to maternally derived glucocorticoids in the programming of metabolic function (Lindsay et al. 1996).

The fetal liver produces key regulators of fuel metabolism and of the developing HPA axis that are altered by glucocorticoids. The local availability of glucocorticoids is regulated, in part, by corticosteroid-binding protein (CBG), GR and by the enzyme 11βHSD. CBG, cortisol’s high-affinity binding protein, regulates levels of free (unbound) bioactive glucocorticoids (Ballard et al. 1982, Berdusco et al. 1993), and the 11βHSD type 1 enzyme (11βHSD1) (converts inactive 11-keto metabolites to bioactive glucocorticoids) (Chapman et al. 1997) regulates local tissue levels of glucocorticoids. Both CBG and 11βHSD1 are present in the fetal liver and their expression is influenced by fetal cortisol exposure in sheep (Berdusco et al. 1993, Yang et al. 1995). It is not known, however, whether repeated maternal glucocorticoid administration alters CBG or 11βHSD1 expression in the fetal liver. We have shown previously that repeated maternal glucocorticoid administration resulted in alterations in fetal growth and HPA function in the sheep (Sloboda et al. 2000). Repeated doses of maternal betamethasone resulted in significant reductions in fetal weight, a significant increase in cord plasma adrenocorticotrophin and a significant increase in cord plasma corticosteroid-binding capacity. We have also shown that maternal betamethasone administration resulted in significantly elevated cortisol responses to a corticotrophin-releasing hormone+vasopressin challenge in offspring at 1 year of postnatal age (Sloboda et al. 2002). These same animals exhibited significantly elevated postnatal insulin responses to a glucose load at 6 months and 1 year of age, as well as significantly higher basal glucose and glucose responses at 1 year of postnatal age (Moss et al. 2001). It is not known whether hepatic function in these offspring was altered, although it is possible that alterations in hepatic gluconeogenesis may contribute to these effects.

In order to investigate the possibility that fetal glucocorticoid exposure alters fetal hepatic glucocorticoid regulation, we set out to determine the expression levels of 11βHSD1, CBG and GR in the liver of fetal sheep at two time-points during gestation following repeated maternal betamethasone administration. Cord plasma glucose and insulin levels were also determined in order to evaluate metabolic regulation. We hypothesised that maternal betamethasone administration would result in changes in fetal regulation of intra-hepatic glucocorticoid levels that might subsequently contribute to alterations in fetal and postnatal metabolic and HPA function.

Materials and Methods

Animals

Merino ewes were mated and singleton pregnancy was confirmed using ultrasound examination at 42 days of gestation (term 150 days). Pregnant ewes were transported to a research station at 90 days of gestation and were kept in pastures, to graze in a field environment. On the evening prior to injections and later delivery, animals were brought into a nearby indoor facility.

Experimental protocols

All animals received an intramuscular injection of 150 mg medroxyprogesterone acetate (Depo Provera; Upjohn, Rydalmer, NSW, Australia) at 98 days of gestation, as reported previously (Moss et al. 2001). This procedure has been previously shown to reduce the incidence of prenatal losses due to maternal betamethasone administration (Sloboda et al. 2000, 2002). Pregnant sheep (n=26) were randomised into either control or treatment groups. Animals in the treatment group received intramuscular injections of 0.5 mg/kg maternal weight of betamethasone (Celestone Chronodose; Schering Plough, Baulkham

Journal of Endocrinology (2002) 175, 535–543

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Hills, NSW, Australia) at 104, 111 and 118 days of gestation. Control animals received saline injections at the same time-points. This injection protocol and dose was designed to mimic clinical administration of synthetic glucocorticoids in an obstetric environment and has been shown previously to improve lung function in fetal sheep (Ikegami et al. 1997). Ewes were sedated with maternal intramuscular ketamine (15 mg/kg) and xylazine (0·1 mg/kg) (Troy Laboratories, Smithfield, NSW, Australia) and spinal anaesthesia was induced by injection of 3–4 ml lidocaine (2%). The fetus was delivered through a midline hysterotomy and arterial blood samples were collected from the umbilical cord, following which the fetus was killed by a lethal dose of pentobarbital (30 mg/kg). At day 125 (control n=5 and betamethasone n=6) and day 146 (control n=7 and betamethasone n=8) of gestation, fetal liver samples were collected for measurement of mRNA and protein levels. Blood samples were centrifuged at 4 °C at 10 000 r.p.m. for 10 min and plasma was stored at −80 °C until later analysis. Animals were killed at these time-points in order to investigate the effects of prenatal betamethasone at a time that coincides with the maturation of the fetal HPA axis but before the onset of a significant rise in endogenous cortisol levels (125 days) and at a time when endogenous cortisol levels are at their highest (146 days or term) (Norman et al. 1985). The protocols were approved by the Institutional Ethics Committees of the Western Australian Department of Agriculture and the Animal Care Committee of the University of Toronto, according to the guidelines of the Canadian Council for Animal Care.

**Measurement of cord plasma glucose and insulin levels**

Cord plasma glucose levels were analysed using a glucose analyser (Beckman Glucose Analyzer 2; Beckman Instruments, Fullerton, CA, USA) via the glucose oxidase method. Cord plasma immunoreactive insulin concentrations were measured using a commercial radioimmunoassay kit (Linco Research, Inc., St Charles, MO, USA). The intra-assay coefficient of variation was 8% and the mean assay sensitivity was 0·1 ng/ml. All samples were analysed in a single assay. The insulin antibody cross-reacts 100% with rat, sheep and porcine insulin; cross-reactivity to rat C-peptide, glucagon, somatostatin, pancreatic polypeptide and insulin-like growth factor-I is undetectable (Linco).

**Northern blot analysis**

Northern blotting was performed as described previously (Fraser et al. 1999). Briefly, total RNA was extracted using TRIZOL reagent (Life Technologies, Inc., Rockville, MD, USA). Chloroform (Sigma Chemical Co., St Louis, MO, USA) was added to allow separation of RNA, DNA and protein. RNA was precipitated out of solution by the addition of 500 µl isopropyl alcohol/1 ml TRIZOL, washed with 1 ml 75% ethanol and dissolved in diethyl pyrocarbonate (DEPC)-treated water at 60 °C. The purity and concentration of RNA in each sample was determined by measuring the spectrophotometric absorbance (Ultrontec 2000; Pharmacia Biotech, Piscataway, NJ, USA) of isolated RNA at 260 nm and at 280 nm. Ratios of the readings at 260:280 nm between 1·6 and 1·8 were considered acceptable for further analysis. The isolated RNA in each sample was assessed for integrity as follows: samples of isolated RNA (10 µg) were electrophoresed on a 1% agarose formaldehyde gel, stained with ethidium bromide overnight (0·001% (v/v) 10 mg/ml ethidium bromide, 0·13% (v/v) 2β-mercaptoethanol), and bands visualised under UV light. Intact RNA was viewed as two distinct bands corresponding to 18S and 28S rRNA. Total RNA from each sample (30 µg) was size-fractioned by horizontal electrophoresis (Horizon 20X25; Life Technologies, Inc.) and transferred to a nylon membrane (Zeta Probe GT Blotting membrane; Bio-Rad Laboratories, Mississauga, Ontario, Canada). The blots were prehybridised and then exposed to buffer containing 32P-labelled cDNA antisense probe overnight at 50 °C. A labelling kit was used to label cDNA probes with α-[32P]deoxy-CTP (Amersham International) using the random priming method (Ready to Go; Pharmacia-Biotech Inc., Baie d’Urfe, Quebec, Canada). The ovine full-length CBG and 11βHSD1 cDNA sequences have been described previously (Yang et al. 1992, Berdusco et al. 1993, 1994). Each membrane was washed in 150 mM sodium phosphate (NaP)/ 0·1% sodium dodecyl sulphate (SDS) at 55 °C followed by washes in 30 mM NaP/0·1% SDS of 15 min each rotating at 55 °C. Membranes were exposed to autoradiographic film (XAR–5; Eastman Kodak Co., Rochester, NY, USA) at −80 °C, with an intensifying screen (Biomax Transcreen LE; Eastman Kodak Co.). Membranes were then stripped of the hybridised label (0·01 × SSC, 0·5% SDS in DEPC water at 95 °C) and reprobed with 32P-labelled cDNA antisense probe to mouse 18S rRNA as an internal control to allow for corrections in gel loading and transfer. The signals for both the mRNA of interest and 18S rRNA were analysed using an image analysis system (Imaging Research Inc., St Catharines, Ontario, Canada) within the linear range of the film and represented as relative optical densities (ROD). Results are expressed as the ratio of ROD for mRNA:18S rRNA.

**Western blot analysis**

Western blotting was performed as described previously (Gymorey et al. 2000). Briefly, total protein was extracted from frozen liver samples in RIPA lysis buffer (50 mM Tris–HCl, 1% (v/v) Triton X–100, 0·1% (w/v) SDS, 150 mM NaCl, 1% (w/v) sodium deoxycholic acid), with 100 µM sodium orthovanadate (Na3VO4) and Complete Mini EDTA-free protease inhibitors (Roche
Table 1: Fetal glucose, insulin and I:G ratios at 125 and 146 days of gestation following either saline or maternal betamethasone administration. Values are expressed as means ± S.E.M.

<table>
<thead>
<tr>
<th>Variables</th>
<th>125 days of gestation</th>
<th>146 days of gestation</th>
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<tbody>
<tr>
<td></td>
<td>Control (n=5)</td>
<td>Betamethasone (n=6)</td>
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<tr>
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<tr>
<td>Glucose (mg/dl)</td>
<td>51.7 ± 14.6</td>
<td>45.6 ± 14.7</td>
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<tr>
<td>Insulin (ng/dl)</td>
<td>0.4 ± 0.04</td>
<td>0.2 ± 0.02*</td>
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<tr>
<td>I:G ratio</td>
<td>0.01 ± 0.002</td>
<td>0.005 ± 0.001</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Control (n=7)</td>
<td>Betamethasone (n=8)</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Glucose (mg/dl)</td>
<td>25.6 ± 2.1</td>
<td>41.1 ± 8.1*</td>
</tr>
<tr>
<td>Insulin (ng/dl)</td>
<td>0.3 ± 0.03</td>
<td>0.3 ± 0.04</td>
</tr>
<tr>
<td>I:G ratio</td>
<td>0.01 ± 0.002</td>
<td>0.008 ± 0.001</td>
</tr>
</tbody>
</table>

*P<0.05.

Diagnóstics, Mannheim, Germany) and stored at −80 °C until protein analysis. Protein concentration of each sample was determined using the Bradford assay (Bradford 1976). Proteins were separated by electrophoresis on 8%-12% polyacrylamide gels at 150 V at 4 °C. Separated proteins were transferred onto nitrocellulose membranes (Bio-Rad Laboratories). The resultant blots were stained with S-Ponceau (0.1% (w/v) Ponceau S in 5% acetic acid (v/v); Sigma Chemical Co.) to verify equal loading and transfer. The blots were washed with phosphate-buffered saline (PBS) and 0.1% Tween-20 (Sigma Chemical Co.) and incubated overnight at 4 °C in blocking solution (5% skim milk powder (w/v) in PBS+Tween-20) on a mechanical shaker to block non-specific binding. Blots were incubated with primary polyclonal antibodies (ovine CBG, generated in this laboratory by Berdusco et al. (1993); ovine 11βHSD1, generated by Yang et al. (1995); and human GR, Affinity Bioreagents, Inc., Golden, CO, USA) diluted in 5% blocking solution (5% skim milk powder (w/v) in PBS+Tween-20) (CBG, 1:500; 11βHSD1, 1:500; GR, 5 µg/ml), for 1 h. Blots were rinsed in PBS+Tween-20 for five 5-min washes. Blots were then incubated with secondary antibodies, conjugated to horseradish peroxidase (anti-rabbit Ig horseradish peroxidase; Amersham Life Sciences, Arlington Heights, IL, USA), diluted in blocking solution (CBG, 1:2000; 11βHSD1, 1:3000; GR, 1:2000), for 1–2 h, followed by six 5-min PBS+Tween-20 washes. Detection of specific protein bands was accomplished using the electrochemiluminescence detection system (ECL; Amersham Life Sciences) and exposed to autoradiographic film (X-Omat Blue XB-1; Eastman Kodak Co.). The signals for the protein of interest were analysed using an image analysis system (Imaging Research Inc.) and represented as arbitrary optical densities (AOD).

Statistical analysis

Changes in cord plasma glucose and insulin levels, and insulin:glucose (I:G) ratios at both 125 and 146 days of gestation were analysed using an unpaired one-tailed Student’s t-test. Hepatic CBG and 11βHSD1 mRNA levels are expressed as ROD mRNA:18S rRNA ROD ratio and CBG, 11βHSD1 and GR protein levels are expressed as AOD units and all results were analysed using an unpaired one-tailed Student’s t-test. Statistical significance was determined as *P<0.05. All values are presented as means ± S.E.M. (Sigma Stat; Jandel Scientific, Chicago, IL, USA).

Results

Effects of maternal betamethasone on cord glucose and insulin levels and I:G ratios

Maternal betamethasone administration did not alter mean cord plasma glucose but significantly decreased cord plasma insulin levels (Table 1; *P<0.05) at 125 days of gestation. The mean I:G ratio was reduced in animals treated with betamethasone but this difference did not reach significance. At 146 days of gestation, cord plasma glucose levels were significantly increased following maternal betamethasone administration (Table 1; *P<0.05), without significant alterations in plasma insulin levels. The mean I:G ratio was reduced with betamethasone treatment but this difference did not reach statistical significance.

Effects of maternal betamethasone on fetal hepatic 11βHSD1, CBG and GR levels

A single transcript of 1.8 kb for 11βHSD1 was detected in RNA samples from fetal livers. Due to RNA degradation as shown by 18S (Fig. 1), three saline-treated animals were compared with five betamethasone-treated animals. Maternal betamethasone administration significantly elevated fetal hepatic 11βHSD1 mRNA levels at 125 days of gestation (Fig. 1; *P<0.05) and was associated with a significant increase in 11βHSD1 protein levels (Fig. 2; *P<0.05). 11βHSD1 protein levels (34 kDa) were not different following maternal betamethasone at 146 days of gestation. In addition to the 34 kDa band, a secondary 32 kDa transcript was also identified in fetal liver.
homogenates at both 125 and 146 days of gestation, although to a much lesser degree. This observation is similar to previous observations in the fetal baboon placenta and liver. Pepe et al. (1999) demonstrated that the 11βHSD1 protein size differed according to tissue type. In human and baboon syncytiotrophoblast, 11βHSD1 was detected as a protein with an apparent molecular size of 32 kDa while the major form in the liver appeared to be a 34 kDa protein, with much less 32 kDa protein levels expressed. The authors described this apparent size difference as the result of differences in the nature or number of glycosylation residues, possibly resulting from post-translational processing. It appears that we have observed this same phenomenon in fetal sheep liver homogenates. The ratio of transcripts (32 vs 34 kDa) was unchanged with maternal betamethasone treatment.

A single 1.8 kb transcript for CBG was found in fetal hepatic RNA samples (Fig. 3). Fetal hepatic CBG mRNA levels at 125 days of gestation were significantly elevated following maternal betamethasone administration (Fig. 3; \( P<0.05 \)), and were not associated with significant alterations in CBG protein levels (57 kDa; Fig. 4). CBG protein levels in the fetal liver at 146 days of gestation were unchanged following maternal betamethasone administration (Fig. 4). Mean GR protein levels in the fetal liver were not statistically different at either 125 or 146 days of gestation after betamethasone treatment (data not shown).

Samples were not available to analyse 11βHSD1 and CBG mRNA levels at 146 days of gestation.

**Discussion**

This study has demonstrated that repeated maternal administration of betamethasone in the sheep resulted in a decrease in cord plasma insulin levels at 125 days and an increase in cord plasma glucose at 146 days of gestation. Basal glucose levels at 125 days of gestation were higher and insulin levels were lower in this study than those previously reported (Houghton et al. 1989). Although this observation may suggest that these animals were stressed at the time of delivery, we have previously found that cord plasma cortisol levels in these same animals were not elevated at this time-point (Sloboda et al. 2000), therefore providing strong evidence that these sheep and this delivery model is not associated with a fetal stress response. It is possible that any discrepancy in basal glucose and
insulin values in our study and those previously published may be due to the breed of sheep or composition of their diet.

Previous studies have demonstrated that fetal glucocorticoid exposure can potentially programme pancreatic development (Phillips 1996, Seckl 1997, Hill 1999, Hill & Duvillie 2000), although almost all evidence is derived from data collected on the rat. GR are present in the β cells of the adult pancreas (Fischer et al. 1990) and glucocorticoids have been shown to regulate pancreatic development (Rall et al. 1977, Hill 1999). Furthermore, it has been shown previously that glucocorticoids inhibit insulin secretion from cultured adult mouse islets (Lambillote et al. 1997). It is not known whether insulin secretion was altered in the present study. It is possible that betamethasone treatment prematurely developed sympathetic suppression of insulin secretion, since previous studies have shown that glucocorticoids have a maturational effect on the sympathetic response at birth (Segar et al. 1998, 2001, 2002). We have previously shown, however, that offspring treated with prenatal glucocorticoids exhibit exaggerated insulin responses to a glucose bolus at 1 year of postnatal age, rather than inhibited insulin secretion (Moss et al. 2001). Furthermore, since cord insulin levels were not different at 146 days of gestation, any possible effect on the sympathetic regulation of insulin secretion due to betamethasone treatment in this study must have been transient. Any conclusions regarding sympathetic function in these animals is not possible without further measurements of cord plasma catecholamines. Therefore, although the exact mechanisms are unknown, it appears that repeated maternal betamethasone administration of synthetic glucocorticoids in this animal model alters fetal glucose and insulin regulation.

This study has demonstrated an increase in fetal hepatic 11βHSD1 mRNA and protein levels as well as significant increases in CBG mRNA expression levels at 125 days of gestation following repeated maternal administration of synthetic glucocorticoids. Although it is puzzling that CBG mRNA levels were increased at 125 days of gestation without changes in protein levels, it remains possible that small changes in steady-state CBG protein levels were present but could not be detected by Western blotting, since we have demonstrated previously that repeated maternal betamethasone administration resulted in an increase in plasma corticosteroid-binding capacity at 125 days of gestation. The observations in the present study are consistent with previous studies that have reported that fetal growth restriction (McMillen et al. 2000) and fetal dexamethasone infusion significantly elevated fetal hepatic 11βHSD1 (Yang et al. 1994) and CBG (Berduco
et al. 1993, Zhao et al. 1997) mRNA expression late in
gestation. Furthermore, Yang et al. (1994) demonstrated
that elevations in 11βHSD1 mRNA expression levels
were associated with a twofold increase in enzymatic
activity, supporting the idea that glucocorticoids regulate
functional activity of this enzyme. Whether the increased
expression levels in this study have a functional signi-
ficance is uncertain; however, given the previously estab-
lished relationship between 11βHSD1 and CBG mRNA
expression and functional activity (Berdusco et al. 1994, Yang et al. 1994), it appears likely that 11βHSD1
activity and corticosteroid binding in these animals
would have increased following maternal betamethasone
administration.

The role of hepatic 11βHSD1 in facilitating an increase
in local glucocorticoid concentrations in the liver has been
suggested by other studies (Langlois et al. 1995, Jamieson
et al. 1999, 2000). In vivo, hepatic 11βHSD1 acts primarily
as a reductase enzyme, converting inactive cortisone/
11βHSD1 and GR have been co-localized in the liver of the
rat (Whorwood et al. 1992) suggesting that 11βHSD1
may regulate ligand access to GR (Whorwood et al. 1992,
Jamieson et al. 2000, Seckl & Chapman 2000). Gluco-
corticoids in turn regulate 11βHSD1 expression and activity (Voice et al. 1996). CBG is primarily produced in
the fetal liver (Ballard et al. 1982, Berdusco et al. 1993) and
regulates local and circulating levels of cortisol, resulting
in an overall decrease in bioactive glucocorticoids (Berdusco
et al. 1993, Challis et al. 1995). Many studies have reported
that glucocorticoids regulate both CBG expression levels
and activity (Challis et al. 1985, 1995, Berdusco et al.
1993, 1994, Jeffray et al. 1995). It has been demonstrated
previously that increasing levels of plasma cortisol correlate
positively with the activity of key hepatic enzymes
involved in gluconeogenesis, such as PEPC and glucose-
6-phosphatase (Fowden et al. 1990, 1993). Moreover,
in 11βHSD1-knockout mice, gluconeogenic enzyme
expression levels are reduced (Kotelevtsev et al. 1997),
suggesting the importance that local tissue levels of gluco-
corticoids have on liver metabolic processes. Therefore,
inappropiate increases in intra-hepatic levels of gluco-
corticoids, through a change in hepatic 11βHSD1 or CBG
expression levels, could influence metabolic regulation.
Previously, Nyirenda et al. (1998) have demonstrated that
maternal dexamethasone administration in the rat late in
gestation resulted in a decrease in birth weight, impaired
glucose tolerance and a significant increase in hepatic
PEPC and GR mRNA expression in adult offspring. In
the present study, fetal GR protein levels were not signifi-
cantly different following maternal betamethasone. This
discrepancy may be due to differences in treatment
protocols. Nyirenda et al. (1998) administered dexam-
ethasone to pregnant rats for an entire week while, in
the present study, pregnant ewes were given discrete doses
of betamethasone 1 week apart. It is possible that in the
present study subtle changes in hepatic GR expression, as
the result of betamethasone treatment, may not become
evident until postnatal life. Alternatively, it may be that
prenatal betamethasone administration in our sheep model
results in changes in local levels of endogenous cortisol in
the liver through alterations in 11βHSD1 and CBG
expression and not alterations in GR expression.

In conclusion, the observations in this study indicate
that prenatal glucocorticoid treatment results in alterations
in gene expression in the fetal sheep liver and fetal glucose
homeostasis. The safety and long-term implications of
prenatal glucocorticoid treatment for pregnancies at risk of
preterm birth in humans is currently the subject of clinical
trials. The results of the present study indicate that
consideration will need to be given to ongoing evaluation
of individuals enrolled in these and future studies to ensure
that prenatal glucocorticoid treatment is not associated
with life-long compromise of metabolic function.

Acknowledgements

This work was supported by The National Health and
Medical Research Council of Australia project grant
number 980578, and the Women and Infants Research
Foundation and the Canadian Institutes and Health
Research (CIHR) Group in Fetal and Neonatal Health
and Development.

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Received in final form 22 July 2002
Accepted 23 July 2002