Central role for melanocortin-4 receptors in offspring hypertension arising from maternal obesity

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Melanocortin-4 receptor (Mc4r)–expressing neurons in the autonomic nervous system, particularly in the paraventricular nucleus of the hypothalamus (PVH), play an essential role in blood pressure (BP) control. Mc4r-deficient (Mc4rKO) mice are severely obese but lack obesity-related hypertension; they also show a reduced pressor response to salt loading. We have previously reported that lean juvenile offspring born to diet-induced obese rats (OffOb) exhibit sympathetic-mediated hypertension, and we proposed a role for postnatally raised leptin in its etiology. Here, we test the hypothesis that neonatal hyperleptinemia due to maternal obesity induces persistent changes in the central melanocortin system, thereby contributing to offspring hypertension. Working on the OffOb paradigm in both sexes and using transgenic technology to restore Mc4r in the PVH of Mc4rKO (Mc4rPVH) mice, we have now shown that these mice develop higher BP than Mc4rKO or WT mice. We have also found that experimental hyperleptinemia induced in the neonatal period in Mc4rPVH and WT mice, but not in the Mc4rKO mice, leads to heightened BP and severe renal dysfunction. Thus, Mc4r in the PVH appears to be required for early-life programming of hypertension arising from either maternal obesity or neonatal hyperleptinemia. Early-life exposure of the PVH to maternal obesity through postnatal elevation of leptin may have long-term consequences for cardiovascular health.

melanocortin-4 receptors | developmental programming | maternal obesity | hypertension | sympathetic nerve activity

The main focus of research into the central melanocortin system has been on melanocortin-4 receptor(s) (Mc4r) and their relation to energy homeostasis, with relatively few studies addressing the role of Mc4r in cardiovascular control (1, 2). However, it is clear that this system plays an important role in the control of blood pressure (BP) (3, 4). In humans with loss-of-function Mc4r mutation, there is severe obesity but no obesity-related hypertension (5). Mc4r-deficient (Mc4rKO) mice exhibit hyperphagia and marked obesity and, similarly, no obesity-related hypertension (3). Mc4r deletion also reduces the pressor response to salt loading, as well as preventing inflammatory and renal damage associated with obesity (6). Pharmacological inhibition of Mc4r in adult rats reduces the obesity-related hypertension and renal sympathetic nerve activity (RSNA) associated with hyperleptinemia (7, 8). Moreover, the highest expression of hypothalamic Mc4r mRNA is found in the paraventricular nucleus of the hypothalamus (PVH), which integrates and responds to a variety of neural and humoral signals regulating RSNA (9–12). It has been shown that leptin stimulates the tonic firing rate of Mc4r PVH neurons in rats, resulting in heightened arterial pressure, a finding that is consistent with causal links between obesity and adult hypertension (13).

The increased prevalence of hypertension among children and young adults has been attributed to sympathetic hyperactivity (14). Although genetic and lifestyle factors undoubtedly contribute to raised BP in young people, hypertension may, at least in part, have origins in fetal and neonatal life (15, 16). In population studies, maternal obesity has been independently linked to adult offspring cardiovascular morbidity and mortality (17). We have previously demonstrated offspring juvenile hypertension in rats, independent of adiposity, resulting from prenatal exposure to maternal diet-induced obesity. This hypertension was associated with a shift in the sympathetic to parasympathetic ratio of heart rate variability (HRV), indicative of heightened sympathetic efferent tone (18, 19), persisting to adulthood (19, 20). These findings, together with the increase in renal norepinephrine and tyrosine hydroxylase (TH) expression (19), led us to propose that increased RSNA contributes to offspring cardiovascular dysfunction secondary to maternal obesity (18).

Previously, we suggested that overexposure to leptin in neonatal rats as a result of maternal obesity leads to hypertension through aberrant development of hypothalamic neuronal networks involved in BP homeostasis (18, 21); this hypothesis is consistent with several reports identifying neonatal leptin as an important neurotrophic factor during periods of early development (22, 23). Here, we address the hypothesis that maternal obesity-related leptin exposure in rodents in early life leads, through changes in the PVH melanocortin system, to chronically increased RSNA, hypertension, and renal dysfunction. Such a process may contribute to primary hypertension in an increasingly obese global human population.

Significance

Obesity is increasing in pregnant women worldwide. Independent associations have been reported between maternal obesity and metabolic cardiorenal disorders in the offspring, including hypertension. In this study, using genetically modified mice, we have identified a role for the hypothalamic paraventricular nucleus (PVH) melanocortin system in the etiology of hypertension. We show that maternal obesity permanently resets the responsiveness of the central sympathetic nervous system via this pathway. We conclude that neonatal leptin exposure is the primary mediator, because exogenous neonatal leptin administration to pups of lean mice leads to the same phenotype mediated by PVH melanocortin-4 receptors. Thus, primary hypertension of sympathetic origin can result from early-life exposure to maternal obesity, and the melanocortin pathway presents a target for intervention.

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The previous use of mice with global Mc4r deletion in which Mc4r was restored in the sympathetic preganglionic neurons in the brainstem using Cre-lox methodology has led to recognition of a role in obesity-associated hypertension for Mc4r in these locations (24). Using a similar approach, we have now addressed the specific role of Mc4r PVH in the hypertension arising from maternal obesity in the mouse. In parallel experiments, we have also addressed the role of Mc4r PVH in the hypertension associated with experimental neonatal hyperleptinemia. The rat has also been used as a model to demonstrate the role of the Mc3/4 pathway in diet-induced obesity-related hypertension (25). To explore the origins of juvenile hypertension further, we also carried out pharmacological studies in offspring of diet-induced obese rats (OffOb). To determine the consequences for renal function, we examined renal histology, the renin/angiotensin system, oxidative stress, and inflammation.

Results

Mc3/4r Antagonism Attenuates Juvenile Hypertension in Rats Without Changing HR. Juvenile (30-d-old) Sprague–Dawley rat OffOb had raised mean arterial pressure (MAP) vs. offspring of control dams (OffCon) (Fig. 1 *A*–*C*), which occurred before development of increased body weight (BW) induced by hyperphagia (Fig. S1 *A*–*D*). Chronic intracerebroventricular (ICV) Mc3/4r antagonist (SHU9119) infusion lowered MAP in male and female offspring (Fig. 1 *B* and *C*), with a greater reduction in hypertensive OffOb vs. normotensive OffCon rats (Fig. 1 *F* and *G*). Heart rate (HR) was unaffected in both sexes (Fig. 1 *D* and *E*). Renal denervation in OffOb rats led to normalization of MAP, suggesting that hypertension in the OffOb involves RSNA (Fig. 1 *H* and *I*). MAP was unaffected by vehicle treatment in any group (Fig. S2 *A* and *B*). We also assessed the action of the Mc3/4r agonist melanotan II (MTII) on cardiovascular responses in male littermates in adulthood (360 d) (Fig. S3*A*). The i.p. administration of MTII rapidly increased MAP, without any effect on HR (Fig. S3 *B*–*E*). These experiments supported a role for Mc3/4r in hypertension arising from maternal obesity. Data on food intake (FI) and BW in these rats are provided in *Supporting Information* (Figs. S1 and S3). SHU9119 infusion for 5 d increased BW and FI more in OffOb, compared with OffCon (Fig. S1 *A*–*D*). MTII challenge reduced weight gain and FI in both OffOb and OffCon, compared with vehicle (Fig. S3 *F* and *G*).

MAP in WT, Mc4rKO, and PVH of Mc4rKO Mice with Maternal Diet-Induced Obesity. To examine the role of Mc4r in the PVH on MAP, we used genetically modified mice (Fig. 2 and Tables S1 and S2). As in the rat (Fig. 1 *B* and *C*), MAP was raised in adult male and female OffOb-WT mice (Fig. 3 *A* and *D*). Mc4rKO mice showed no effect on MAP associated with maternal diet-induced obesity. OffOb mice with Cre-lox–induced Mc4r restoration in the PVH of Mc4rKO (Mc4rPVH; Fig. 2) mice showed greater MAP compared with OffOb-WT mice ($P < 0.05$). There was no change in HR except in male Mc4rPVH mice, which showed increased HR in OffOb vs. OffCon (Fig. 3 *B* and *E*). These findings in OffOb-Mc4rPVH mice were associated with an enhanced low-frequency/high-frequency (LF/HF) ratio in HRV spectral analysis (Fig. 3 *C* and *F*), heightened MAP elevation in response to the Mc3/4r agonist MTII (Fig. 3 *G*–*I*), and Mc4r restoration in the PVH (Fig. 3 *J* and *K*). Linear growth curves, body composition, and energy expenditure (EE) in these mice are provided in *Supporting Information* (Fig. S4 *A* and *B* and Table S3). It is notable

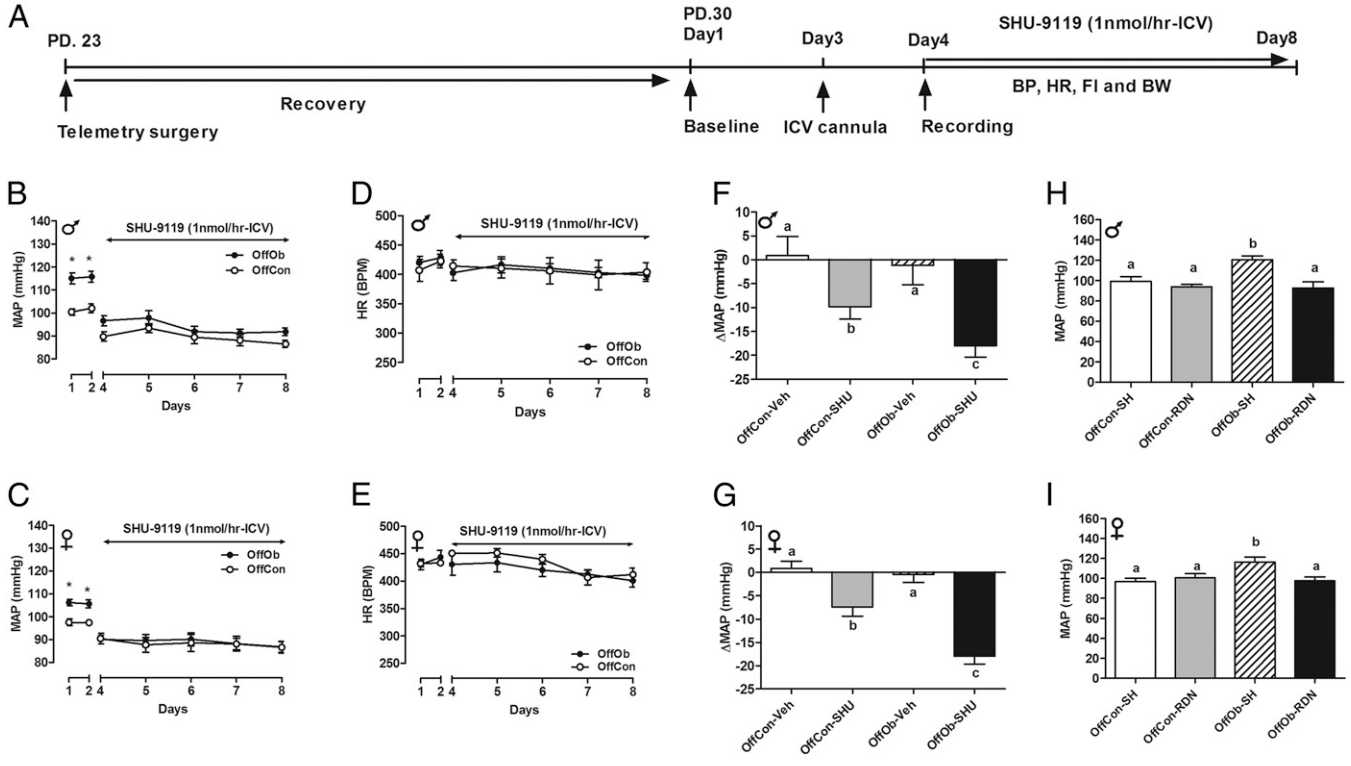

Fig. 1. Chronic Mc3/4r antagonist treatment in Sprague–Dawley rats (SHU-9119, 1 nmol·h^{-1}, ICV) attenuates juvenile hypertension, independent of heart rate (HR). Data in *B*–*I* were collected over 5 d (from day 33 to day 37) in OffOb and OffCon. (*A*) Mc3/4r antagonist (SHU-9119) or vehicle was infused for 5 d using an osmotic minipump. Mean arterial pressure (MAP) and HR responses were continuously monitored using radiotelemetry in male and female rats, respectively. MAP (*B* and *C*), HR (*D* and *E*), and changes in MAP (*F* and *G*) are shown. BPM, beats per minute. (*H* and *I*) Renal denervation (RDN) in OffOb rats normalized the MAP compared with sham-operated (SH) rats. Data are expressed as the daily average of MAP and HR per group ($n = 5$–6; mean ± SEM). *$P < 0.001$ vs. OffCon using the Student *t* test. Means not sharing the same letter are significantly different from each other ($P < 0.05$) by generalized least squares (GLS) regression analysis.

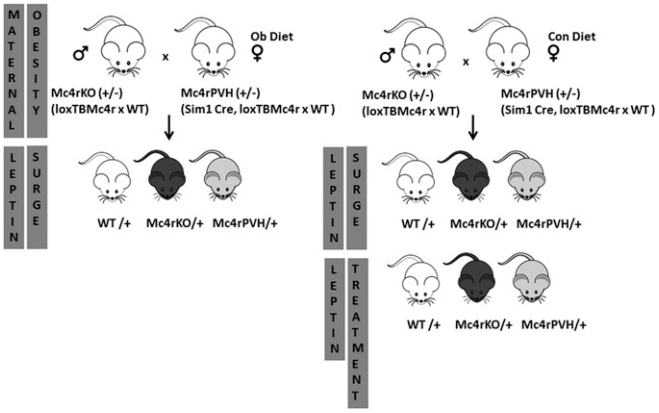

Fig. 2. Breeding and experimental protocol. Nontransgenic heterozygous Mc4rKO males (loxTBMc4r) were mated with transgenic heterozygous Mc4rPVH females (Sim1-Cre, loxTB Mc4r) to generate WT, homozygous Mc4rKO, and Mc4rPVH offspring. All mice are on a mixed C57Bl6/J, 129Sv, and FVB background. Littermates were used for all studies to avoid partial genetic background effects. In experimental protocol 1, dams were fed either a control diet (Con) or highly palatable obesogenic diet (Ob) 5 wk before mating and during pregnancy and lactation. OffCon- and OffOb-WT, -Mc4rKO, and -Mc4rPVH mice were weaned to a control diet at 21 d of age, genotyped, and then phenotyped at 6 mo of age. In experimental protocol 2, neonatal WT, Mc4rKO, and Mc4rPVH littermates born to obese (OffOb) or control (OffCon) dams were killed at PD6, PD9, and PD15 to trace the neonatal serum leptin surge. In experimental protocol 3, neonatal WT, Mc4rKO, and Mc4rPVH littermates were treated with leptin (NL, 3 mg/kg, twice daily, i.p.) or with vehicle (NS) on PD9–PD14. This neonatal hyperleptinemia protocol was designed to mimic the augmented and prolonged leptin surge found in the OffOb. More details are provided in *Supporting Information*.

that OffOb-WT and OffOb-Mc4rPVH (male) mice showed increased BW compared with OffCon-WT and OffCon-Mc4rPVH mice, respectively (Fig. S4). The reduced EE observed in the obese Mc4rKO mice was not rescued in Mc4rPVH mice (Table S3), indicating that PVH Mc4r are not involved in mediating the effects of melanocortins on EE.

Neonatal Leptin Profile in WT, Mc4rKO, and Mc4rPVH Mice. Given that our previous findings in rats implicated an augmented postnatal leptin surge in the etiology of hypertension and obesity in OffOb (18, 21), we next addressed possible links between postnatal leptin and Mc4r in relation to hypertension in male and female OffOb mice. All groups showed a postnatal serum leptin surge (Fig. 4 *A*–*C*, sexes combined): The concentrations were higher at postnatal day (PD) 9 and PD15 in OffOb-WT vs. OffCon-WT and in OffOb-Mc4rPVH vs. OffCon-Mc4rPVH (Fig. 4 *A* and *C*), with OffOb-Mc4rPVH showing an advanced elevation by PD6 (Fig. 4*C*). However, on PD9 and PD15, the elevated leptin concentrations in OffOb- and OffCon-Mc4rKO showed no additional influence of maternal diet-induced obesity (Fig. 4*B*). In all groups, the changes in neonatal leptin from PD6–PD15 (Fig. 4 *D*–*F*) did not correspond to the changes in neonatal BW, a finding that is consistent with the previous report that leptin does not influence energy balance in neonatal mice (26).

Effects of Neonatal Leptin Treatment on MAP in WT, Mc4rKO, and Mc4rPVH Mice. To assess the importance of neonatal hyperleptinemia in the onset of hypertension arising from maternal diet-induced obesity, WT, Mc4rKO, and Mc4rPVH mice born to control dams were treated twice daily with i.p. leptin on PD9–PD14 to mimic the neonatal leptin surge in OffOb mice (Fig. 2). In each genotype, this treatment resulted in metabolic profiles (Table S4) and BP profiles (Fig. S5 *A* and *D*) similar to the profiles found in the same genotype following exposure to maternal obesity, including absence of hypertension in the neonatal leptin-treated (NL)-Mc4rKO mice (Fig. S5 *A* and *D*). These findings indicate that neonatal leptin exposure leads to hypertension in a process that is dependent on Mc4r. The similarities in MAP, HR, and HRV between the NL (Fig. S5 *A*–*F*) and OffOb (Fig. 3 *A*–*F*) mice strengthened the evidence for a causative role for neonatal hyperleptinemia in the hypertension that arises from maternal diet-induced obesity.

Effects of Acute Leptin Treatment in WT, Mc4rKO, and Mc4rPVH Mice. We have shown previously that juvenile OffOb rats lack the normal satiety response to leptin, despite maintenance of the pressor response (selective leptin sensitivity) (19). We therefore examined the acute effect of exogenous leptin in OffOb and OffCon mice (sexes combined) in WT, Mc4rKO, and Mc4rPVH genotypes to assess the role of Mc4r in selective leptin resistance. Leptin increased MAP in all groups except OffOb-Mc4rKO and OffCon-Mc4rKO mice (Fig. 5 *A*–*C*), with the highest pressor response being obtained in the OffOb-Mc4rPVH mice (Fig. 5*C*). Thus, the greater leptin-induced MAP elevation in OffOb mice seems to involve activation of Mc4r in the PVH. Leptin-induced suppression of appetite (Fig. 5*D*) and weight gain (Fig. 5*E*) were lost in the OffOb mice, thus demonstrating selective leptin sensitivity.

Development of Renal Dysfunction in WT and Mc4rPVH Mice with Neonatal Exposure to Leptin. Having implicated heightened sympathetic activation via Mc4r in the hypertension induced by either maternal obesity or experimental neonatal hyperleptinemia, we hypothesized that Mc4r deletion would protect against renal dysfunction associated with hypertension in the NL mice, and that Mc4rPVH restoration of Mc4r in the PVH would reverse this protection. This hypothesis was confirmed with an impaired glomerular filtration rate (GFR) in NL-WT and NL-Mc4rPVH male and female mice compared with respective neonatal saline-treated (NS) mice, whereas Mc4rKO male and female mice showed a similar GFR in NL vs. NS mice. Albuminuria, a marker of obesity-related renal injury, was elevated in all NL mice, with a threefold increase in the NL-Mc4rPVH mice, compared with NS-Mc4rPVH mice. Urinary markers of renal injury [neutrophil gelatinase-associated lipocalin (NGAL) and kidney injury molecule-1 (KIM-1)] were increased in NL-WT and NL-Mc4rPVH mice; Mc4rKO mice were protected against NL-induced renal injury. Fig. 6 shows data for these parameters in males; females were similar. Mc4rKO mice were also partly protected against renal injury. NL-WT and NL-Mc4rPVH male and female mice had enhanced cortical fibrogenesis, tubulointerstitial infiltration, and inflammation [cluster of differentiation 36 (CD36, macrophage scavenger)], compared with NL-Mc4rKO mice. Fig. S6 *A*–*F* shows these variables for males; females were similar. Renal injury was also associated with enhanced oxidative stress. Components of the reactive oxygen species were all increased accordingly to renal injury: thiobarbituric acid reactive substance(s) (TBARS; Fig. S7 *S* and *T*), NAPDH oxidase-4 (Nox-4) mRNA (Fig. S7 *Q* and *R*), and nitrotyrosine immunoreactivity (Fig. S6 *G* and *H*). These data provide further evidence for the importance of Mc4rPVH in the etiology of hypertension and renal disease resulting from exposure to maternal diet-induced obesity or experimental neonatal hyperleptinemia.

Mc4rKO mice also showed reduced RSNA and renin angiotensin system (RAS) as assessed by reduced mRNA expression for TH, renin, and angiotensin II receptor 1a (AT1a). Restoration of Mc4r in PVH neurons returned RSNA and RAS in Mc4rKO mice secondary to maternal obesity (Fig. S7 *A*–*F*) or neonatal hyperleptinemia (Fig. S7 *K*–*P*) to values similar to the values observed in the WT mice. Collectively, the data suggest that Mc4rPVH-mediated hypertension of sympathetic origin leads to renal injury.

Discussion

These experiments demonstrate (*i*) that functional Mc4r in the PVH are sufficient for early-life programming of hypertension of

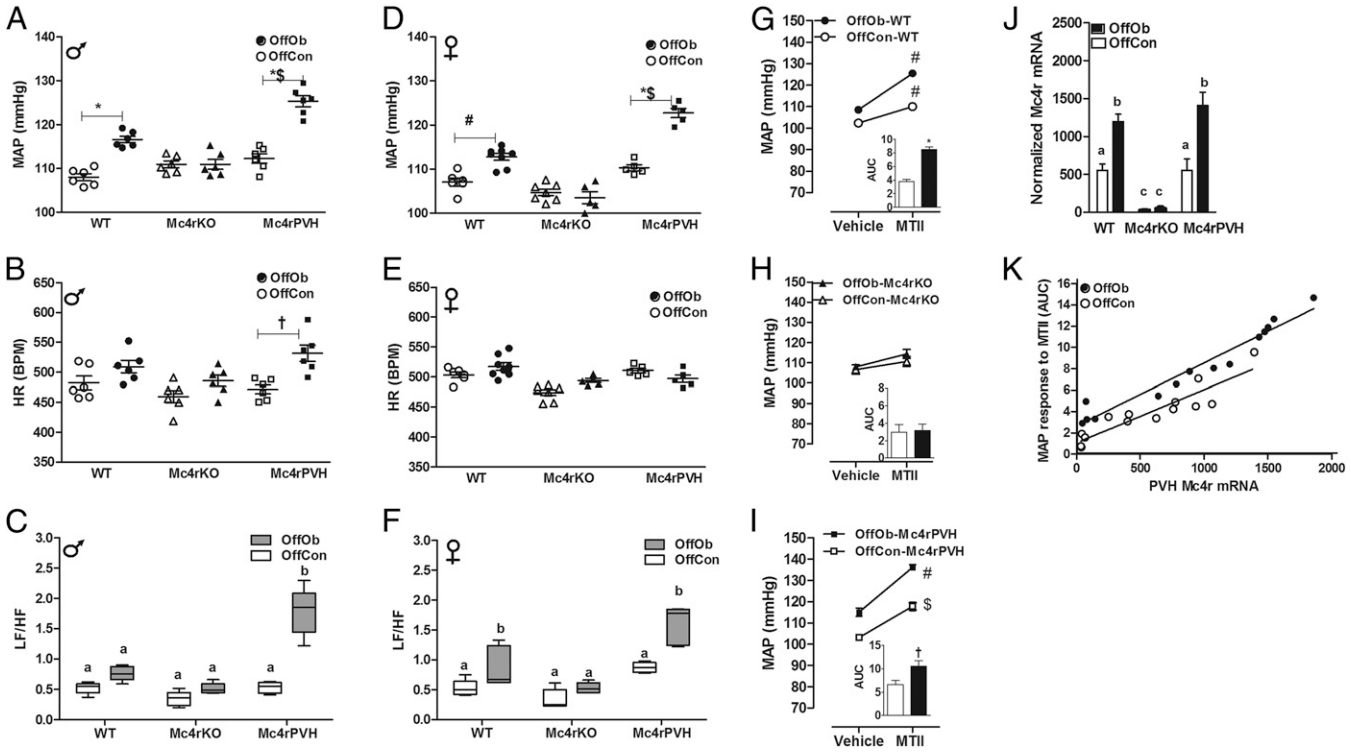

Fig. 3. Mc4r deletion (Mc4rKO) blunts the MAP in OffOb, whereas reactivation of Mc4r in the PVH completely rescued the increased MAP. Data in each panel were collected as average 24-h recordings from 6-mo-old male and female OffOb (black)- and OffCon (white)-WT, -Mc4rKO, and -Mc4rPVH mice. MAP (*A* and *D*), HR (*B* and *E*), and LF/HF ratio (*C* and *F*; LF, 0.04–0.15; HF, 0.15–0.40). $*P < 0.001$, $^{\dagger}P < 0.01$, and $^{\#}P < 0.05$ vs. OffCon; $^{\$}P < 0.05$ vs. OffOb-WT using the Student *t* test ($n = 6$–8 per group, mean ± SEM). (*G*–*I*) MAP responses to MTII challenge (Mc3/4r agonist, 10 mg/kg, i.p.). Responses are demonstrated as area under the curve (AUC). $^{\#}P < 0.001$ and $^{\$}P < 0.05$ vs. Vehicle; $*P < 0.001$ and $^{\dagger}P < 0.05$ vs. OffCon using the Student *t* test ($n = 6$–8 per group, sex combined, mean ± SEM). (*J*) Mc4r mRNA in laser-dissected PVH normalized to the housekeeping genes β-actin and RPL13A (using the GeNorm program; $n = 4$–6 per group, sex combined). Means not sharing the same letter are significantly different from each other ($P < 0.05$) by generalized least squares (GLS) regression analysis. (*K*) α-MSH sensitivity curve with MAP response to MTII (*y* axis) vs. PVH Mc4r mRNA expression (*x* axis) in 6-mo-old OffCon (white)- vs. OffOb (black)-WT, -Mc4rKO, and -Mc4rPVH mice. OffOb showed a higher slope ($P < 0.05$) in the α-MSH sensitivity curve vs. OffCon [analysis of covariance (ANCOVA), $n = 13$].

sympathetic origin arising from maternal obesity, (*ii*) that neonatal hyperleptinemia is a likely mediator, and (*iii*) that the hypertension is associated with deterioration of kidney function. The adult phenotype identified in the mice studied here bears a striking resemblance to human hypertension of sympathetic origin (27).

Reversal of the hypertension by Mc3/4r antagonism (SHU-9119) in young, lean OffOb rats suggests that early-onset primary hypertension, independent of BW, is mediated by the melanocortin system activating the renal sympathetic system. Use of this antagonist cannot distinguish between Mc3r or Mc4r effects, or identify the anatomical location of the responsible receptors. We therefore sought to refine our investigative method. Because Mc4r is highly expressed in parvocellular neurons of the PVH (28), in a subset of neurons that control renal sympathetic tone (29, 30), we focused on Mc4rPVH mice. Using genetically modified mice in which Mc4r had been either completely deleted (Mc4rKO) or reinstated locally in the PVH (Mc4rPVH) (31), we found that the presence of Mc4r in the PVH was sufficient to restore early-life programming of raised BP. These results suggest a pivotal role for MC4r in the PVH; they do not detract from the reported BP effects of Mc4r at other sites, such as the nucleus tractus solitaries (32).

The increased LF/HF ratio in HR spectral analysis in OffOb-WT and OffOb-Mc4rPVH mice provided confirmation of sympathetic hyperactivity. In contrast, OffOb- and OffCon-Mc4rKO mice remained normotensive with evidence of both parasympathetic excitation and sympathosuppression. The higher BP in OffOb-Mc4rPVH mice than in OffOb-WT mice may indicate that Mc4r activation at other central locations (e.g., within the hypothalamus or brainstem) antagonizes Mc4r-mediated cardiovascular control pathways from the PVH. An alternative explanation could be development of Mc4r hypersensitivity in the Mc4rPVH mice in response to neonatal hyperleptinemia. Restoration of Mc4r in the PVH completely rescued the increased BP observed in WT mice arising from maternal diet-induced obesity.

The independence of the heightened arterial pressure from the HR in the OffOb-Mc4rPVH mice strongly suggests that Mc4r in the PVH regulates sympathetic innervation in the kidney, but not in the heart, consistent with the rat model of dietary-induced obesity in which Mc3/4r antagonism reduced arterial pressure more in high-fat–fed compared with normal-fat–fed rats, independent of HR (25). We conclude that maternal obesity leads to increased juvenile offspring renal sympathetic tone and BP, which is offset by vagal-mediated adjustments in HR.

Strikingly similar phenotypes were obtained in offspring exposed to maternal diet-induced obesity or to experimental neonatal hyperleptinemia (mimicking the augmented leptin surge seen in the former group). Both experimental models resulted in elevated BP and greater BP responsiveness to exogenous leptin in adulthood. The postnatal leptin surge has been shown to have neurotrophic effects in the developing brain (23) and to influence plasticity of the melanocortin system (33). We have previously demonstrated in rats that neonatal hyperleptinemia associated with maternal obesity leads to juvenile hypertension and cardiac dysfunction (18, 21). The present results in mice with an experimentally enhanced leptin surge point to a role for maternal obesity-related neonatal hyperleptinemia in the restored PVH Mc4r expression and the onset of hypertension. Whether this increase in receptor expression within the PVH is associated with an increased local availability of

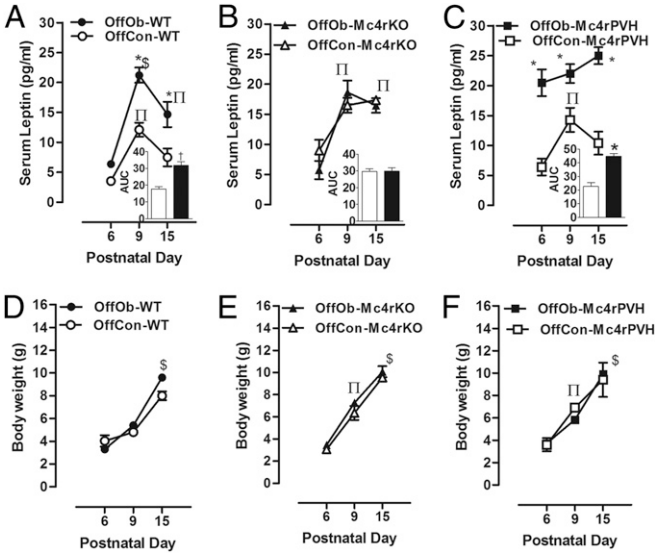

Fig. 4. Neonatal leptin surge (at PD6, PD9, and PD15) was augmented and prolonged in WT and Mc4rPVH OffOb mice vs. WT and Mc4rPVH mice born to lean dams (OffCon). The neonatal serum leptin (*A–C*) and BW (*D–F*) were recorded at PD6, PD9, and PD15. Data are presented as AUC from baseline (n = 6–8 per group, sex combined). Data are expressed as mean ± SEM. $^{*}P <$ 0.001 and $^{\dagger}P < 0.01$ vs. OffCon using the Student t test; $^{\$}P < 0.001$ and $^{\Pi}P <$ 0.05 vs. PD6 using the Student t test.

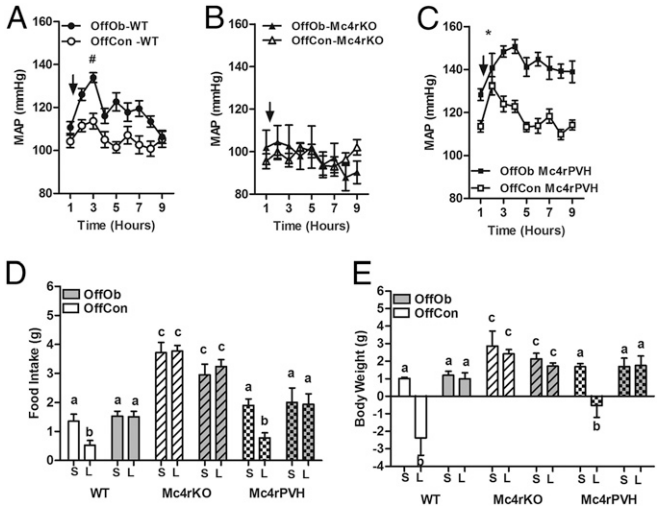

Fig. 5. Selective leptin sensitivity arising from maternal diet-induced obesity is mediated via Mc4r PVH. Mice (6 mo) were injected with saline (S, vehicle) or leptin (L, 10 mg/kg, i.p.) after an overnight fast in OffOb- and OffCon-WT, -Mc4rKO, and -Mc4rPVH mice, and FI and BP (MAP) were monitored. (*A–C*) MAP after leptin challenge in OffOb- vs. OffCon-WT, -Mc4rKO, and -Mc4rPVH mice. MAP returned to baseline (1) in all mice except OffOb-Mc4rPVH. Mc4rKO mice showed no pressor response to leptin. FI (*D*) and weight gain (*E*) after an overnight fast in OffOb-WT Mc4rKO and Mc4rPVH offspring are compared with respective controls. Mc4rKO mice were insensitive to the effect of leptin and failed to reduce FI and BW. Data are expressed as mean ± SEM (n = 6–8 per group, sexes combined). $^{*}P < 0.001$ and $^{\#}P < 0.05$ vs. OffCon using the Student t test. Means not sharing the same letter are significantly different from each other ($P < 0.05$) by generalized least squares (GLS) regression analysis.

α-melanocyte-stimulating hormone (α-MSH) is unknown. A previous study found no changes in α-MSH-immunoreactivity projections from the arcuate nucleus to the preautonomic division of the PVH in leptin-null mice with or without postnatal leptin replacement (22). However, the experimental model used in the present study involved leptin in excess rather than as a replacement for deficiency.

Leptin-induced sympathetic overactivity is a well-established phenotype for obesity-related hypertension (8) and is mediated by Mc4r (3). Our study confirms that acute pressor responses to leptin require functional Mc4r; it also makes the observation that these responses require Mc4r in the PVH. Our hypothesis that the pressor response would be higher than normal in OffOb or NL animals was confirmed. We conclude that programmed changes in melanocortin receptor expression are responsible for the heightened pressor responsiveness to exogenous leptin. Should these mouse models be translatable to the human condition, it may be expected that prenatal exposure to maternal obesity would result in an exaggerated pressor response to endogenous leptin.

The present study has confirmed that OffOb develop hypertension due to sympathetic overactivity. We pursued the hypothesis that maternal obesity could lead to offspring hypertension and renal dysfunction. The discovery of increased renal renin, AT1a, and TH expression further emphasizes the RSNA origins of the hypertension. Markers of oxidative stress (TBARS, Nox-4, and nitrotyrosine) and of leukocyte infiltration suggest pathways leading to renal injury, as evidenced by fibrosis, reduced GFR, and increased albumin, NGAL, and KIM-1 excretion. All of these observations were paralleled in the NL mice. Protection against neonatal leptin-induced renal injury in the Mc4rKO mice establishes a necessary role for this receptor. Thus, Mc4rKO mice were protected not only against maternal obesity-related hypertension but also against the associated maternal obesity-related renal injury. Despite being obese and hyperphagic, with prolonged exposure to metabolic disturbances, including hyperinsulinemia and hyperleptinemia, Mc4rKO OffOb or Mc4rKO NL mice showed no signs of hypertension or renal injury.

Increases in the prevalence of chronic kidney disease in childhood have paralleled the rise in overweight and obesity in children. Although the mechanisms responsible for obesity-induced chronic kidney disease are not fully understood, there is considerable evidence that abnormal sympathetic activation plays a key role (34), but this abnormal sympathetic activation has been generally attributed directly to obesity. The present study indicates origins of sympathetic overactivity in young adults that are

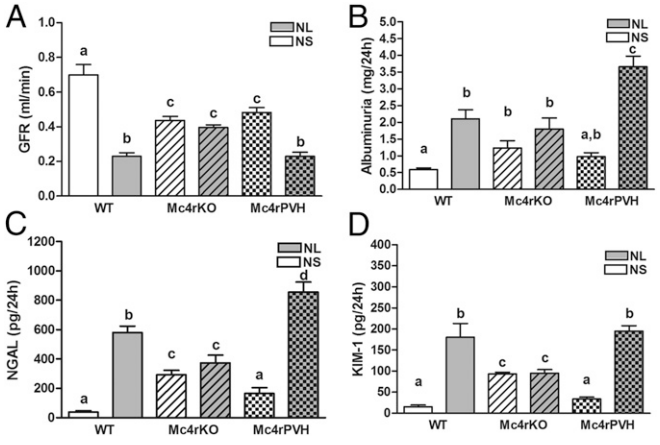

Fig. 6. Evidence of kidney dysfunction and injury in NL male mice. Mc4rKO mice are protected against neonatal leptin-induced renal injury. GFR (*A*, milliliters per minute), excretion of albumin (*B*, milligrams per 24 h), and the early renal damage markers NGAL (*C*, picograms per 24 h) and KIM-1 (*D*, picograms per 24 h) are shown. Data are expressed as mean ± SEM (n = 5–6 per group). Means not sharing the same letter are significantly different from each other ($P < 0.05$) by generalized least squares (GLS) regression analysis. Data for females were similar.

independent of obesity; it identifies a specific hypothalamic region and receptor system involved in early programming of hypertension and kidney disease induced by maternal obesity or experimental neonatal hyperleptinemia.

Materials and Methods

Experimental details are provided in *Supporting Information*.

Animals. All experiments were approved by the Local Ethics Committee of the University of King's College London and were conducted according to the Home Office Animals (Scientific Procedures) Act of 1986 (United Kingdom). Sprague–Dawley rats were bred and maintained as described previously (18) and treated with the Mc3/4r antagonist (SHU-9119, 1 nmol, ICV) or the Mc3/4r agonist MTII (2 mg/kg, i.p.).

Mc4rKO (loxTB MC4R) and Mc4rPVH (Sim1-Cre, loxTB MC4R) mice were generated as previously described (31). Sim1-Cre genetically modified mice were crossed with homozygous loxTB MC4R mice to obtain homozygous Sim1-Cre, loxTB MC4R mice. Nongenetically modified heterozygous loxTBMC4R and heterozygous Sim1-Cre, loxTB MC4R mice were used in the different experimental protocol (Fig. 2). To investigate the effect of in utero and early postnatal exposure to maternal obesity in all three offspring genotypes (WT, Mc4rKO, and Mc4rPVH), the dams were fed either a highly palatable energy-rich obesogenic diet or a control standard laboratory chow diet 5 wk before mating and throughout pregnancy and lactation, as described previously (20). The highly palatable diet consists of 20% animal lard, 10% simple sugars, 28% polysaccharide, and 23% protein (wt/wt) and energy of 4.5 kcal/g (Special Dietary Services, Wittam, U.K.), supplemented with sweetened condensed milk [~55% simple sugars and 8% fat (wt/wt); Nestlé], which was fortified with 3.5% mineral mix and 1% vitamin mix (wt/wt) (AIN 93G; Special Diets Services). To validate the genetically modified mice, ear punch samples were collected for genotyping using three primers: (*i*) 5′GCAGTACAGCGAGTCTCAGG3′, (*ii*) 5′GTGCAAGTGCAGGTGCCAG3′, and (*iii*) 5′CTCCAACAGGCTTATGACACC3′. Primers *ii* and *iii* detect the loxP-modified allele, whereas primers 1and 3 detect an endogenous genomic Mc4r fragment. A detailed description is provided in *Supporting Information*. At 6 mo of age, BP monitoring was conducted using mouse transmitters (TA11PA-C10; Data Science International, Inc.). After 1 wk of recovery, continuous data collection was monitored using the Dataquest A.R.T. Acquisition System (LabPRO Acquisition System version 3.01; Data Science International, Inc.). All hemodynamic data were analyzed using hourly means. To determine the influence of maternal obesity and neonatal hyperleptinemia on pressor and satiety responses to exogenous leptin in adulthood, as well as the role of the Mc4r, a leptin challenge (10 mg/kg, i.p.) was performed after an overnight fast as described (18) in male and female 6-mo-old mice. FI was measured by indirect calorimetry using the Comprehensive Laboratory Animal Monitoring System (TSE). To assess renal function, mice were fasted with ad libitum access to sugar water (1%); 24-h urine samples were measured and collected; and serum samples were analyzed to examine renal hemodynamics and renal injury markers. Tissues were harvested immediately, with the left kidneys being placed in formalin for fixation and later histological analysis, whereas the right kidneys were snap-frozen in liquid nitrogen. Details are provided in *Supporting Information*.

Statistical Analysis. Data are expressed as mean ± SEM. The effects of diet, genotype, and sex were investigated by random effects generalized least squares regression, grouping by dam, with robust variance estimates (35). Cardiovascular analysis was performed by the Student *t* test or one-way ANOVA for repeated measurements, followed by the Tukey post hoc test. Analysis was carried out using the statistical package Stata version 14 (StataCorp) or Prism 6 (GraphPad Software, Inc.).

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