

## Prenatal programming of angiotensin II type 2 receptor expression in the rat

Sarah McMullen<sup>1</sup>, David S. Gardner<sup>2</sup> and Simon C. Langley-Evans<sup>1\*</sup>

<sup>1</sup>School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough, Leics., UK

<sup>2</sup>Academic Division of Child Health, School of Human Development, University Hospital, Nottingham NG7 2UH, UK

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Exposure to undernutrition during fetal life has been proposed as an underlying cause of adult hypertension. Epidemiological studies demonstrating relationships between low birth weight and later CVD are supported by animal experiments indicating that manipulations of the maternal diet in pregnancy exert programming effects upon blood pressure control. Pregnant female Wistar rats were fed a control diet ( $n$  13) or a low-protein diet ( $n$  12) throughout pregnancy. At delivery all animals were fed the same standard laboratory chow diet. Analysis of nephron number in kidneys obtained from 4-week-old offspring showed that this was significantly ( $P < 0.05$ ) reduced in animals exposed to maternal protein restriction. At this age rats exposed to low-protein diets *in utero* had systolic blood pressures that were significantly greater than those of control animals (+23 mmHg,  $P < 0.05$ ). Administration of ascending doses of angiotensin II (1–40 ng/kg body weight intravenously) to 10-week-old anaesthetised female rats showed that the pressor response to the peptide was greater and more prolonged in animals exposed to low-protein diets *in utero*. Renal expression of mRNA for the angiotensin II type 1A receptor was similar in the two groups of rats, but low-protein-exposed animals had significantly lower renal expression of the type 2 receptor ( $P = 0.023$ ). These results suggest that maternal nutritional status programmes expression of the renal angiotensin II type 2 receptor. This may play a key role in the impairment of renal development and the elevation of blood pressure noted in rats exposed to intra-uterine protein restriction.

### Angiotensin II receptors: Fetal programming: Low-protein diet

Epidemiological evidence from large cohorts in developed and developing countries indicates that there are relationships between characteristics at birth and disease in adult life (Barker, 1995; Campbell *et al.* 1996; Curhan *et al.* 1996; Forsen *et al.* 1999). Low birth weight has been linked to increased risk of later non-insulin-dependent diabetes (Hales *et al.* 1991), hypertension (Law *et al.* 1993) and CHD (Fall *et al.* 1995), and similar associations are reported for relative thinness and reduced abdominal circumference at birth (Phillips *et al.* 1994; Martyn *et al.* 1995). These findings have provided the basis for the fetal programming hypothesis, which suggests that the risk of disease in adult life is determined by the environment encountered before birth (Barker, 1995). Specifically, it is suggested that a less than optimal diet in pregnancy induces fetal adaptations that include permanent alterations to cell number and type within key organs and subsequent modulation of gene expression (Langley-Evans, 2001).

The strength of reported associations between birth characteristics and adult disease patterns has recently been challenged by Huxley *et al.* (2002), who reported that the relationship between adult blood pressure and weight at birth was attributable to measurement error,

observer bias and random chance. Work with animal models, however, suggests that nutritional programming in fetal life does indeed have an impact upon lifelong blood-pressure control (Langley-Evans *et al.* 1994, 1996a,c; Gardner *et al.* 1997), glucose handling (Dahri *et al.* 1991; Iglesias-Barreira *et al.* 1996) and other indices of health and well-being (Beach *et al.* 1982; Sayer *et al.* 2001; Mehta *et al.* 2002).

Our previous studies have demonstrated that feeding a low-protein diet in rat pregnancy programmes an elevation of blood pressure in the resulting offspring (Langley-Evans *et al.* 1994, 1996a,c; Gardner *et al.* 1997). Fetal over-exposure to glucocorticoids of maternal origin has been proposed to initiate the progression to hypertension (Edwards *et al.* 1993), but upregulation of the renin–angiotensin system may directly increase blood pressure in young rats exposed to low-protein diets in fetal life (Sherman & Langley-Evans, 2000). Early treatment of these animals with angiotensin-converting enzyme inhibitors or the angiotensin II type 1 receptor (AT<sub>1</sub>R) antagonist losartan permanently reverses the blood-pressure-raising effect of maternal undernutrition (Sherman & Langley-Evans, 2000). A role for AT<sub>1</sub>R in the programming of

**Abbreviations:** AT<sub>1</sub>R, angiotensin II type 1 receptor; AT<sub>2</sub>R, angiotensin II type 2 receptor.

\* **Corresponding author:** Dr Simon Langley-Evans, fax +44 115 951 6122, email Simon.Langley-Evans@nottingham.ac.uk

hypertension is also suggested by recent observations that young rats exposed to a low-protein diet *in utero* have increased levels of AT<sub>1</sub>R protein in the kidney (Sahajpal & Ashton, 2003).

There are three types of angiotensin II receptors in peripheral tissues of the rat, all of which are expressed in the kidney (Siragy, 2002). AT<sub>1A</sub>R and AT<sub>1B</sub>R mediate increases in blood pressure upon hormone binding (Allen *et al.* 2000). Receptor stimulation promotes vasoconstriction and the reabsorption of Na. AT<sub>1A</sub>R sites are widely distributed throughout the kidney, and AT<sub>1B</sub>R sites are found in lower densities in renal mesangial cells, juxtamedullary cells and in the renal pelvis. The angiotensin II type 2 receptor (AT<sub>2</sub>R), located in cortical tubules, glomeruli and interstitial cells, appears to have opposing effects to AT<sub>1</sub>R and mediates the release of bradykinins, prostaglandins and NO, leading to vasodilation and decreased peripheral resistance (Siragy & Carey, 1997).

The kidney appears to be particularly vulnerable to the programming effects of maternal undernutrition (Hoy *et al.* 1998; Langley-Evans *et al.* 1999; Manalich *et al.* 2000; Marchand & Langley-Evans, 2001; Vehaskari *et al.* 2001) and is a primary controller of systemic blood pressure. The hypothesis explored in the present paper was that maternal protein restriction programmes the relative expression of renal AT<sub>1</sub>R and AT<sub>2</sub>R and hence renal development and blood pressure.

## Methods

### *Chemicals and reagents*

Unless indicated otherwise in the text, all chemicals were of reagent or molecular biology grade and were purchased from Sigma-Aldrich (Poole, Dorset, UK).

### *Animals*

Twenty-five virgin female Wistar rats (Harlan Ltd, Belton, Leics., UK) were mated at weights between 200 and 250 g. Upon confirmation of mating by the appearance of a semen plug on the cage floor, the rats were allocated to be fed either a control diet (180 g casein/kg, *n* 13) or a low-protein diet (90 g casein/kg, *n* 12), as described previously by Langley-Evans *et al.* (1994). The full composition of the diets is published elsewhere (Langley-Evans *et al.* 1994). The diets were isoenergetic, the difference in energy between the control and low-protein diets being made up with additional carbohydrate (starch–sucrose; 2:1, w/w).

The rats remained upon the semisynthetic diets until they gave birth at 22 d gestation. All animals were then transferred to standard laboratory chow diet (B&K Universal Ltd, Hull, UK, rat and mouse diet;) and the litters were culled to a maximum of eight pups to minimise variation in the nutrition of the pups during suckling. The offspring of the control and low-protein-fed dams thus differed only in terms of their prenatal nutritional exposures.

At 4 weeks of age, offspring were weaned onto chow diet and two animals from ten litters in each group were killed using an overdose of sodium pentobarbital after determination of blood pressure. Where the sex ratio of the litters made it possible, one male and one female

animal were selected at random from each litter. Kidneys were rapidly excised, the left kidney being fixed for histological examination and the right kidney snap-frozen in liquid N<sub>2</sub> before storage at –80°C and later analyses. Female offspring from the remaining five litters were retained until 10 weeks of age, when sensitivity to the pressor effects of intravenously administered angiotensin II was assessed.

### *Determination of blood pressure*

Systolic blood pressure and pulse were determined using an indirect tail-cuff method as previously reported (Langley-Evans *et al.* 1996c). The method has been extensively characterised and validated in our laboratory and elsewhere (Bunag, 1991; Sherman & Langley-Evans, 1998). Our earlier studies have demonstrated that previous acclimatisation to a temperature of 27°C for 2 h before measurement, with measurements performed within a period 2–10 min after restraint produces highly reproducible blood pressure readings, without any apparent influence of stress (Langley-Evans *et al.* 1996c; Sherman & Langley-Evans, 1998).

### *Pressor effect of angiotensin II*

Female animals (10-week-old) were anaesthetised with sodium pentobarbitone (72 mg/kg body weight). The carotid artery and a femoral vein were cannulated using plastic tubing (internal diameter 0.44 mm) filled with heparinised saline (9 g NaCl/l). The carotid was connected to a saline-filled plastic dome containing a distensible membrane, attached to a pressure transducer. This allowed direct determination of blood pressure, which was tracked using a pre-calibrated chart recorder. The femoral line was used for intravenous infusions (Saglikes *et al.* 1985). After 30 min to stabilise blood pressure following surgery, angiotensin II was administered in increasing doses from 1 to 40 ng/kg body weight (intravenously, in saline (9 g NaCl/l)). Each dose was administered twice and the mean response recorded. An interval of at least 5 min between doses was allowed for the clearance of the previous dose, and for the re-establishment of a stable blood pressure baseline following vascular compensation.

### *Determination of nephron number*

Nephron number was determined using a maceration method based upon that reported by Welham *et al.* (2002). At killing, whole left kidneys were fixed in buffered formalin and stored for up to 2 months. For nephron counting, the kidneys were incubated in 0.1 M-HCl at 37°C for 30 min and then homogenised in 5 ml PBS (10 mm-potassium phosphate, 2.7 mM-NaCl, pH 7.4). Aliquots of the homogenate (20 µl) were removed and placed on microscope slides for nephron counting under low power (× 10). Triplicate aliquots were counted for each kidney and the average count multiplied by 250 to derive the number of nephrons per kidney. The CV for this measurement was 2.6% based upon fifteen repeat counts of the same sample.

### Angiotensin receptor expression

Total RNA was isolated from snap frozen kidneys using the TRIzol method (Invitrogen, Renfrew, Renfrewshire, UK). The RNA was treated with DNase (Promega, Southampton, Hants., UK) and subjected to phenol–chloroform extraction and ethanol precipitation. Total RNA (0.5 µg) was reverse-transcribed using MMLV Reverse Transcriptase (Promega). Real-time PCR was performed using an ABI prism 7700 sequence detection system (Applied Biosystems, Warrington, Cheshire, UK). A template-specific primer pair and an oligonucleotide probe (Sigma-Genosys, Cambridge, Cambs., UK) specific to each of AT<sub>1A</sub>R, AT<sub>2</sub>R and the housekeeping gene β-actin were designed using Primer Express, version 1.5 (Applied Biosystems). The full sequences of the primers and probes are shown in Table 1. All primer sets were tested under the Taqman PCR conditions using rat genomic DNA as a template. In all cases a single product of the appropriate size was detected by gel electrophoresis (results not shown). A negative template control and relative standard curve were included on every PCR run. The standard curve was prepared from a pool of sample cDNA at relative dilutions of 0.05, 0.10, 0.20, 0.40, 1.00, 2.50 and 5.00. Relative target quantity was calculated from the standard curve and all samples were normalised to β-actin expression.

### Statistical analysis

Results are presented as means values with their standard errors. AT<sub>1</sub>R mRNA expression data were compared between control and low-protein-exposed groups using independent *t* tests, after verification of the normal distribution of the data using a Kolmogorov–Smirnov Z test. AT<sub>2</sub>R data were not normally distributed and were analysed using the Mann–Whitney U test. Nephron number and blood pressure were analysed using a two-way ANOVA, with a least significance difference test used as a *post hoc* test. Vascular responses to angiotensin II were also analysed using 2-way ANOVA, assessing the interaction of diet × angiotensin II dose. Systolic blood pressure, as assessed using a tail-cuff, is also influenced by body weight. Blood pressure data was therefore subject to multivariate analysis with adjustment for weight. Blood pressure data are also therefore presented after standardisation to a constant weight. Probability ≤ 5% was accepted as statistically significant.

### Results

Systolic blood pressure was significantly elevated in both male and female animals exposed to low-protein diets *in utero* (Fig. 1(A and B)). This effect was not sex-dependent and persisted after adjustment for body weight at the time of measurement. Comparison of blood pressures adjusted for body weight between groups indicated a significant maternal-diet-related elevation in the low-protein group (adjusted blood pressures: control 103 (SEM 4), low protein 126 (SEM 5) mmHg; *P* < 0.05). The maternal protein restriction protocol did not influence pulse rate in these animals (Fig. 1(C and D)).

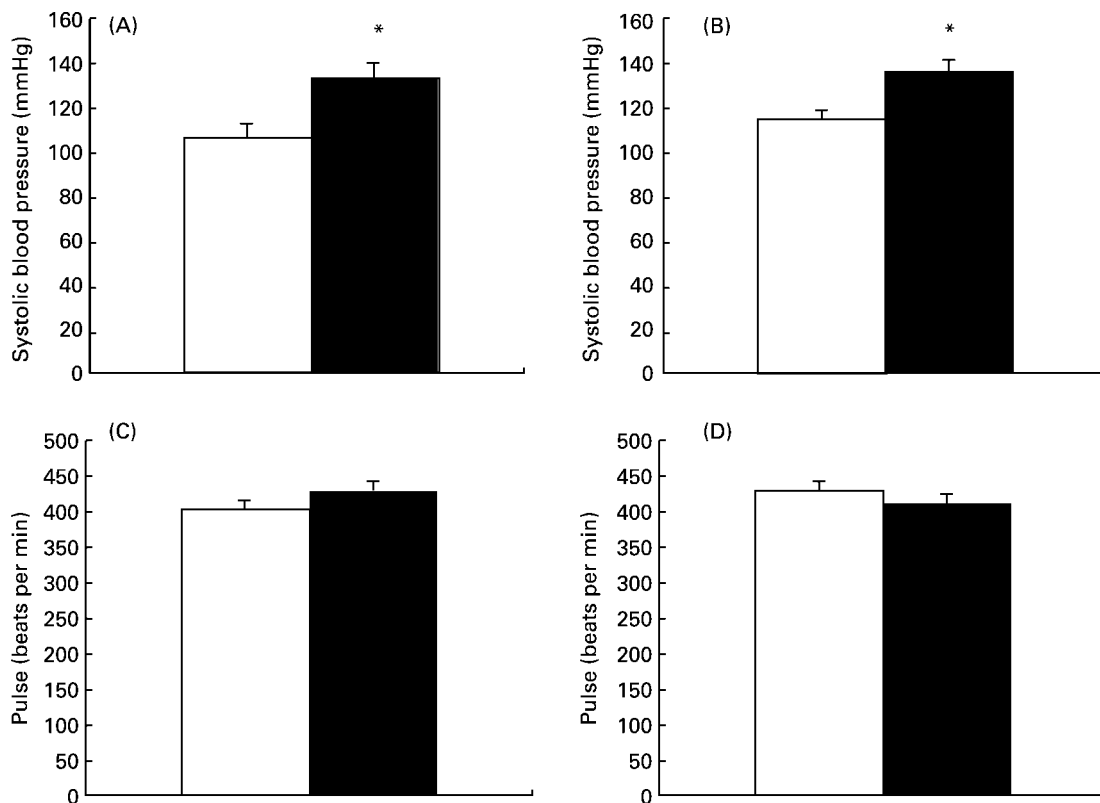
Nephron number was determined in the left kidney at 4 weeks of age. In male animals, nephron number was significantly greater than in female animals (*P* < 0.05). Maternal protein restriction resulted in lower nephron number in both males and female animals (Fig. 2). Data for AT<sub>2</sub>R expression were not normally distributed (Kolmogorov–Smirnov Z score 1.416, *P* = 0.036), and so all mRNA expression data were analysed using the non-parametric Mann–Whitney test and are presented as box plots. These are summary plots based on the median, quartiles and extreme values. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. A line across the box indicates the median. The renal expression of AT<sub>1A</sub>R and AT<sub>2</sub>R mRNA was normalised relative to expression of β-actin mRNA. The expression of this gene was similar in the two groups of animals (results not shown). AT<sub>1A</sub>R expression (Fig. 3) did not differ significantly between control and low-protein-exposed animals. A significantly decreased expression of renal AT<sub>2</sub>R was noted in the low-protein-exposed group relative to control values (Fig. 4, *P* = 0.023). Expression of both AT<sub>1A</sub>R and AT<sub>2</sub>R in renal tissue was not related to the sex of the animals and the diet-related variation in AT<sub>2</sub>R expression was noted in both males and female animals.

Fig. 5 shows the blood pressure responses of anaesthetised female animals to increasing doses of angiotensin II. The maximum blood pressure increase occurred within 10 s of peptide administration at all doses and in all animals. The increase in blood pressure at 10 s post-administration was significantly greater in rats exposed to low-protein diets *in utero* than in control animals at the lower doses of angiotensin II (1 and 5 ng/kg body

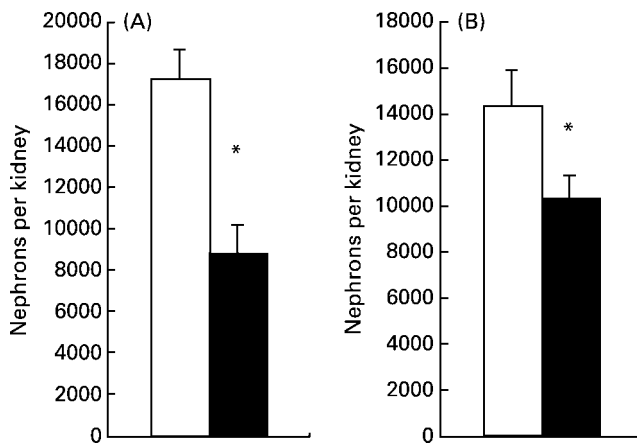
**Table 1.** Primer sequences

Gene		Primer and probe sequence	Genebank accession
AT <sub>1A</sub> R	Forward	5' TCA CAG TGT GCG CGT TTC AT 3'	NM_030985
	Reverse	5' TGG TAA GGC CCA GCC CTA T 3'	
	Probe	5' TGA GTC TCG GAA TTC GAC GCT CCC 3'	
AT <sub>2</sub> R	Forward	5' AAT TAC CCG TGA CCA AGT CTT GA 3'	M87003
	Reverse	5' AGA ACA TGG AAG GGA AGC CA 3'	
	Probe	5' AGC TGC TGT TGT GTT GGC ATT CAT CAT T 3'	
β-Actin	Forward	5' TTC AAC ACC CCA GCC ATG T 3'	NM_031144
	Reverse	5' GTG GTA CGA CCA GAG GCA TAC A 3'	
	Probe	5' CGT AGC CAT CCA GGC TGT GTT GTC C 3'	

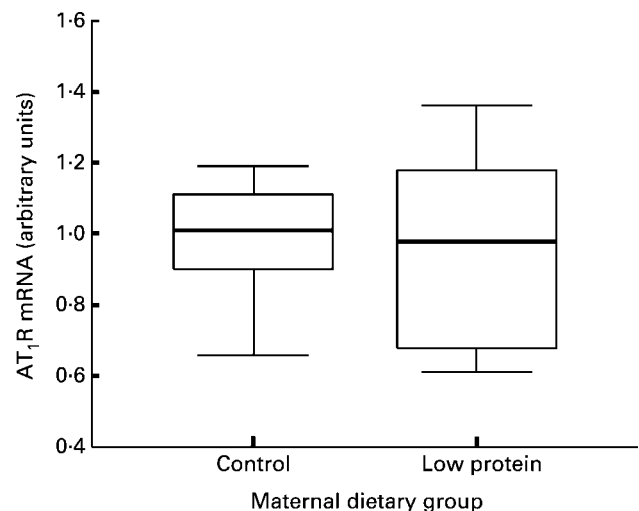
AT<sub>1A</sub>R, angiotensin II type IA receptor; AT<sub>2</sub>R, angiotensin II type 2 receptor.



**Fig. 1.** Effect of maternal low-protein diet on cardiovascular measures in offspring at 4 weeks of age. (A), systolic blood pressure in male rats; (B), systolic blood pressure in female rats; (C), pulse rate in male rats; (D), pulse rate in female rats. Values are means with their standard errors shown by vertical bars. □, Control (eight male, twelve female); ■, low-protein-exposed (eleven male, eight female). For details of diets and procedures, see pp. 134–135. Mean values were significantly different from those of the control group: \* $P < 0.05$ .



**Fig. 2.** Effect of maternal low-protein diet on nephron number in offspring at 4 weeks of age. (A), nephron number in male rats; (B), nephron number in female rats. Values are means with their standard errors shown by vertical bars. □, Control (eight male, twelve female); ■, low-protein-exposed (eleven male, eight female). For details of diets and procedures, see pp. 134–135. Mean values were significantly different from those of the control group: \* $P < 0.05$ .

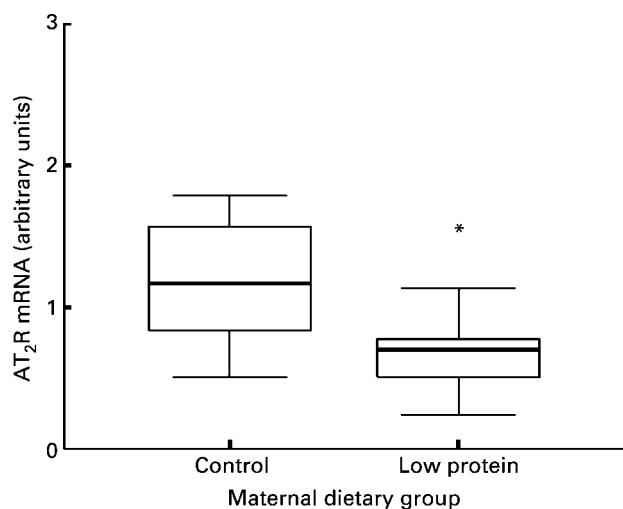


**Fig. 3.** Effect of maternal low-protein diet on expression of angiotensin II type 1 receptor (AT<sub>1</sub>R) in offspring at 4 weeks of age. Values are medians with interquartile ranges (twelve control and nine low-protein-exposed rats). For details of diets and procedures, see pp. 134–135.

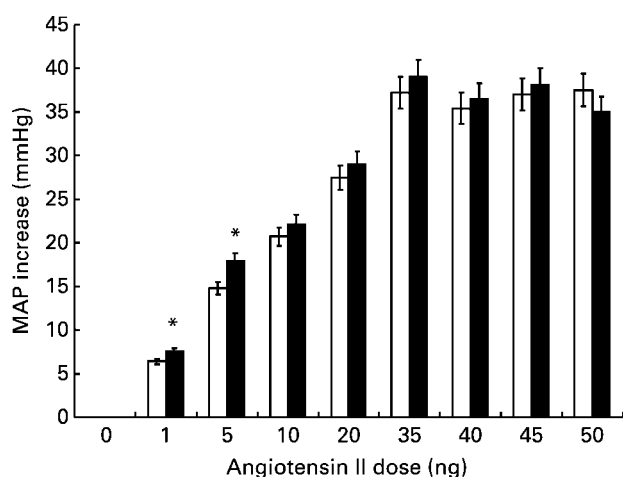
weight; ANOVA showed independent effects of diet ( $P = 0.02$ ) and angiotensin dose ( $P < 0.001$ ). The increase in blood pressure elicited by angiotensin II at lower doses was also more prolonged in low-protein-exposed animals than in control animals (Fig. 6), with blood pressure remaining significantly elevated for up to 120 s post-administration.

## Discussion

In keeping with our previous findings with this rat model of nutritional programming, the present work has demonstrated that the feeding a low-protein diet in rat pregnancy induces relative hypertension in the offspring

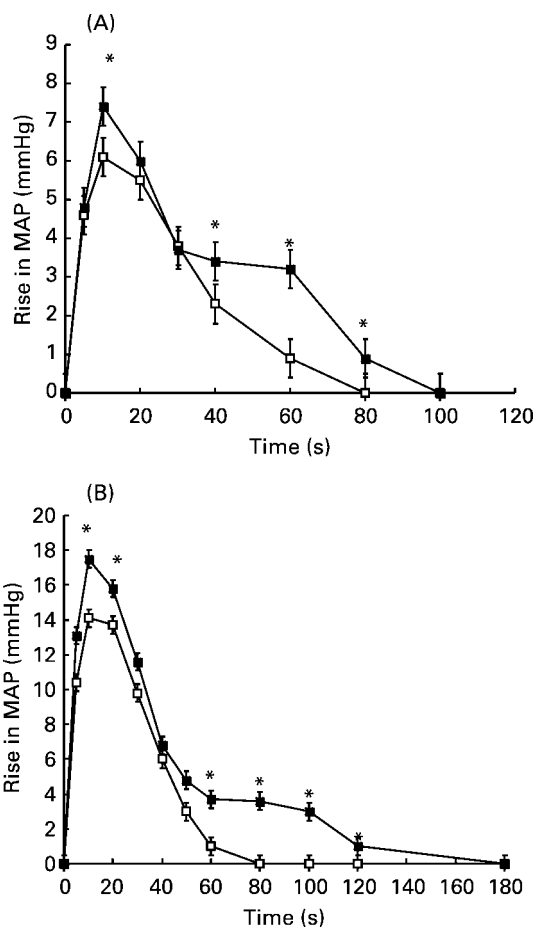


**Fig. 4.** Effect of maternal low-protein diet on expression of angiotensin II type 2 receptor (AT<sub>2</sub>R) in offspring at 4 weeks of age. Values are medians with interquartile ranges (twelve control and nine low-protein-exposed rats). For details of diets and procedures, see pp. 134–135. Mean value was significantly different from that of the control group: \* $P=0.023$ .



**Fig. 5.** Effect of maternal low-protein diet on blood pressure increase in offspring in response to the intravenous administration of angiotensin II. Blood pressure change was assessed 10 s after the administration of angiotensin II. MAP, mean arterial pressure. □, Control; ■, low-protein-exposed. Values are means with their standard errors (five female rats per group). For details of diets and procedures, see pp. 134–135. Mean values were significantly different from those of the control group: \* $P<0.05$ .

(Langley-Evans *et al.* 1993, 1996a,c; Gardner *et al.* 1997). This clearly manifests early in postnatal life and the effect persists into adulthood and is presumed to be lifelong (Langley-Evans, 2001). We have also previously noted a decrease in the number of nephrons in kidneys from low-protein-exposed animals, although the decrease seen in male animals (50%) is greater than in our earlier studies (Langley-Evans *et al.* 1999; Marchand & Langley-Evans, 2001). Although the findings relating to blood pressure and nephron number are not novel, they are reported in the present paper to illustrate the occurrence of these physiological changes alongside programmed changes in



**Fig. 6.** Effect of maternal low-protein diet on blood pressure response in offspring to intravenous angiotensin II administration. Blood pressure changes were monitored for up to 3 min after the administration of angiotensin II at 1 (A) or 5 (B) ng/kg body weight. MAP, mean arterial pressure. □, Control; ■, low-protein-exposed. Values are means with their standard errors shown by vertical bars (five female animals per group). For details of diets and procedures, see pp. 134–135. Mean values were significantly different from those of the control group: \* $P<0.05$ .

angiotensin receptor expression and responses to administered angiotensin II.

Using direct arterial measurements, elevated basal systolic blood pressure was also noted in anaesthetised 10-week-old female rats exposed to low-protein diets *in utero* (control 130 (SEM 3), low protein 143 (SEM 4) mmHg;  $P<0.05$ ). These animals showed greater and more prolonged pressor responses to angiotensin II administration. Importantly these effects occurred only at doses of angiotensin II that were within normal physiological limits. The pressor effect of angiotensin II is wholly mediated through actions upon receptors within the vasculature and the kidney. The increased reactivity noted in low-protein-exposed rats could be explained either by an increase in expression of AT<sub>1</sub>R sites or through a decrease in expression of the AT<sub>2</sub>R sites, which favour vasodilation and the attenuation of the response to the peptide (Siragy & Carey, 1997).

Our initial hypothesis for the present study was that renal expression of AT<sub>1A</sub>R would be upregulated in rats

exposed to the low-protein diet *in utero* and that this may explain their raised blood pressure. The basis for this hypothesis was that Western blotting studies have indicated higher levels of AT<sub>1</sub>R protein in the kidneys of low-protein-exposed rats (Sahajpal & Ashton, 2003). The finding that low-protein-exposed female rats had increased vascular reactivity to intravenously administered angiotensin II appears to be consistent with this hypothesis and with the finding that losartan administration in early postnatal life overcomes the programming effect of fetal undernutrition (Sherman & Langley-Evans, 2000). AT<sub>1</sub>R effects may therefore be critical in programming of long-term cardiovascular function. AT<sub>1</sub>R are particularly important during fetal development, as they mediate mitogenic effects of angiotensin II and promote deposition of extracellular matrix (Weber *et al.* 1994), so disruption of normal patterns of expression may have an impact upon development of both the kidneys and the vasculature.

AT<sub>1</sub>R expression is subject to regulation by glucocorticoids (Goto *et al.* 1997). This class of hormones appears to play a central role in mediating the programming effects of undernutrition in fetal life. Evidence of increased glucocorticoid action in brain and liver has been demonstrated in both fetal and neonatal rats exposed to low-protein diets *in utero* (Langley-Evans & Nwagwu, 1998) and increased expression of glucocorticoid receptors persists into adult life, mediating a hypersensitivity to corticosteroids (Langley-Evans *et al.* 1996b; Bertram *et al.* 2001). It was surprising therefore to note that AT<sub>1A</sub>R mRNA expression in the kidney at 4 weeks of age was apparently not influenced by prenatal nutritional status. The discrepancy between this finding and that of Sahajpal & Ashton (2003) may be explained in a number of ways. First, the finding of increased levels of AT<sub>1</sub>R protein in the kidneys of low-protein-exposed rats, in the absence of raised mRNA expression, may be taken as evidence of programmed differences in translation, post-translational events or the longevity of the receptors. This will require further investigation. It is also important to point out that the study of Sahajpal & Ashton (2003) did not distinguish between AT<sub>1A</sub>R and AT<sub>1B</sub>R subtypes. The hypertensive effect of angiotensin II appears to be largely mediated by the AT<sub>1A</sub>R. Studies with knockout mice suggest that the AT<sub>1B</sub>R subtype only becomes involved in the control of basal blood pressure if expression of AT<sub>1A</sub>R is deficient or the receptors are inactive (Oliverio *et al.* 1997). The functional role of renal AT<sub>1B</sub>R sites is not well understood, but may relate to aspects of basal blood pressure control.

AT<sub>2</sub>R is less well characterised than AT<sub>1</sub>R, but is known to mediate the opposite effect. AT<sub>2</sub>R sites are predominantly expressed in fetal life and were thought to be absent from adult tissues. The present work confirms the findings of other studies using sensitive methods (Miyata *et al.* 1999) that show AT<sub>2</sub>R expression in kidneys of maturing and adult animals. Knockout mice lacking AT<sub>2</sub>R have increased blood pressure (Ichiki *et al.* 1995), whilst transgenic mice over-expressing this receptor show low sensitivity to the pressor effects of angiotensin II (Sheuer & Perrone, 1993). The low expression of AT<sub>2</sub>R mRNA seen in rats exposed to low-protein diets is therefore entirely consistent with their raised blood pressures

and with their increased responses to angiotensin II. The potential influence of AT<sub>2</sub>R on the development of hypertension in rats subjected to prenatal undernutrition is emphasised when the balance of AT<sub>1</sub>R:AT<sub>2</sub>R expression is considered as an arbitrary ratio (control 0.90 (SEM 0.14), low protein 1.57 (SEM 0.25);  $P=0.029$ ). This clearly shows the change in the overall pattern of expression to favour a hypertensive state.

In the present paper we report that the blood pressure response of female rats exposed to low-protein diets *in utero* to angiotensin II is both greater and more prolonged. If AT<sub>2</sub>R sites are responsible for the attenuation of the pressor response to angiotensin II, then the downregulation of expression that we have reported may explain the prolonged nature of the observed vascular response. Of course, blood pressure control will not solely be mediated through renal receptors and we would predict that resistance vessels may also show an increased AT<sub>1</sub>R:AT<sub>2</sub>R ratio expression, hence favouring hypertension. We cannot exclude an increase in AT<sub>1</sub>R sites in extra-renal locations as a contributor to this ratio.

The pattern of renal expression of both the AT<sub>1A</sub>R and AT<sub>2</sub>R subtypes observed in the present study may relate to the impact of low-protein diet in fetal life upon the morphological development of the kidney. AT<sub>1A</sub>R is found in most cells of the kidney, with particularly high densities in glomeruli and in cells of the macula densa. AT<sub>2</sub>R subtypes in the mature kidney are found in the cortical glomeruli and tubules (Miyata *et al.* 1999). As the low-protein diet appears to reduce nephron number without significantly reducing the overall size of the organ or having an impact on cell numbers (Langley-Evans *et al.* 1999), a decrease in the numbers of cortical nephrons may selectively impact upon AT<sub>2</sub>R expressing cell types without significant effects upon the near ubiquitous AT<sub>1A</sub>R.

The alternative viewpoint is that the changes in receptor expression could occur earlier in life and explain the effect of undernutrition on renal development. AT<sub>2</sub>R is the predominant angiotensin II receptor in the kidney during fetal life (Siragy, 2002). Binding to this site appears to be critical in the normal process of organogenesis and tissue differentiation (Goto *et al.* 1997). In the present study we have noted under-expression of AT<sub>2</sub>R at 4 weeks of age. If this were also the case in fetal life, or during the first 10 d of postnatal life, during which renal development continues in the rat, then a lack of AT<sub>2</sub>R sites might explain the observed reduction in nephron number. Interestingly, cultured fetal mesangial cells from the spontaneously hypertensive rat strain, which shares many characteristics with rats subjected to intrauterine protein restriction, do not express AT<sub>2</sub>R (Goto *et al.* 1997). Further work is needed with the present model system to assess the relative expression of all three angiotensin II receptor subtypes in the fetal and neonatal kidney.

The present paper has replicated findings from earlier work demonstrating that the development of the kidney and subsequent blood pressure in the rat are subject to programming influences of the maternal diet. This adds support to the argument that in man risk of both renal and CVD may be influenced by prenatal factors, including

maternal nutritional status. Determination of renal receptor expression clearly provides a limited view of the influences of maternal nutrition upon the rennin–angiotensin system and in turn upon the development of hypertension and renal dysfunction. However, earlier findings have demonstrated that maternal protein restriction upregulates the activity of angiotensin-converting enzyme, in the absence of significant changes in systemic angiotensin II concentrations (Langley-Evans & Jackson, 1995); we have gathered sufficient evidence to suggest that angiotensin II receptors play a key role in programming of hypertension (Sherman & Langley-Evans, 2000). Our current finding of increased vascular reactivity to angiotensin II adds weight to this argument. Importantly, we have here demonstrated for the first time that maternal undernutrition can exert long-term effects upon the expression of key genes involved in renal function and blood pressure control.

### Acknowledgement

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