Hyperuricemia induces a primary renal arteriolopathy in rats by a blood pressure-independent mechanism

MARILDA MAZZALI, JOHN KANELLIS, LIN HAN, LILI FENG, YI-YANG XIA, QIANG CHEN, DUK-HEE KANG, KATHERINE L. GORDON, SUSUMU WATANABE, TAKAHIKO NAKAGAWA, HUI Y. LAN, AND RICHARD J. JOHNSON
Division of Nephrology, Baylor College of Medicine, Houston, Texas 77030

Received 21 March 2001; accepted in final form 4 December 2001

The presence of an elevated serum uric acid is associated with hypertension and cardiovascular disease (reviewed in Ref. 22). Despite the strength of the association and the ease in treating this condition, it remains unknown whether elevated uric acid has a pathogenic role in cardiovascular disease or whether it simply represents a “marker” for other cardiovascular risk factors with which it is commonly associated, such as hypertension, renal disease, obesity, insulin resistance, and diuretic use (22). Epidemiological studies have been unable to resolve this issue (1, 5, 8), and experimental studies have been thwarted by the lack of an animal model of mild hyperuricemia that mimics the human condition, a paucity of cell culture studies, and the absence of a tenable mechanism by which uric acid could cause cardiovascular disease or hypertension.

Recently, our group developed an animal model of mild hyperuricemia by feeding oxonic acid to rats (14, 15). Oxonic acid is an inhibitor of uricase, a hepatic enzyme present in most mammals that degrades uric acid to allantoin. Humans and the great apes lack this enzyme because of several mutations that occurred during early hominoid evolution 8–20 million years ago (29). Rats fed low doses of oxonic acid developed a mild increase in serum uric acid without intrarenal crystal deposition or acute renal failure, which occurred in previous models (14, 15). Hence, this model was considered ideal for studying the effects of mild hyperuricemia on cardiovascular disease.

An unexpected finding in this model was the observation that mild hyperuricemia induced a blood pressure elevation after several weeks (14). Systolic blood pressure (SBP) directly correlated with serum uric acid levels, and a 1 mg/dl change in uric acid was associated with a 30- to 40-mmHg increase in blood pressure. The effect of hyperuricemia on blood pressure was particularly evident in the presence of a sodium-restricted diet, but an increase in blood pressure was also shown under normal-salt-diet conditions. Evidence that the increase in blood pressure was due to the uric acid was demonstrated by preventing the increase in uric acid in oxonic acid-treated rats by administering allopurinol (a xanthine oxidase inhibitor) or benziodarone (a uricosuric agent). Both drugs prevented the development of hyperuricemia and the increase in blood pressure (14).

Further studies clarified the mechanism by which uric acid induced the blood pressure elevation (15). Hyperuricemic rats had elevated juxtaglomerular renin expression as well as a decrease in nitric oxide synthase-1 (NOS-1) in the macula densa. Macula densa generates nitric oxide, which has an important role in modulating afferent arteriolar tone and tubuloglomerular feedback (28). Stimulation of renin and angiotensin II

Address for reprint requests and other correspondence: R. J. Johnson, Div. of Nephrology, Alkek 5th Floor Renal Research Laboratory, 1 Baylor Plaza, Baylor College of Medicine, Houston, TX 77030 (E-mail: rjohnson@bcm.tmc.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

http://www.ajprenal.org 0363-6127/02 $5.00 Copyright © 2002 the American Physiological Society F991
inhibition of macula densa NOS-1 would be expected to result in increased renal vascular resistance and increased proximal tubule sodium reabsorption, which is compatible with reports in humans that hyperuricemia is associated with increased plasma renin activity (23), increased renal vascular resistance (16), and increased sodium reabsorption in the proximal tubules (4).

We now report another effect of uric acid in our model, which is to induce a medial vascular thickening of the preglomerular vessels in the kidney. We further show that the mechanism of the afferent arteriopathy is independent of blood pressure and that it is partially dependent on angiotensin II.

METHODS

Experimental Design

Male Sprague-Dawley rats (200–250 g; Simonsen Laboratories, Gilroy, CA) were housed in individual cages, and blood pressure and serum uric acid were measured at multiple time points. After a week of adaptation to the blood pressure measurements, rats were divided into groups, matched according to SBP, body weight, and serum uric acid levels, and followed for 7 wk.

Experiment I. To analyze the effect of hyperuricemia on blood pressure and renal vasculature, rats were divided into groups as follows. Control animals (n = 5) were administered a low-salt diet (0.125% NaCl). Hyperuricemia rats (n = 5) were fed a low-salt diet plus 2% oxonic acid. Allopurinol rats (n = 6) were administered a low-salt and oxonic acid diet with allopurinol (150 mg/l) in the drinking water. Benziodarone rats (n = 5) were administered a low-salt and oxonic acid diet with benziodarone (10 mg·kg⁻¹·day⁻¹) in the drinking water.

Experiment II. To evaluate the effect of blood pressure control on vascular changes, two additional groups of rats were included. Results were compared with control and hyperuricemic rats. Hydrochlorothiazide (HCTZ) rats (n = 5) were fed a low-salt diet plus 2% oxonic acid. Allopurinol rats (n = 6) were administered a low-salt and oxonic acid diet with allopurinol (150 mg/l) in the drinking water. Enalapril rats (n = 6) were fed a low-salt and oxonic acid diet with enalapril (1 mg·kg⁻¹·day⁻¹) in the drinking water.

Experiment III. To analyze the role of the renin-angiotensin system in the presence of normal-salt conditions, we studied four additional groups. Normal-salt controls were fed a normal-salt (0.26% NaCl) diet. Hyperuricemia rats were fed a normal-salt and oxonic acid diet. Enalapril treatment rats were fed a normal-salt and oxonic acid diet with enalapril (1 mg·kg⁻¹·day⁻¹) in the drinking water. Losartan treatment rats were fed a normal-salt and oxonic acid diet with losartan (10 mg·kg⁻¹·day⁻¹) in the drinking water.

Drugs

Allopurinol (100 mg), benziodarone (50 mg; Sanofi), enalapril (5 mg; Merck), HCTZ (50 mg), and losartan (50 mg; Merck) tablets were diluted in the drinking water. The amount of drug added to the drinking water was adjusted every 2 days according to body weight and water intake to provide doses (in mg·kg⁻¹·day⁻¹) of 3 HCTZ, 1 enalapril, 10 losartan, and 10 benziodarone. In the benziodarone group, the daily dose was increased to 15 mg·kg⁻¹·day⁻¹ at 2 wk because the original dose was insufficient to lower the uric acid levels.

Evaluation

In all studies, SBP was measured by using a tail-cuff sphygmomanometer with an automated system and photoelectric sensor (ITC). All animals were preconditioned for blood pressure measurements 1 wk before each experiment. Serum uric acid was measured by the carbonate phosphotungstate method (13). Serum blood urea nitrogen was measured by using a standard kit (Sigma).

Renal Histology

Renal biopsies were fixed in methyl Carnoy’s solution and embedded in paraffin. Sections of methyl Carnoy’s fixed tissue (4 μm) were stained with periodic acid-Schiff (PAS) reagent or analyzed by indirect immunoperoxidase staining with the primary antibodies monoclonal mouse anti-vascular actin (DAKO) and monoclonal mouse anti-α-smooth muscle actin (Sigma).

Quantification of Morphology

All quantifications were performed in a blinded fashion. Only vessels adjacent to glomeruli in the outer cortex were selected. Afferent arterioles were distinguished from efferent arterioles by the presence of an internal elastic lamina and by thin, flattened endothelial cells (7). By using immersion-fixed tissue, afferent arteriolar wall thickness was measured by computer image analysis. For each arteriole, the outline of the vessel and its internal lumen (excluding the endothelium) were generated by using computer analysis to calculate the total medial area (outline-inline) in a minimum of 12 arterioles/biopsy. Vessels that were cross-sectioned or not sectioned transversally, providing an asymmetrical wall, were excluded from the present study. Although perfusion-fixed tissue is often preferred for morphometric measurements (17), immersion-fixed tissue is acceptable for measuring medial thickness (24), and comparisons are also valid because all samples were treated with the same method. The media-to-lumen ratio was calculated by the outline-inline relationship. A tubulointerstitial injury score (0–5) was based on the degree of tubular injury observed by using light microscopy with PAS-stained tissue as previously described (14).

Smooth Muscle Cell Culture

Primary rat aortic vascular smooth muscle cells (SMCs) from passages 8–20 were cultured in DMEM supplemented with 5% fetal bovine serum, penicillin (100 U/ml), and streptomycin (100 μg/ml) (9). Cells were incubated at 37°C in a humidified atmosphere of 95% air-5% CO₂. The medium was changed every 3 days, and cells were subcultured by treatment with 0.05% trypsin-0.02% EDTA solution.

Proliferation Assay

Cells were growth arrested for 24 h in serum-free media (DMEM). Cells were suspended in DMEM at a concentration of 5 × 10⁴ cells/ml, and 200 μl were added to a 96-well tissue culture plate with uric acid (3 mg/dl; Sigma) in the presence or absence of losartan (0.1 and 0.5 μM). At 48 h, cell proliferation was assessed by using a 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay (Promega) and expressed as cell counts per well. For each experiment, 8–16 wells/group were used.

Statistical Analysis

Values are expressed as means ± SD. Differences between groups were evaluated by ANOVA with appropriate correction for multiple comparisons (Bonferroni and Dunn). The relationship between variables was assessed by Pearson correlation analysis. Significance was defined as P < 0.05.
RESULTS

Hyperuricemic Rats Develop Hypertension and an Afferent Arteriopathy

The administration of 2% oxonic acid to rats on a low-salt (0.125% NaCl) diet resulted in mild hyperuricemia compared with control rats on a low-salt diet alone (1.84 vs. 1.39 mg/dl, 7 wk, oxonic acid diet vs. control, P < 0.01) in association with the development of mild hypertension (SBP 147 ± 8 vs. 127 ± 5 mmHg, 7 wk, oxonic acid vs. control, P < 0.01). Both hyperuricemia and elevation in blood pressure were prevented by the administration of either allopurinol (a xanthine oxidase inhibitor) or benziodarone (a uricosuric agent; Table 1). Renal function, as assessed by blood urea nitrogen levels, was slightly reduced in the hyperuricemic rats, and this reduction was also prevented by either allopurinol or benziodarone (Table 1).

Light microscopy (PAS staining) of the kidney appeared unremarkable in hyperuricemic rats, although there were minor changes consisting of tubular dilatation and atrophy in <10% of the renal cortex (14). However, on careful examination, one could observe thickening of the afferent arterioles and some interlobular arteries, with sparing of the larger vessels. The thickening of the afferent arterioles was universal, and rare afferent arterioles displayed hyalinosis (Fig. 1, A–C). Afferent arterioles from hyperuricemic rats showed a relative increase in immunostaining for α-smooth muscle actin (Fig. 1F) compared with control rats (Fig. 1D). The interlobular arteries of hyperuricemic rats also showed a qualitative increase in vimentin staining (Fig. 1G) compared with controls (Fig. 1E). By using computer image analysis, a 35% increase in afferent arteriolar cross-sectional surface area was documented in hyperuricemic vs. control rats (P < 0.05). An increase in the arteriolar medial-to-lumen ratio was also present (Table 1). The arteriolar thickening and increased arteriolar medial-to-lumen ratio were not observed in low-salt-diet controls or in low-salt- and oxonic acid-treated animals that received allopurinol or benziodarone (Table 1). The afferent arteriolar thickness correlated with both SBP (r² = 0.52, P < 0.05) and serum uric acid levels (r² = 0.34, P < 0.05; Fig. 1, H and I).

Hyperuricemia-Induced Arteriopathy Is a Primary Event and Is Not Secondary to Hypertension

Arteriolar disease in hypertension is often considered a vascular response to the increased blood pressure (26). Therefore, we examined the effect of controlling blood pressure on the development of the arteriopathy in oxonic acid-treated rats. Rats were placed on a low-salt and oxonic acid diet and treated with HCTZ (3 mg·kg⁻¹·day⁻¹) or with the angiotensin-converting enzyme (ACE) inhibitor enalapril (1 mg·kg⁻¹·day⁻¹) to maintain blood pressure in the normal range during the entire study period.

Both antihypertensive agents prevented the development of hypertension in the oxonic acid-treated rats (Fig. 2A). As expected, uric acid levels were slightly increased (although not significantly) with HCTZ treatment (Table 2). Despite maintaining normal blood pressure, the development of the arteriolar lesions was not prevented by HCTZ therapy (Fig. 2B). In these rats, the arteriolar medial thickness was not different from the oxonic acid-treated rats. However, the medial-to-lumen ratios were partially but significantly reduced. In contrast, enalapril significantly reduced the arteriolar thickening and the increase in the medial-to-lumen ratio in hyperuricemic rats, and the values were similar to normouricemic controls (Fig. 2B, Table 2).

The previous experiments were performed under low-salt-diet conditions, because the effect of hyperuricemia on blood pressure is most pronounced under these dietary conditions (14). Therefore, we performed additional experiments in the presence of a normal-salt diet. Rats were treated with normal salt (0.26% NaCl), normal salt and oxonic acid, or normal salt and oxonic acid with either losartan (10 mg·kg⁻¹·day⁻¹) or enalapril (1 mg·kg⁻¹·day⁻¹) for 7 wk. Oxonic acid-treated rats developed hyperuricemia, hypertension, and the renal afferent arteriopathy (Table 3). Both enalapril and losartan prevented the increase in blood pressure induced by oxonic acid (Fig. 3A), and both prevented the arteriopathy (Table 3). Interestingly, uric acid levels tended to be lower in the losartan group compared with untreated controls (P = 0.054, Table 3), which likely relates to the fact that losartan has some uricosuric activity (3, 20).

Uric Acid Stimulates SMC Proliferation in Vascular SMCs: Role of Angiotensin II

The observation that hyperuricemic rats develop an arteriopathy by means of a blood pressure-independent effect suggested that uric acid might be acting directly on the vascular SMCs. SMCs incubated with uric acid (3 mg/dl) for 48 h showed a marked increase in cell proliferation (Fig. 3). Proliferation was not observed with oxonic acid (3 mg/dl; data not shown). The

Table 1. Hyperuricemia is associated with afferent arteriopathy

<table>
<thead>
<tr>
<th></th>
<th>Control*</th>
<th>Oxonic Acid (2%)</th>
<th>Allopurinol, 150 mg/l</th>
<th>Benziodarone, 15 mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum uric acid, mg/dl</td>
<td>1.39 ± 0.07</td>
<td>1.84 ± 0.21†</td>
<td>1.32 ± 0.06</td>
<td>1.40 ± 0.13</td>
</tr>
<tr>
<td>Systolic blood pressure, mmHg</td>
<td>126.8 ± 4.9</td>
<td>146.9 ± 8.5†</td>
<td>119.3 ± 5.6</td>
<td>127.8 ± 6.3</td>
</tr>
<tr>
<td>Arteriolar area, μm²</td>
<td>128.1 ± 13.4</td>
<td>170.7 ± 20.1†</td>
<td>127.8 ± 4.9</td>
<td>139.1 ± 8.6</td>
</tr>
<tr>
<td>Media-to-lumen ratio</td>
<td>3.07 ± 0.24</td>
<td>4.26 ± 0.29†</td>
<td>3.10 ± 0.37</td>
<td>3.15 ± 0.17</td>
</tr>
<tr>
<td>Blood urea nitrogen, mg/dl</td>
<td>15.6 ± 3.8</td>
<td>20.5 ± 3.8†</td>
<td>11.8 ± 1.8</td>
<td>12.2 ± 3.5</td>
</tr>
</tbody>
</table>

*Low-salt diet. †P < 0.05 vs. other groups.
cell proliferation could be partially blocked by losartan at both 0.1 and 0.5 μM (Fig. 3). A similar inhibition in cell proliferation in response to uric acid could be shown with irbesartan at the same concentrations (data not shown).

**DISCUSSION**

Hyperuricemia is associated with hypertension and cardiovascular disease, but a pathogenic mechanism to explain this association has been lacking. Recently, we...
Serum uric acid, mg/dl 1.39

Increase in arteriolar area is independent of blood pressure control

Table 2. Inhibition of NOS-1 in macula densa (14).

<table>
<thead>
<tr>
<th></th>
<th>Control*</th>
<th>Oxonic Acid (2%)</th>
<th>Enalapril</th>
<th>Hydrochlorothiazide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum uric acid, mg/dl</td>
<td>1.39 ± 0.07</td>
<td>1.84 ± 0.21†</td>
<td>1.86 ± 0.21†</td>
<td>1.94 ± 0.07†</td>
</tr>
<tr>
<td>Systolic blood pressure, mmHg</td>
<td>126.8 ± 4.9</td>
<td>146.9 ± 8.5†</td>
<td>122.5 ± 4.5§</td>
<td>126.0 ± 6.8§</td>
</tr>
<tr>
<td>Tubulointerstitial score</td>
<td>0.11 ± 0.09</td>
<td>0.24 ± 0.06†</td>
<td>0.14 ± 0.09</td>
<td>0.28 ± 0.10§</td>
</tr>
<tr>
<td>Arteriolar area, µm²</td>
<td>128.1 ± 13.4</td>
<td>170.7 ± 20.13§</td>
<td>137.1 ± 16.5</td>
<td>161.1 ± 6.9§</td>
</tr>
<tr>
<td>Media-to-lumen ratio</td>
<td>3.07 ± 0.24</td>
<td>4.28 ± 0.29§</td>
<td>3.08 ± 0.17§</td>
<td>3.57 ± 0.24†§</td>
</tr>
</tbody>
</table>

*Low-salt diet. †P < 0.05 vs. control. ‡P < 0.05 vs. oxonic acid. §P < 0.05 vs. enalapril. All ANOVA and Fisher’s protected least significant difference tests.

AJP-Renal Physiol • VOL 282 • JUNE 2002 • www.ajprenal.org
The AT1 receptor may be important in the vascular remodeling, as has been observed in other systems (6). However, losartan could be partially inhibited by losartan (0.1 and 0.5 μM). (21) had previously reported that uric acid could induce platelet-derived growth factor A-chain expression and cell proliferation in vascular SMCs, and we also confirmed the proliferative effect of uric acid. Consistent with the in vivo results, we also found that the SMC proliferation in response to uric acid in vitro could be partially blocked by losartan.

Recently, we have found that hyperuricemia (induced by oxonic acid administration) also exacerbates the microvascular and tubulointerstitial disease induced by cyclosporine (15). Rats administered oxonic acid and cyclosporin showed higher serum uric acid levels in association with worse afferent arteriolar lesions and more severe tubulointerstitial disease (15). Like the uric acid model, the arteriolopathy in experimental cyclosporin nephropathy can also be prevented by enalapril or losartan (2).

The observation that experimental hyperuricemia can cause renal microvascular disease that is not blocked by thiazide therapy despite control of blood pressure may be clinically relevant. Indeed, despite the great benefit of diuretics in lowering hypertension-associated mortality, there is some evidence that the protection is less than expected for the degree of blood pressure control (27). Even in situations of treated hypertension, cardiovascular events continue, and this correlates with the degree of hyperuricemia present (1). A recent analysis of the Systolic Hypertension in the Elderly Program trial found that those individuals who developed hyperuricemia on chlorthalidone therapy continued to have cardiovascular events similar to untreated patients (10). We suggest that one mechanism by which thiazide-induced hyperuricemia may counter the beneficial effect of thiazides to lower blood pressure could be by means of the stimulation of SMC proliferation and the development of vascular disease.

In summary, we have demonstrated that hyperuricemia induces a primary arteriolaropathy of the afferent arteriole in rats. An important caveat is that one must be careful in extrapolating animal models to the human condition. Nevertheless, the observation that hyperuricemia results in an afferent arteriolaropathy in the rat may provide one of the mechanisms long sought by Goldblatt (11) to account for the primary renal microvascular disease that he postulated underlies the human condition. Nevertheless, the observation that hyperuricemia results in an afferent arteriolaropathy in the rat may provide one of the mechanisms long sought by Goldblatt (11) to account for the primary renal microvascular disease that he postulated underlies the pathogenesis of hypertension. We suggest that further studies on the mechanisms by which uric acid influences cardiovascular disease are warranted.

The suggestions and technical help of Katherine L. Gordon and Yi-Yang Xia are greatly appreciated.

This work was supported by an unrestricted grant from Merck, Inc. M. Mazzali was supported by the postdoctoral program of the...
REFERENCES