Early Onset Salt-Sensitive Hypertension in Bradykinin B₂ Receptor Null Mice

Ludek Cervenka, Lisa M. Harrison-Bernard, Susana Dipp, Ginny Primrose, John D. Imig, Samir S. El-Dahr

Abstract—Kinins have been implicated in the hemodynamic adaptation to postnatal life. The present study examined the impact of bradykinin B₂ receptor (B₂R) gene disruption on the postnatal changes in blood pressure (BP) and the susceptibility to early onset salt-sensitive hypertension in mice. B₂R null (−/−) and wild-type (+/+) mice were fed normal (NS, 1% NaCl) or high (HS, 5% NaCl) salt diets during pregnancy. After birth, the pups remained with their mothers until they were weaned and were subsequently continued on the respective maternal salt intake until 4 months of age. The age-related changes at 3 and 4 months in tail-cuff BP and anesthetized mean arterial pressure at 4 months were not different in NS/B₂R−/− and NS/B₂R+/+ mice. However, there was a mild increase in BP in NS/B₂R−/− at 2 months versus NS/B₂R+/+. In contrast, HS/B₂R−/− mice manifested early onset and persistent elevations of tail-cuff BP (P<0.05) at 2, 3, and 4 months versus other groups. MAP was also higher in HS/B₂R−/− than HS/B₂R+/+, NS/B₂R−/−, and NS/B₂R+/+ (91±3 versus 75±5, 74±2, and 70±2 mm Hg, respectively; P<0.05). Kidney renin and angiotensin type 1 receptor mRNA levels were not different. Additional studies showed that a delay in the initiation of HS until after birth was accompanied by later development of hypertension, although postnatal discontinuation of HS resulted in a gradual return of BP to normal values by 4 months of age. The results demonstrate that (1) kinins protect the developing animal from salt-sensitive hypertension, (2) lack of B₂R from early development does not alter the maturation of BP under conditions of normal sodium intake, and (3) exposure to a HS diet during fetal life is not sufficient in itself to induce long-term hypertension in either wild-type or B₂R null mice. (Hypertension. 1999;34:176-180.)

Key Words: kallikrein-kinin system ▪ renin-angiotensin system ▪ receptors, bradykinin ▪ blood pressure

The recent development of genetically engineered mice with targeted disruption of the bradykinin B₂ receptor (B₂R) gene has provided a unique opportunity to investigate the physiological relevance of the kallikrein-kinin system in the absence of pharmacological interventions. Alfie et al demonstrated that although B₂R null mutant mice maintained on a normal salt (NS) diet are normotensive, chronic high salt (HS) intake provokes hypertension and decreases renal blood flow compared with wild-type controls. Studies by Madeddu et al and Emanuelli et al have shown that B₂R null mice have a slightly higher resting blood pressure (BP) than wild-type controls and that salt loading or deoxycorticosterone treatment causes hypertension in these mice. Thus, B₂R gene inactivation results in salt-sensitive hypertension in the adult animal.

Although the role of kinins in the regulation of renal and cardiovascular homeostasis in the adult animal has received much attention, the role of the kallikrein-kinin system in developmental physiology is largely unknown. Emerging evidence indicates that the developing distal nephron is endowed with a local kinin-generating system. In addition, there is a considerable amount of kallikrein-like activity and bradykinin (BK) B₂R mRNA in the developing vascular wall and heart. Therefore, it is conceivable that endogenous kinins counterbalance the effects of vasoconstrictor and antinatriuretic systems during normal growth and development. Accordingly, the present study was designed to (1) compare the maturational changes in BP in wild-type and B₂R null mice, and (2) examine the impact of B₂R ablation on the susceptibility to early salt-sensitive hypertension. In addition, to assess the contribution of the renin-angiotensin system, we examined the effects of B₂R inactivation and differing salt diets on renal renin and angiotensin type 1 (AT₁) gene expression and angiotensin II (Ang II) levels.

Methods

Animal Groups

Targeted disruption of the B₂R gene was accomplished by homologous recombination in embryonic stem cells as described by

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Borkowski et al.1 B2R null mice (−/−) of mixed 129Sv × C57BL/6J genetic background (F1) were generously provided by Drs Fred Hess and Howard Chen (Merck Research Laboratory, Rahway, NJ) and were bred on C57BL/6J background up to F1 at Tulane School of Medicine vivarium (New Orleans, La). This was performed to limit the possible effects of genetic background on the BP phenotype. Wild-type C57BL/6J [B2R+/+] mice were obtained from Charles Rivers Laboratories (Wilmington, Mass). Experiments were performed on male and female mice (5 to 7 pups per litter). The experimental protocol was approved by the Tulane School of Medicine Animal Care Committee and the procedures followed were in accordance with institutional guidelines.

Male and female B2R+/+ and B2R−/− mice were placed on either NS 1% (TD#90229) or HS 5% (TD#92102) isocaloric diets (Harlan Laboratories) 1 day before mating, and the diets were continued for the duration of pregnancy. After delivery, the pups remained with their mothers on the respective diets. Four groups of mice were designated as follows: NS/B2R+/+ (N = 6), HS/B2R+/+ (N = 6), NS/ B2R−/− (N = 14), and HS/B2R−/− (N = 12). Additional B2R−/− mice received (1) NS during gestation and the diet was switched to HS on day 1 or 10 after birth (end of nephrogenesis in mice): these groups were designated NS→HS, groups 1 (N = 16) and 2 (N = 18), respectively; or (2) HS during gestation and switched to NS on day 10 after birth (HS→NS, N = 10). We used the term NS to indicate a lower salt content than HS (5-fold difference). The NS diet used in this study contained a slightly higher NaCl content than the standard laboratory chow (0.7%).

**BP Measurement**

Tail-cuff BP was measured in trained prewarmed conscious mice at 2, 3, and 4 months of age with a tail-cuff apparatus (IITC model 29 pulse amplifier, IITC Inc). Arterial pulsations detected by the tail-cuff photocell were displayed with output from the cuff pressure transducer on a digital storage oscilloscope (Tektronix model 2211, Tektronix, Inc) and measured with a built-in cursor function. Tail-cuff pressure values were derived from an average of 8 to 10 measurements per animal at each time point. The reproducibility of this method was tested periodically by repeating the BP measurements on the same animals on different days.

To measure intra-arterial mean arterial pressure (MAP), 4-month-old mice were anesthetized with a combination of thiobutabarbital (Inactin; 100 mg/kg) and ketamine (Ketaset; 10 mg/kg) IP and placed on a servo-controlled surgical table to maintain body temperature at 37°C. A tracheostomy was performed and a short polyethylene (PE-90) tube was inserted to maintain a patent airway. The right jugular vein was cannulated with a PE-10 catheter for infusion of fluids and drugs. The right carotid artery was cannulated with a short PE-10 catheter connected to PE-50 catheter and a polygraph (Grass Instrument Co) by a polygraph transducer (Gulton-Statham Transducers, Inc) for arterial pressure monitoring and blood sampling. The bladder was exposed and catheterized through a suprapubic incision with the use of a PE-50 tube for urine collections. During surgery, an isotonic saline solution that contained 6% albumin was infused at a rate of 5 μL/min. After surgical preparation, an isotonic saline solution that contained 1% albumin was infused. The animals were allowed to breathe air enriched with O2 by placing the exterior end of the tracheal cannula inside a small plastic chamber into which humidified 95% O2/5% CO2 is continuously passed. This procedure improves the cardiovascular stability of animals. After completion of the surgical procedure, a 20-minute equilibration period was allowed. Control MAP under anesthesia was monitored for a 20-minute period. Vasodepressor dose of BK (50 ng IV) followed by vasopressor dose of Ang II (50 ng IV) was administered as a bolus in 100 μL volume. The aim of BK injection was to confirm the functional absence of B2R in −/− mice. The aim of Ang II injection was to evaluate whether the absence of functional B2R leads to increased vasopressor sensitivity to exogenous Ang II. Drug testing occurred in 5-minute intervals. At the end of the experiment, the animals were euthanized with excess IV anesthesia.

![Figure 1](http://hyper.ahajournals.org/)

**Figure 1.** Body weights measured at 2, 3, and 4 months, and kidney and body weight index at 4 months in maturing B2R wild-type (+/+) and null (−/−) mice on gestational HS and NS salt diets. NS/B2R+/+, n = 6; HS/B2R+/+, n = 6; NS/B2R−/−, n = 14; and HS/B2R−/−, n = 12.

**Northern Blot Analysis**

RNA extraction, gel electrophoresis, RNA transfer to membrane, and hybridization procedures were performed as previously described.5,7 The Northern blots were hybridized with random-primed 32P-labeled cDNAs for rat renin or mouse AT1 that were stripped and reprobed with human GAPDH. Signals were detected by autoradiography and quantified by scanning densitometry (Ultronscan, Pharmacia LKB).

**Measurement of Plasma and Kidney Ang II**

Plasma and kidney Ang II levels were measured in anesthetized mice by a radioimmunoassay with rabbit anti–Ang II antibody (Jean Sealy, Cornell School of Medicine, New York),9 monoiodinated 125I-labeled Ang II (Amersham), and Ang II standard as previously described.10 Results are reported in femtomoles per gram kidney weight or mL of plasma. The sensitivity of the Ang II assay is <5 fmol/g. The percentage of specific binding for Ang II averaged 39%, with nonspecific binding of 2.7%.

**Data Analysis and Statistics**

Comparisons among the groups were performed by Student t test or ANOVA followed by Tukey test. P < 0.05 was considered statistically significant. All data are reported as mean ± SEM.

**Results**

**Effect of B2R Ablation on BP Under NS or HS Conditions**

Body weights and kidney weight-to-body weight ratios at 2, 3, and 4 months of age are not different among the experimental groups, which indicates that the differences in BP cannot be related to differences in body size (Figure 1). Systolic BP (SBP) measured by the tail-cuff method in NS/B2R−/− mice is significantly higher than NS/B2R+/+ at 2 months but not at 3 or 4 months of age, which indicates that lack of kinin activity from early development does not have a long-lasting effect on the maturation of BP under conditions of NS intake (Figure 2A). SBP in HS/B2R−/− is not different from that of NS/B2R+/+ mice at any time point, thus indicat-
ing that lifelong HS intake alone does not cause hypertension in wild-type mice. However, the combination of lifelong HS intake and B2R ablation (HS/B2R−/−) induces an early and progressive elevation of tail-cuff pressure at 2, 3, and 4 months of age (Figure 2A). To determine whether fetal exposure to HS is required for the development of hypertension in B2R null mice, we examined the effects of delaying the initiation of HS until day 1 (NS → HS, group 1) or 10 (NS → HS, group 2) after birth (Figure 2B). The results revealed that SBP in both B2R−/− NS → HS groups were comparably elevated and values were not significantly different from the HS/B2R−/− mice that received lifelong HS. In contrast, discontinuation of HS on day 10 after birth (HS → NS) was associated with a gradual decrease in SBP to normal values by 4 months of age (Figure 2).

Anesthetized MAP, which was measured at 4 months of age, is similar in NS/B2R+/+, HS/B2R+/+, and NS/B2R−/− mice (Figure 3A). In contrast, HS/B2R−/− mice have a significantly higher MAP compared with HS/B2R+/+, NS/B2R+/+, and NS/B2R−/− mice (91±3 versus 75±5, 70±2, and 74±2 mm Hg, respectively), which is consistent with the results of SBP obtained in the conscious state.

As shown in Figure 3B, BK (50 ng IV) caused a significant drop of MAP in B2R+/+ mice (−12±3 mm Hg) but did not alter MAP in B2R−/− mice, which confirmed the functional absence of B2R. Ang II (50 ng IV) increased MAP to the same extent (40±3 to 55±4 mm Hg) in all the groups, thus indicating that Ang II–induced vascular responses are preserved in B2R−/− mice (Figure 3C). Urinary sodium excretion, which was measured in anesthetized mice, was 3-fold higher in HS/B2R−/− than NS/B2R−/− mice (0.98±0.1 versus 0.32±0.05 μEq · min⁻¹ · g⁻¹, P<0.001, N=6 and 5, respectively), which reflected the higher salt intake.

**Effects of B2R Ablation and Lifelong HS on the Renin-Angiotensin System**

To evaluate whether increased expression of renin and/or AT1 receptors contributes to hypertension in B2R−/− mice on lifelong HS, we measured kidney renin and AT1 mRNA levels by Northern blot analysis (Figure 4A). The results showed that kidney renin mRNA levels were not different between NS/B2R−/− and HS/B2R−/− groups. However, renin mRNA levels were significantly lower in B2R mutants than wild-type controls irrespective of the salt intake (Figure 4A). Additionally, no significant differences were observed in renal AT1 mRNA levels between HS/B2R−/− and NS/B2R−/− mice (Figure 4B).

Plasma and kidney Ang II levels were measured at 5 months of age in 2 groups of B2R−/− mice that were switched from NS → HS or HS → NS on day 10 after birth (Figure 5). Plasma Ang II levels were not different between the 2 groups. In contrast, kidney Ang II levels were significantly suppressed in the HS → NS group versus the HS → NS group (306±38 versus 143±36 fmol/g, P<0.001).

**Discussion**

The major finding of this study was that disruption of the B2R gene in mice confers a susceptibility to early onset salt-sensitive hypertension. The timing of the initiation of HS...
A targeted disruption of the B2 R gene in which the open reading frame of the B2 R gene was replaced by a neomycin cassette. These mice lack all physiological responses to exogenous BK. With the use of adult B2 R<sup>+/−</sup> mice (weight 26 to 30 g) derived from an inbred strain on a 129Sv genetic background, Alfie et al<sup>2</sup> examined the effects of permanent loss of endogenous kinin activity on BP and renal hemodynamics. In B2 R<sup>−/−</sup> mice maintained on a HS diet (3% in food and 1% saline in drinking water) for 8 weeks, tail-cuff BP and anesthetized MAP were 15 and 35 mm Hg higher than in null mice on NS, respectively. In contrast, there was no difference in tail-cuff BP or MAP in control mice fed either a NS or HS diet. In addition, renal blood flow was reduced by 20% and renal vascular resistance was doubled in B2 R<sup>−/−</sup> on HS compared with controls. Subsequent studies by Madeddu et al<sup>3</sup> in adult B2 R null mice (weight 23 g) bred onto 129Sv genetic background reported that SBP and MAP were 15 mm Hg higher in B2 R<sup>−/−</sup> than B2 R<sup>+/+</sup> mice on NS. B2 R<sup>−/−</sup> mice showed exaggerated vasopressor responses to Ang II, and chronic administration of an AT<sub>1</sub> receptor antagonist reduced the BP of B2 R<sup>−/−</sup> to the levels of B2 R<sup>+/+</sup> mice.<sup>3</sup> However, renin and AT<sub>1</sub> gene expression were not different between the groups. In addition, chronic salt loading (0.84 mmol/g chow for 15 days) increased tail-cuff BP of B2 R<sup>−/−</sup> mice by 35 mm Hg, whereas it was ineffective in B2 R<sup>+/+</sup>. Additional studies by the same group of investigators found that B2 R null mice are highly susceptible to mineralocorticoid-induced hypertension.<sup>4</sup> Together, these studies indicate that kinins play an important role in the prevention of salt-sensitive hypertension and that this may be achieved by maintaining renal blood flow under conditions of HS intake.

To our knowledge, the BP phenotype in B2 R mutants of younger age groups has not been reported. Likewise, the effect of HS intake on the maturation of BP in B2 R null mice is unknown. Madeddu et al<sup>4</sup> administered the B2 R antagonist icatibant (formerly known as Hoe 140) to pregnant Wistar rats and subsequently to their offspring maintained on NS diet. At 9 weeks of age, rats that were administered icatibant during prenatal and postnatal phases of life showed a modest BP elevation (≈8 mm Hg) versus vehicle-treated controls. In the present study, we found that permanent inactivation of B2 R does not cause adult hypertension nor does it alter the maturation of BP under conditions of NS intake. We observed a small but statistically significant rise in tail-cuff SBP of NS/B2 R<sup>−/−</sup> compared with NS/B2 R<sup>+/+</sup> at 2 months of age. However, this difference in BP was not sustained and could no longer be observed at 3 and 4 months of age, which indicated that the B2 R null mutation did not have a long-lasting effect on the maturation of BP. In this regard, our findings are in agreement with those of Alfie et al<sup>2</sup> who found that the BP of adult B2 R null mice maintained on normal sodium intake is not different from wild-type controls. A technical limitation of investigations with mice is that measurement of BP is not feasible in young animals (<1 month of age). Therefore, the earlier changes in BP during the evolution of hypertension in HS/B2 R<sup>−/−</sup> mice were not determined. The BL6 strain used in this study is known to have a reduced BP when compared with other mouse strains, which suggests that protective genes might overcome the lack of B2 R signaling and mask hypertension during early development.
The development of salt-sensitive hypertension in young B2R null mice suggests that the kallikrein-kinin system plays an important role in the hemodynamic adaptation to postnatal life under conditions of HS intake. We have demonstrated previously that the renal and cardiovascular systems express local, developmentally regulated, kinin-generating systems. Vascular and renal kallikrein-like activity increases 10- to 20-fold from birth to adulthood in the rat. In addition, B2R and kininogen gene expression in the kidney, aorta, and heart is 10- to 30-fold higher in developing animals versus adult animals. Accordingly, we speculate that lack of kinin’s natriuretic and vasodilator activities contribute to the pathogenesis of the salt-sensitive hypertension in B2R-deficient mice. In addition, we tested whether the renin-angiotensin system contributes to the hypertension in B2R null mice on lifelong HS. No significant differences were detected in renal renin or AT1 receptor mRNA levels in the mutant animals on HS, and kidney Ang II levels were appropriately suppressed in mutant mice that received HS from early postnatal life. We also found that the BP responses to intravenous Ang II were similar in B2R null mutants and wild-type mice. However, the latter data should be interpreted with caution because of the small number of animals in the NS/B2R−/− group, the possible influence of anesthesia on Ang II activity, and that a full dose-response curve was not performed. As suggested previously, unopposed activity of Ang II in the absence of kinin activity may contribute to hypertension in B2R null mice on HS. The role of the renin-angiotensin system in mediating salt sensitivity in B2R mutants deserves additional study.

Barker has proposed that adult arterial hypertension has its roots during early development. Developmental insults or stressors may alter the maturation of blood pressure and/or predispose to salt sensitivity. For example, intrauterine protein undernutrition is associated with later development of hypertension in the offspring. In the present study, we found that exposure to a HS environment only during fetal life is not sufficient in itself to cause long-term hypertension in B2R null mice. Altered renal development is less likely to be a factor in the development of hypertension because delaying salt loading until the end of nephrogenesis in mice (day 10) was associated with the same magnitude of hypertension as in null mice on lifelong HS.

On the basis of these and other results, we conclude that the kallikrein-kinin system protects both developing and mature animals from salt-sensitive hypertension. The B2R-deficient mouse is a monogenic model that can be used to study the developmental aspects of salt-sensitive hypertension.

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References

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