Angiotensin Type 2 Receptor Mediates Valsartan-Induced Hypotension in Conscious Rats

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Abstract—Inhibition of the renin-angiotensin system is associated with vasodilation and reduction in blood pressure. We hypothesized that angiotensin type 1 (AT_1) receptor (AT_1R) blockade is associated with increased production of renal nitric oxide (NO) mediated by release of bradykinin (BK). By use of a microdialysis technique, changes in renal interstitial fluid (RIF) BK, NO end products nitrite and nitrate (NOX), and cGMP were monitored in response to intravenous infusion of the AT_1R blocker valsartan (10 mg/kg), the angiotensin type 2 (AT_2) receptor (AT_2R) blocker PD123319 (50 µg · kg^{-1} · min^{-1}), and the BK B_2 receptor blocker icatibant (10 µg · kg^{-1} · min^{-1}) in conscious rats (n=10) during low sodium intake. RIF BK, NOX, and cGMP significantly increased during valsartan treatment, whereas AT_1R blockade caused a significant decrease in these autacoids. During icatibant infusion, RIF NOX and cGMP decreased by 64% and 40%, respectively, whereas BK increased. Combined administration of valsartan and icatibant, of valsartan and PD123319, or of valsartan, PD123319, and icatibant prevented the increase in RIF cGMP and NOX in response to valsartan alone. These data demonstrate that AT_1R blockade with valsartan is associated with release of renal BK, which in turn mediates NO production. The results suggest that increased angiotensin II, in response to sodium restriction and valsartan infusion, stimulates AT_1R, which mediates a BK and NO cascade. (Hypertension. 2000;35:1074-1077.)

Key Words: receptors, angiotensin II ▪ bradykinin ▪ nitric oxide ▪ cyclic GMP ▪ valsartan

All components of the renin-angiotensin system are present within the kidney.1 Angiotensin II (Ang II) is the most active component of this system. The tissue production of Ang II in proximity to its receptors on the target cells constitutes a paracrine function for this hormone. Ang II plays a major role in regulating body fluid and electrolyte homeostasis and blood pressure. The majority of the effects of Ang II are mediated by stimulation of the angiotensin type-1 (AT_1) receptor. Inhibition of the AT_1 receptor results in increased renin secretion,2 resulting in a subsequent increase in Ang II production, a decrease in blood pressure, diuresis, and natriuresis.3 The interaction between Ang II and other vasoactive peptides contributes to the preservation of these functions. One of the important peptides that is produced in the kidney is bradykinin (BK). Mainly by inducing diuresis and natriuresis, BK has been shown to regulate renal functions4 in a manner opposite that induced by Ang II.

In the present study, we evaluated the effect of AT_1 receptor blockade on renal production of BK and its mediators, nitric oxide (NO) and cGMP. We hypothesized that AT_1 receptor blockade is associated with increased production of renal interstitial fluid (RIF) BK. We used a novel microdialysis technique to monitor changes in RIF BK, the NO end products nitrite and nitrate (NOX), and cGMP during AT_1, angiotensin type-2 (AT_2), or BK B_2 receptor blockade.

Methods

Renal Microdialysis Technique
To determine the levels of renal RIF BK, NOX, and cGMP, we constructed a microdialysis probe as described previously.5,6 The dialysis membrane was obtained from Hospal. In vitro recoveries of cold and radiolabeled BK or cGMP by the dialysis probes were 55% and 78%, respectively, for BK7 and 59% and 70%, respectively, for cGMP.5,7 Negligible amounts of these peptides stick to the polyethylene tubes of the dialysis probes, as demonstrated by recovery of >99.8% of these substances in the perfusate.5,7

Animal Preparation
The experiments, which were approved by the University of Virginia Animal Research Committee, were conducted in 4-week-old Sprague-Dawley rats (Harlan Teklad, Madison, Wis). The rats were placed under general anesthesia with ketamine (80 mg/kg IM) and xylazine (8 mg/kg IM), and the right and left kidneys were exposed by a midline abdominal incision. To obtain a vascular access, a heparinized polyethylene tube was inserted into the right jugular vein. This tube was flushed daily with 10% heparin in 5% dextrose in water and capped with a small piece of copper wire. The exterior end of this tube was secured in place by suturing it to the skin at the exit site and was covered with a stainless-steel spring (to prevent the rats from damaging it). Rats were housed under controlled conditions (temperature 21±1°C, humidity 60±10%, and light 8 to 20 hours). Experiments were started at the same time each day (8 AM) to prevent any diurnal variation of the measured plasma renin activity (PRA) or systolic blood pressure (SBP). For in vivo determinations of RIF BK,
NOX, and cGMP, the microdialysis probes were placed in the cortex of both kidneys while the rats were under general anesthesia. All RIF measurements were made on experimental day 7 after implanting the probes. For collection of RIF, the inflow tube of the dialysis probe was connected to a gas-tight syringe filled with lactated Ringer’s solution and perfused at 3 μL/min. The effluent was collected from the outflow tube of the dialysis probe for 30-minute sample periods.

**Analytical Methods**

Urinary sodium concentrations were measured by using a NOVA Biomedical analyzer. PRA was measured by radioimmunoassay. SBP was measured at 30-minute intervals in the tail, and recorded values were averaged for each study period. RIF BK levels were measured by ELISA. The sensitivity is 2.5 ng/mL and is 100% specific for BK. It does not react with any other peptides. RIF NOX and cGMP levels in dialysate samples were measured by using an enzyme immunoassay kit. The sensitivity is 2.5 μmol/L and 0.11 μmol/L for NOX and cGMP, respectively, and the specificity is 100% for both. The intra-assay and interassay cross-reactivities with other cyclic nucleotides were <0.01%.

**Effects of AT₁, AT₂, and BK B₂ Receptor Blockade Individually or Combined**

Animals (n=10) were placed in metabolic cages. Each animal served as its own control, and different treatments were carried out in the same group of animals. One day before surgery, while rats were consuming a normal sodium diet (0.28% NaCl), baseline body weight, PRA, and SBP were measured, and a 24-hour urine sample was collected for calculation of urinary volume and sodium excretion (UNa V). After surgery, the animals served as its own control, and different treatments were carried out in the same group of animals. One day before surgery, while rats were consuming a normal sodium diet (0.28% NaCl), baseline body weight, PRA, and SBP were measured, and a 24-hour urine sample was collected for calculation of urinary volume and sodium excretion (UNa V). After surgery, the animals were placed on a low sodium diet (0.04% NaCl) for 10 days (experimental days 1 to 6). On experimental day 6, body weight, PRA, SBP, and a 24-hour urine collection were obtained. On experimental days 7 to 10, SBP, RIF BK, NOX, and cGMP were monitored during right jugular vein administration (20 μL/min for 30 minutes), in random order, of 5% dextrose in water vehicle (20 μL/min); valsartan, a nonpeptide Ang II antagonist at the AT₁ receptor (10 mg/kg); PD123319 (PD), an AT₂ receptor antagonist (50 μg · kg⁻¹ · min⁻¹); icatibant, a potent and specific BK B₂ receptor antagonist (10 μg · kg⁻¹ · min⁻¹); or combined administration of these treatments.

**Statistical Analysis**

Comparisons among pharmacological agents and controls were examined by ANOVA, including a repeated measure term, by use of the general linear models procedure of the Statistical Analysis System. Multiple comparisons of individual pairs of effect means were conducted by using the least squares method of pooled variance. Data are expressed as mean±SE. Statistical significance was identified at P<0.05.

**Results**

**Changes in PRA, 24-Hour Urinary Volume, UNa V, and Blood Pressure Responses to Low Sodium Intake**

PRA during normal sodium intake was 1.6±1 ng · mL⁻¹ · h⁻¹ and increased to 13.8±3.1 ng · mL⁻¹ · h⁻¹ (P<0.0001) by day 6 of low sodium intake. In contrast, 24-hour urinary volume and UNa V decreased significantly from 22.3±2.0 mL/d and 1150±30 μmol/d to 3.1±0.8 mL/d and 173±8 μmol/d (P<0.0001), respectively, in response to low sodium intake. SBP was 118±4 mm Hg during normal sodium intake and did not change in response to low sodium intake.

**Figure 1.** RIF BK, NOX, and cGMP increased in response to low sodium intake. Values are mean±SE (n=10). *P<0.0001 vs normal.

RIF BK, NOX, and cGMP Response to Low Sodium Intake

During normal sodium intake, RIF BK, NOX, and cGMP recoveries were 53±12 pg/min, 0.1±0.02 μmol/min, and 0.12±0.02 μmol/min, respectively. By day 6 of low sodium intake, there were significant increases (Figure 1) in recovery of RIF BK, NOX, and cGMP to 360±20 pg/min, 0.28±0.01 μmol/min, and 0.9±0.01 μmol/min (P<0.0001), respectively.

**Changes in SBP in Response to AT₁ and BK B₂ Receptor Blockade During Low Sodium Intake**

There were no changes in SBP in response to vehicle (5% dextrose) administration. Administration of valsartan (the AT₁ receptor blocker) caused a significant decrease in SBP (Figure 2) from 119±3 to 110±2 mm Hg (P<0.05). In contrast, icatibant (the BK B₂ receptor antagonist) increased SBP from 118±2 to 124±3 mm Hg (P<0.05). There was no change in SBP during PD administration. Combined administration of valsartan and icatibant, of valsartan and PD, or of valsartan, PD, and icatibant completely prevented (to similar levels) the decrease in SBP that was observed with valsartan alone (Figure 2).

**Changes in RIF BK, NOX, and cGMP in Response to AT₁ and BK B₂ Receptor Blockade**

There were no changes in RIF BK, NOX, and cGMP during time-control vehicle administration. RIF BK, NOX, and
cGMP increased \((P<0.001)\) during valsartan treatment (Figure 3). Similarly, RIF BK increased during icatibant treatment or combined valsartan and icatibant treatment \((P<0.001)\). However, in contrast to valsartan, icatibant decreased RIF NOX and cGMP by 64\% \((P<0.0001)\) and 40\% \((P<0.001)\), respectively (Figure 3). PD alone or combined with valsartan decreased RIF BK, NOX, and cGMP to those levels observed during normal sodium intake \((P<0.0001)\). Combined administration of valsartan and icatibant or of valsartan, PD, and icatibant prevented the increase in RIF cGMP and NOX. Similarly, combined treatment with valsartan, PD, and icatibant reduced RIF BK \((P<0.0001)\) to levels similar to those observed during treatment with PD alone or PD and valsartan.

**Discussion**

The present study demonstrates that AT\(_1\) receptor blockade is associated with an increase in renal tissue levels of BK, NO, and cGMP. Our results suggest that the vasodilator response to AT\(_1\) receptor blockade is mediated, at least in part, by the concomitant increase in tissue BK, which is stimulated via the AT\(_2\) receptor. Further vasodilator action is obtained via BK stimulation of NO in this pathway. The observed levels of RIF BK, NOX, and cGMP are not due to changes in renal hemodynamics induced by the use of various drugs, according to our previous studies,\(^6,7\) which have demonstrated the following: (1) Losartan, a renal vasodilator agent, and Ang II, a renal vasoconstrictor hormone, increase RIF BK. (2) Ang II increases RIF cGMP, whereas \(N^\text{G}-\text{nitro-L-arginine methyl ester}\), an NO synthase inhibitor and a renal vasoconstrictor, decreases RIF cGMP. These data demonstrate that changes in recovered RIF substances are specific to each treatment regardless of the general effects of treatments on renal hemodynamics.

Sodium depletion is associated with an increase in RIF Ang II and BK concentrations.\(^10,11\) It is likely that the increase in RIF BK is secondary to the increase in RIF Ang II levels. This thesis is strengthened by the observations that exogenous Ang II increases RIF BK during normal sodium intake.\(^7\) BK increases NO production,\(^12\) which activates soluble guanylyl cyclase, releasing cGMP into the RIF. This response is mediated at the BK\(_B_2\) receptor, because it can be blocked by icatibant, a specific BK\(_B_2\) receptor antagonist. In the present and previous studies,\(^6,7\) the RIF BK, NOX, and cGMP levels during time-control studies were stable and did not change from day to day. However, we should caution that these studies were not designed to determine the absolute levels of recovered substances.

The AT\(_1\) receptor blocker valsartan and the AT\(_2\) receptor blocker PD were used to evaluate whether the AT\(_1\) or AT\(_2\) receptor was involved in the process of increasing renal BK levels. RIF BK increased during sodium depletion. RIF BK levels further increased during valsartan treatment and decreased during PD administration. These responses suggest that the AT\(_2\) receptor is responsible for the increase in RIF BK and that during sodium depletion, BK formation is tonically stimulated by Ang II at the AT\(_2\) receptor. In the presence of AT\(_1\) receptor blockade at the level of renal juxtaglomerular cells, increased circulating Ang II\(^13\) enhances BK production through stimulation of the unblocked AT\(_2\) receptor.

Our previous studies\(^5\) demonstrated that under conditions of increased Ang II levels, AT\(_1\) receptor stimulation is associated with an increase in RIF cGMP, the production of which is mediated by AT\(_2\) receptor stimulation of NO.\(^6\) In the

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**Figure 2.** Effect of Ang II and BK receptor blockade on systolic blood pressure (BP). Valsartan (V) significantly \((P<0.05\) vs vehicle) reduced BP, whereas icatibant (I) increased BP. Combined blockade of the AT\(_1\) and BK receptors \((V+I)\) totally prevented the decrease in BP induced by valsartan. Blockade of the AT\(_2\) receptor with PD alone did not affect BP, but PD blocked the BP reduction in response to valsartan. TC indicates time control (vehicle administration). The solid bars represent data obtained in the group treated with 5\% dextrose in water (vehicle), whereas the open bars are the results for the treated groups. Values are mean±SE \((n=10)\).

**Figure 3.** Changes in RIF BK, NOX, and cGMP. Valsartan (V) increased BK, NOX, and cGMP \((P<0.001\) vs vehicle), whereas icatibant (I) increased BK but decreased NOX and cGMP \((P<0.001\) vs vehicle). AT\(_2\) receptor blocker (PD) alone or combined with valsartan decreased BK, NOX, and cGMP to levels observed during normal sodium intake \((**P<0.0001\) vs vehicle). Values are mean±SE \((n=10)\). Solid and open bars are similar to those in Figure 2.
present study, AT2 receptor stimulation of BK production offers clarification of the mechanisms leading to NO release. Whether the changes in RIF BK stimulated by Ang II contribute to the regulation of renal hemodynamic and excretory function awaits further investigation.

In the present study, it was technically impossible to measure UNO or renal blood flow in conscious rats during the different experimental manipulations. However, changes in blood pressure suggest that the hypotensive effect of AT2 receptor blockade is at least partially mediated by BK release through stimulation of the AT2 receptor. In addition, present knowledge suggests that the renal kallikrein-kinin system is involved in the regulation of sodium and water excretion and may participate in blood pressure control.14 BK is known to release NO from vascular endothelial, renal interstitial, or epithelial cells.12 At least a portion of the renal effects of kinins appears to be mediated by NO, because inhibition of NO synthesis reduces the renal vasodilator response to BK.15

Previously, we have shown that AT2 receptor stimulation mediates NO release.6 Furthermore, acute administration of icatibant reduced NO to levels similar to those observed during AT2 receptor blockade.7 The present study clearly indicates that partial renal NO production is mediated by the AT2 receptor via increased production of BK. AT2 receptor blockade shifts Ang II toward stimulation of the unblocked AT2 receptor to release BK. Consequently, AT2 receptor blockade reduces renal BK and NO.

The mechanism whereby AT2 receptor stimulation releases BK is unclear. However, our data suggest that the increase in kinin production under such conditions counters the vasoconstrictor mechanisms activated in response to increased Ang II. The observed increase in blood pressure during icatibant treatment confirms the role of bradykinin in blood pressure regulation.16 In the present study, BK B2 receptor blockade completely prevented the blood pressure–reducing effects of valsartan. The specific contribution of AT2 receptor–mediated BK to the hypotensive effects of valsartan is supported by the fact that combined valsartan and PD prevented the valsartan hypotensive response to the same magnitude produced by combined valsartan and icatibant. Combined administration of valsartan, PD, and icatibant did not have any potentiation or synergistic effects on blood pressure or RIF BK; this finding suggests that PD and icatibant are influencing the same pathway. These data support our previous finding that BK partially mediates the hypotensive effects of AT2 receptor blockade.7 Additionally, our results are supported by a recent finding that in mice overexpressing the AT2 receptor, the AT2 receptor–mediated vasodilation was caused by the effect of BK, leading to activation of endothelial NO/cGMP.17 Combined administration of valsartan and PD caused a greater decrease in renal tissue levels of NO and cGMP than did combined treatment with valsartan and icatibant. These results suggest that the AT2 receptor can directly stimulate NO in addition to its effect through kinin release. Thus, AT2 receptor–mediated BK release and the subsequent generation of NO via BK B2 receptor stimulation directly contribute to the blood pressure–lowering effects of valsartan. Because RIF cGMP levels parallel changes of RIF NOX during AT1, AT2, and BK B2 receptor blockade, it is likely that cGMP may be important in vasodilator signal transduction.

In conclusion, AT2 receptor blockade with valsartan is associated with hypotension and increased production of renal BK, NO, and cGMP. AT2 receptor blockade with PD inhibited both the hypotension and renal autacoid responses to valsartan, confirming that during AT1 receptor blockade, there is concomitant stimulation of the AT2 receptor. The increase in renal NO and cGMP during AT2 receptor stimulation is mediated by BK because BK B2 receptor blockade inhibited this response.

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References

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