Influence of Eicosanoids on Renal Function of DOCA-Salt Hypertensive Rats

RICHARD J. ROMAN, MARY L. KALDUNSKI, DAVID L. MATTSON, MAHESH MISTRY, AND ALBERTO NASJLETTI

SUMMARY The present study examined the contribution of changes in the synthesis or degradation (or both) of renal eicosanoids to the alterations in renal hemodynamics observed in deoxycorticosterone acetate (DOCA)-salt hypertensive rats. Renal blood flow and glomerular filtration rate were markedly reduced in DOCA-salt hypertensive rats compared with values observed in control rats given water or saline to drink. The abnormalities in renal hemodynamics in the hypertensive rats were associated with an increase in the excretion of thromboxane B2, an increase in the release of thromboxane B2 from renal cortical tissue slices, and a diminished release of prostaglandin E2 (PGE2) from renal medullary tissue. Additionally, the urinary excretion of PGE2 and 6-keto-prostaglandin F1α (6-keto-PGF1α) and the release of 6-keto-PGF1α from renal cortical and medullary tissue were elevated in rats with DOCA-salt hypertension. Since the excretion of PGE2 and 6-keto-PGF1α and the release of 6-keto-PGF1α by medullary tissue were also elevated in normotensive rats given 1% NaCl solution to drink, these latter changes probably were related to an elevation of sodium intake rather than to the development of hypertension. The functional significance of the alterations in the renal production of thromboxane in DOCA-salt hypertensive rats was evaluated by comparing the effects of a thromboxane synthesis inhibitor and a receptor antagonist on renal function in normotensive and DOCA-salt hypertensive rats. The administration of the thromboxane synthetase inhibitor furegrelate and the thromboxane receptor blocker SQ 29548 had no effect on renal hemodynamics in either group. These results suggest that the elevated renal production of thromboxane A2 is not responsible for the reduction of renal blood flow and glomerular filtration rate in rats with established DOCA-salt hypertension. (Hypertension 12: 287–294, 1988)

KEY WORDS • prostaglandins • thromboxane • renal function • furegrelate • medofenamate • hemodynamics

RECENT studies by Sugai et al.1 and Zambraski and Ciccone2 demonstrated that the kidneys of deoxycorticosterone acetate (DOCA)-salt hypertensive animals require a higher perfusion pressure to excrete equivalent amounts of sodium and water to amounts from control animals. Accordingly, in DOCA-salt hypertension, the chronic renal function curve depicting the relationship between renal perfusion pressure and the urinary excretion of sodium and water is shifted to the right.3 These shifts in the pressure-diuresis and pressure-natriuresis relationships could be caused by renal vasoconstriction or by an increase in tubular reabsorption of water and electrolytes.3 In animals with DOCA-salt hypertension, renal vasoconstriction and augmented tubular reabsorption of sodium and water may be related to elevations in renal sympathetic nerve activity4 or vasopressin levels5 or disturbances in the production of eicosanoids by the kidney.5

Although the urinary excretion rate of prostaglandin E2 (PGE2) is increased in animals treated with mineralocorticoid hormones, the synthesis of PGE2 is depressed in DOCA-salt hypertensive rats.8 A defect in the renal production of PGE2 may play a role in the changes in renal function in these animals because PGE2 is a renal vasodilator that promotes the excretion of salt and water.8 Renal vasoconstriction also may be the manifestation of enhanced production of thromboxane A2 (TXA2) by the kidney.9 In this regard, increased renal TXA2 synthesis is known to contribute to the elevated renal vascular resistance observed during potassium
depletion, a condition that accompanies the development of DOCA-salt hypertension.

The present study examined whether alterations in the renal production of eicosanoids contribute to the changes in renal hemodynamics and sodium and water excretion that accompany the development of DOCA-salt hypertension. First, we determined whether the development of DOCA-salt hypertension in rats was associated with changes in urinary excretion of PGE₂, 6-keto-prostaglandin F₆₇₆ (6-keto-PGF₂α) and thromboxane B₂ (TXB₂) or in the production of these eicosanoids by renal cortical or medullary tissue. Second, we investigated the effects of an inhibitor of thromboxane synthetase, furegrelate (U-63557A), and a TXA₂ receptor antagonist, SQ 29548, on renal hemodynamics and excretory function in DOCA-salt hypertensive rats and normotensive controls. Finally, we evaluated the contribution of vasodilator prostaglandins in maintaining renal function in DOCA-salt hypertensive rats by studying the effects of meclofenamate in rats pretreated with furegrelate or SQ 29548.

Materials and Methods

Experiments were performed on 71 male Sprague-Dawley rats purchased from Harlan Laboratories (Madison, WI, USA). The rats weighed approximately 250 g at the beginning of the study and were housed in stainless steel cages. Rat chow containing 1% NaCl by weight was provided ad libitum throughout the study. All surgical procedures were conducted with strict adherence to published guidelines, and the protocols in this study received prior approval by the animal care committees of the Medical College of Wisconsin and the University of Tennessee.

The rats were anesthetized with ketamine (100 mg/kg) and acepromazine (2 mg/kg) or pentobarbital (60 mg/kg), and the right kidney was surgically removed. The animals were given 40,000 units of Penstrep (penicillin G, streptomycin) postoperatively to prevent infection. One week later, the rats were assigned to one of three groups. Group 1 served as the normal salt diet control group. These rats were given tap water to drink and received a 0.3-ml intramuscular injection of 0.9% NaCl once a week throughout the study. Group 2 served as the high salt diet control group. These rats were given 1% NaCl solution to drink throughout the study and received weekly injections of 0.9% NaCl. Group 3 consisted of the DOCA-salt hypertensive rats. These rats received an intramuscular injection of deoxycorticosterone pivalate (25 mg/kg) at weekly intervals and were given a 1% NaCl solution to drink. After 5 weeks of treatment, the rats were studied in one of two protocols.

Systolic blood pressure was measured at weekly intervals by tail sphygmography using an electrohgomomanometer (Narco Bio-Systems, Houston, TX). The reported values are the average of four determinations made during the fifth week of treatment with DOCA or vehicle.

Protocol 1: Biochemical Studies

Biochemical studies were performed to assess the effects of a chronically elevated sodium intake and DOCA-salt hypertension on the urinary excretion of PGE₂, 6-keto-PGF₂α (a prostacyclin metabolite), and TXB₂ (a TXA₂ metabolite), as well as on the in vitro release of these eicosanoids by renal cortical and medullary tissue. In the fifth week of the experiment, six rats from each group were placed individually in metabolic cages and a 24-hour urine sample was collected from each rat in a container kept on dry ice for measurement of the urinary excretion of eicosanoids. Urinary concentrations of PGE₂, 6-keto-PGF₂α, and TXB₂ were determined by radioimmunoassay after extraction of the samples using methods previously described. The urinary excretion of each eicosanoid was calculated as the product of the 24-hour urine volume times the urinary concentration and was expressed as nanograms excreted per 24 hours.

After the excretion of eicosanoids was measured, the rats were anesthetized by an intraperitoneal injection of pentobarbital, the kidneys were removed, and the rates of release of eicosanoids from renal cortical and medullary tissue were determined. The kidneys were first flushed with 50 to 60 ml of Krebs-Ringer solution containing 118 mM NaCl, 4.7 mM KCl, 2.5 mM CaCl₂, 1.2 mM KH₂PO₄, 1.17 mM MgSO₄, 8.4 mM dextrose, and 25 mM NaHCO₃. The kidneys were hemisected, and the inner medulla was removed from the cortex. The inner medulla and cortex were sliced into 0.5-mm sections using a Stadie-Riggs microtome (Thomas Scientific, Philadelphia, PA, USA). The tissue slices were placed in flasks containing 2 ml of Krebs solution and arachidonic acid (16.5 μM; Nu-Check, Elysisan, MN, USA). The tissue slices were incubated for 15 minutes with agitation (100 cycles/min) at 37 °C under an atmosphere of 5% CO₂ and 95% O₂. The selection of a 15-minute incubation period was based on preliminary experiments indicating that the rate of eicosanoid release was linear for the first 20 minutes of an incubation. At the end of the incubation period, the tissue slices were removed from the flasks and dried in an oven. Eicosanoids released into the incubation media were measured by radioimmunoassay as described previously. The results are presented as nanograms of immunoreactive eicosanoids released during the 15-minute incubation period per milligram dry weight of tissue.

Protocol 2: Renal Clearance Studies

Clearance experiments were performed on the normotensive control rats given tap water to drink (Group 1), the control rats given a 1% NaCl solution to drink to elevate sodium intake (Group 2), and the rats with DOCA-salt hypertension (Group 3). The rats were anesthetized with an intraperitoneal injec-
tion of Inactin (100 mg/kg) and were placed on a warming table to maintain body temperature at 37°C. Cannulas were placed in the jugular vein for infusions and in the femoral artery for measurement of mean arterial pressure. The ureter of the left kidney was cannulated for urine collections, and a 2-mm flowprobe was placed on the left renal artery for measurement of renal blood flow (RBF) using an electromagnetic flowmeter (Model 501, Carolina Instruments, King, NC, USA). During the experiment, the rats were infused with a 0.9% NaCl solution at a rate of 100 μl/min. [3H]Inulin (2 μCi/ml) was included in the infusion solution to allow for the measurement of glomerular filtration rate (GFR).

After the surgical procedure and a 1-hour equilibration period, urine and plasma samples were collected during two 20-minute periods. The rats (Group 1, n = 6; Group 2, n = 7; Group 3, n = 6) then received an intravenous injection of furegrelate (2 mg/kg) to inhibit thromboxane synthesis. After a 30-minute equilibration period, urine and plasma samples were collected during two 20-minute experimental periods. The rats were then given an intravenous injection of meclofenamate (2 mg/kg) to inhibit cyclooxygenase. After a 30-minute equilibration period, urine and plasma samples were again collected during two additional 20-minute experimental periods.

In preliminary experiments (n = 13) we found that TXB$_2$ levels in blood samples allowed to clot for 30 minutes fell significantly from 26 ± 6 to 7 ± 3 ng/ml after administration of a 2 mg/kg dose of furegrelate. In previous experiments, we demonstrated that a 2 mg/kg dose of meclofenamate effectively inhibits renal cyclooxygenase activity and reduces urinary PGE$_2$ excretion in surgically prepared rats. Moreover, we performed experiments on six control rats maintained on a high salt diet (Group 2) and on six DOCA-salt hypertensive rats (Group 3) to determine the effects of furegrelate on the urinary excretion of TXB$_2$. These rats were surgically prepared as described except that [3H]inulin was not infused. Urine samples were collected for measurement of TXB$_2$ excretion during a control period and after the administration of furegrelate and meclofenamate.

In other experiments, we examined the effects of a thromboxane receptor antagonist on the renal function of seven control rats (Group 2) and seven rats with DOCA-salt hypertension (Group 3). The experimental protocol was identical to that just described except that, after the control period, the rats received an intravenous infusion of the TXA$_2$ receptor antagonist SQ 29548 (2 μg/kg/min), instead of furegrelate. We have previously reported that an SQ 29458 infusion of 2 μg/kg/min blocked the pressor effect of the thromboxane receptor agonist U-46619 in rats.

**Analytical Techniques**

[3H]Inulin concentrations of urine and plasma samples were measured using a liquid scintillation spectrophotometer. GFR was calculated as the urine-plasma inulin concentration ratio times urine flow and was factored per gram kidney weight. The sodium and potassium concentrations of all samples were determined using flame photometry. The osmolality of the samples was measured using a freezing point osmometer (Precision Instruments, Sudbury, MA, USA).

**Statistics**

Mean values ± 1 SE are presented. The significance of differences in mean values, measured during several periods within a group, was evaluated using an analysis of variance for repeated measures followed by a Bonferroni test. Between-group comparisons were evaluated using a one-way analysis of variance and the Bonferroni test. A p value below 0.05 using a two-tailed test was considered significant.

**Results**

Systolic arterial pressure averaged 138 ± 3 and 141 ± 4 mm Hg, respectively, in the control rats given water and 1% NaCl solution to drink for 5 weeks. Systolic pressure was significantly elevated to 212 ± 5 mm Hg in the DOCA-salt hypertensive rats. The effects of these treatments on the urinary excretion of eicosanoids are summarized in Figure 1. Urinary excretion rates of TXB$_2$, 6-keto-PGF$_{1α}$, and PGE$_2$ were all significantly elevated in the DOCA-salt hypertensive rats relative to the values in control rats given tap water to drink (Group 1). Urinary TXB$_2$ excretion in the DOCA-salt hypertensive rats was also higher than that observed in control rats given saline to drink (Group 2). In contrast, the urinary excretion rates of PGE$_2$ and 6-keto-PGF$_{1α}$ were not different in the DOCA-salt hypertensive rats and the control rats given 1% NaCl solution to drink.

Figure 2 illustrates the in vitro release of eicosanoids from renal cortical and medullary tissue slices. Relative to the eicosanoid release by renal tissue of the control rats given water or 1% NaCl solution to drink, DOCA-salt hypertensive rats exhibited increased release of TXB$_2$ and 6-keto-PGF$_{1α}$ from slices of renal cortex and a diminished release of PGE$_2$ from renal medullary slices. The release of 6-keto-PGF$_{1α}$ by the renal medulla of DOCA-salt hypertensive rats exceeded the values observed in control rats given water to drink, but it was not different from the values observed in the control rats given 1% NaCl solution to drink.

The effects of furegrelate and meclofenamate on renal hemodynamics and sodium and water excretion are depicted in Figures 3 and 4. In the control rats given water to drink, furegrelate had no effect on urine flow, sodium excretion, RBF, or GFR. Subsequent administration of meclofenamate to block renal cyclooxygenase activity also did not alter renal hemodynamics or the excretion of sodium and water in these animals. In contrast, furegrelate altered renal function in the control rats given 1.0% NaCl solution to drink (Group 2). Urine flow declined...
FIGURE 1. Twenty-four-hour urinary excretion of thromboxane B<sub>2</sub>, 6-keto-PGF<sub>1α</sub>, and PGE<sub>2</sub> in DOCA-salt hypertensive rats and in uninephrectomized control rats given tap water or 1% NaCl solution to drink before the experiment. Mean values ± 1 SE from six rats per group are presented.

by 38% (see Figure 3), and urine osmolality increased significantly from 484 ± 39 to 674 ± 78 mosm/kg · H<sub>2</sub>O after administration of furegrelate. Subsequent administration of meclofenamate had no additional effect on urine flow or urinary osmolality in these animals.

Sodium excretion was not significantly altered after administration of furegrelate in the control rats drinking saline solution, but it did fall by 38% after these rats received meclofenamate. Furegrelate produced a small but nonsignificant rise in RBF in the control rats drinking 1% NaCl solution. GFR was unaltered by furegrelate. Administration of meclofenamate to this group of control rats had no effect on renal hemodynamics.

In DOCA-salt hypertensive rats, mean blood pressure was elevated 50 mm Hg in comparison to pressures measured in either control group (see Figure 4). Basal urine flow and sodium excretion, however, were not different in the three groups of rats. RBF and GFR were reduced by 50% in the DOCA-salt hypertensive rats in comparison to the values measured in control rats drinking water or saline (see Figure 4). Meclofenamate did not affect renal hemodynamics in DOCA-salt hypertensive rats.
Figure 4. Effect of furegrelate and meclofenamate (meclo) on renal blood flow (RBF), glomerular filtration rate (GFR), and mean arterial pressure in DOCA-salt hypertensive rats and control rats drinking water or 1% NaCl solution. Asterisk indicates significant difference (p < 0.05) from respective control value. There was no significant difference between values after furegrelate and values after furegrelate and meclofenamate. Double dagger indicates significant difference (p < 0.05) from the corresponding values measured in either normotensive control group. Mean values ± 1 SE from six to seven rats per group are presented. kwt = kidney weight.

Figure 5. Effect of furegrelate and meclofenamate (meclo) on the urinary excretion of thromboxane B2 (TXB2) in DOCA-salt hypertensive rats and control rats drinking 1% NaCl. Asterisk indicates significant difference (p < 0.05) from respective control value. Dagger indicates significant difference (p < 0.05) between value after furegrelate and value after furegrelate and meclofenamate. Mean values ± 1 SE from six rats per group are presented.

Discussion

This study demonstrates that RBF and GFR are reduced in rats with established DOCA-salt hypertension. These changes in renal hemodynamics are associated with an elevated urinary excretion of TXB2, an increased release of TXB2 from renal cortical tissue slices, and a diminished release of PGE2 from renal medullary tissue. Additionally,
DOCA-salt hypertensive rats feature an augmented urinary excretion of PGE\(_2\) and 6-keto-PGF\(_{1\alpha}\) and increased release of 6-keto-PGF\(_{1\alpha}\) from slices of the renal cortex and the medulla. The urinary excretion of PGE\(_2\) and 6-keto-PGF\(_{1\alpha}\) and the release of 6-keto-PGF\(_{1\alpha}\) from renal medullary slices also were elevated in normotensive control rats given saline to drink, suggesting that these latter changes in renal eicosanoid excretion and release probably are related to an elevation in sodium intake rather than to the development of hypertension. The association of hypertension and changes in the urinary excretion and production of TXB\(_2\) by renal tissue was first reported in spontaneously hypertensive rats.\(^{20,21}\) Subsequently, it was confirmed in rats with reduced renal mass hypertension,\(^{22}\) Dahl salt-sensitive hypertensive rats,\(^{23}\) two-kidney, one clip hypertensive rats,\(^{24}\) and rats with angiotensin II-salt-induced hypertension.\(^{18}\) In DOCA-salt hypertensive rats, the augmentation of the urinary excretion of TXB\(_2\) and the release of this substance from renal cortical tissue may be related to disturbances in electrolyte balance or to hypertensive glomerular injury with attendant infiltration by white blood cells or to the stimulation of other cells in the kidney that express thromboxane synthetase (or to all three). In this regard, DOCA-salt hypertensive rats are known to become hypernatriemetic and hypokalemic. Potassium depletion has been shown to augment TXB\(_2\) release from renal tissue slices in rats.\(^{9}\) Similarly, the release of TXB\(_2\) from renal tissue was also found to increase in dogs made chronically hypernatriemetic by arterial infusion of hypertonic NaCl solution.\(^{25}\)

The urinary excretion of 6-keto-PGF\(_{1\alpha}\) is increased in rats with angiotensin II-induced hypertension\(^{14}\) and in hypertensive rats of the Lyon strain,\(^{26}\) but it is unchanged in rats with two-kidney, one-clip hypertension.\(^{27}\) In DOCA-salt hypertensive rats, the increased urinary excretion and renal tissue release of 6-keto-PGF\(_{1\alpha}\) may be the consequence of an elevated sodium intake alone, since in our study similar abnormalities in the urinary excretion and renal tissue release of 6-keto-PGF\(_{1\alpha}\) were noted in normotensive control rats given 1% NaCl solution to drink. The urinary excretion of PGE\(_2\) is unchanged\(^{28}\) or decreased\(^{29}\) in spontaneously hypertensive rats, decreased in hypertensive Dahl salt-sensitive rats,\(^{30}\) and unchanged in rats with two-kidney, one-clip hypertension.\(^{27}\) In the present study, augmentation of urinary PGE\(_2\) excretion in DOCA-salt hypertensive rats was associated with a diminished release of PGE\(_2\) from renal medullary tissue slices. The dissociation between the excretion of PGE\(_2\) and its release from renal medullary tissue cannot be explained in unequivocal terms. One possibility is that, while the release of eicosanoids from renal tissue slices is an index of their synthesis and metabolism, this in vitro information may not always reflect the production of eicosanoids in vivo.

The functional significance of the augmented production of renal eicosanoids is amenable to clarification by investigation of the effects of eicosanoid synthesis inhibitors and receptor antagonists on renal hemodynamics and the excretion of water and electrolytes. For example, inhibitors of thromboxane synthesis have been reported to increase RBF or GFR (or both) in potassium-depleted rats,\(^{10}\) during the development of hypertension in the spontaneously hypertensive rat,\(^{20}\) and in rats with reduced renal mass.\(^{22}\) From these observations it may be deduced that, in each of these experimental conditions in which renal production of TXA\(_2\) is increased,\(^{9,20,22}\) changes in thromboxane levels in the kidney partially contribute to the reduction in RBF.

In the present study, rats with established DOCA-salt hypertension also exhibited depressed RBF and GFR that was associated with an increased urinary excretion and tissue release of TXB\(_2\). However, inhibition of thromboxane synthesis by furosemide and blockade of TXA\(_2\) receptors by SQ 29548 did

### Table 1. Effect of a Thromboxane A\(_2\) Receptor Antagonist (SQ 29548) and Meclofenamate on Renal Function of Uninephrectomized Rats Drinking 1% NaCl or Rats with DOCA-Salt Hypertension

<table>
<thead>
<tr>
<th>Variable</th>
<th>1% NaCl</th>
<th>1% NaCl + DOCA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>SQ 29548</td>
</tr>
<tr>
<td>Urine flow (µl/min/g kwt)</td>
<td>56.4±10.2</td>
<td>47.3±6.0</td>
</tr>
<tr>
<td>Urine osmolality (mosm/kg - H(_2)O)</td>
<td>525±126</td>
<td>518±39</td>
</tr>
<tr>
<td>Na(^+) excretion (µEq/min/g kwt)</td>
<td>7.1±1.1</td>
<td>8.0±0.9</td>
</tr>
<tr>
<td>Renal blood flow (ml/min/g kwt)</td>
<td>6.3±0.8</td>
<td>6.3±0.8</td>
</tr>
<tr>
<td>Glomerular filtration rate (ml/min/g kwt)</td>
<td>0.99±0.14</td>
<td>1.02±0.12</td>
</tr>
<tr>
<td>Mean blood pressure (mm Hg)</td>
<td>154±9</td>
<td>156±9</td>
</tr>
</tbody>
</table>

Values are means ± SE obtained from seven rats per group. kwt = kidney weight.

*\(p < 0.05\), compared with control value.

†\(fp < 0.05\), compared with SQ 29548 value.
not increase RBF or GFR. Accordingly, TXA2 does not appear to be responsible for the abnormalities in renal hemodynamics in rats with established DOCA-salt hypertension. Such perturbations in renal hemodynamics may be attributable to increased sympathetic activity and vasopressin responses to structural abnormalities in renal vasculature such as glomerulosclerosis and thickening of the glomerular basement membrane. Since the excretions of PGE2 and 6-keto-PGF1 alpha were elevated in DOCA-salt hypertensive rats, it is unlikely that the reduction in RBF and GFR was caused by a deficit in the renal levels of vasodilator eicosanoids. Indeed, our finding that meclofenamate lowered GFR in DOCA-salt hypertensive rats pretreated with SQ 29548 suggests that GFR is supported in part by elevated levels of vasoactive eicosanoids.

Blood pressure in DOCA-salt hypertensive rats fell during treatment with SQ 29548, but it was not affected by the administration of furegrelate. Blood pressure also fell after meclofenamate was given to DOCA-salt hypertensive rats pretreated with furegrelate or SQ 29548. These findings raise the possibility that eicosanoids contribute to the hypertension in DOCA-salt hypertensive rats. Relative to this point, a recent study suggested that eicosanoids are contributory elements in the pathogenesis of severe angiotensin II-salt-induced hypertension in rats.

In summary, this study demonstrates that rats with severe DOCA-salt hypertension exhibit depressed RBF and GFR, increased urinary excretion of TXB2, increased release of TXB2 from renal cortical tissue slices, and diminished release of PGE2 from renal medullary tissue slices. Additionally, DOCA-salt hypertensive rats feature increased urinary excretion of PGE2 and 6-keto-PGF1 alpha and augmented release of 6-keto-PGF1 alpha from renal cortical and medullary tissue. Neither inhibition of thromboxane synthesis by furegrelate nor blockade of TXA2 receptors by SQ 29548 increased RBF and GFR in DOCA-salt hypertensive rats. These data suggest that changes in the renal production of TXA2 are not responsible for the abnormal renal hemodynamics in rats with established DOCA-salt hypertension.

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