Distinct Renal Injury in Early Atherosclerosis and Renovascular Disease

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Background—Atherosclerotic renovascular disease may augment deterioration of renal function and ischemic nephropathy compared with other causes of renal artery stenosis (RAS), but the underlying mechanisms remain unclear. This study was designed to test the hypothesis that concurrent early atherosclerosis and hypoperfusion might have greater early deleterious effects on the function and structure of the stenotic kidney.

Methods and Results—Regional renal hemodynamics and function at baseline and during vasoactive challenge (acetylcholine or sodium nitroprusside) were quantified in vivo in pigs by electron-beam computed tomography after a 12-week normal (n=7) or hypercholesterolemic (HC, n=7) diet, RAS (n=6), or concurrent HC and a similar degree of RAS (HC+RAS, n=7). Flash-frozen renal tissue was studied ex vivo. Basal cortical perfusion and single-kidney glomerular filtration rate (GFR) were decreased similarly in the stenotic RAS and HC+RAS kidneys, but tubular fluid reabsorption was markedly impaired only in HC+RAS. Perfusion responses to challenge were similarly blunted in the experimental groups. Stimulated GFR increased in normal, HC, and RAS (38.3±3.6%, 36.4±7.6%, and 60.4±9.3%, respectively, P<0.05), but not in HC+RAS (6.5±15.1%). These functional abnormalities in HC+RAS were accompanied by augmented perivascular, tubulointerstitial, and glomerular fibrosclerosis, inflammation, systemic and tissue oxidative stress, and tubular expression of nuclear factor-κB and inducible nitric oxide synthase.

Conclusions—Early chronic HC+RAS imposes distinct detrimental effects on renal function and structure in vivo and in vitro, evident primarily in the tubular and glomerular compartments. Increased oxidative stress may be involved in the proinflammatory and progrowth changes observed in the stenotic HC+RAS kidney, which might potentially facilitate the clinically observed progression to end-stage renal disease. (Circulation. 2002;106:1165-1171.)

Key Words: atherosclerosis ■ kidney ■ regional blood flow

Renal artery stenosis (RAS) is the most common cause for secondary hypertension and may lead to deterioration of renal function and renal tissue injury (“ischemic nephropathy”). Up to 90% of stenotic lesions are caused by atherosclerosis, the prevalence of which as an underlying cause for end-stage renal disease (ESRD) is on the rise, especially in the elderly population. Hence, there is a pressing need to define the underlying mechanisms responsible for renal damage in this disease. Notably, compared with fibromuscular dysplasia, atherosclerotic RAS is associated with poorer outcomes in terms of hypertension and renal function, suggesting that atherogenic factors other than stenosis itself are involved in the mechanism of renal injury in atherosclerotic RAS. However, these factors are yet to be identified.

Renal injury in RAS may be initiated by a reduction in nitric oxide (NO) bioavailability and increased intrarenal activity of the renin-angiotensin system, resulting in inflammation and the predominance of vasoconstrictors and growth-promoting factors. Similar alterations also characterize atherosclerosis and hypercholesterolemia (HC), which are risk factors for progression of renal disease. Furthermore, both ischemic nephropathy and HC are associated with increased generation of reactive oxygen species (ROSs) and other radicals or increased oxidative stress. ROSs may further interact with NO and decrease its bioavailability, thereby generating the pro-oxidant peroxynitrite, and may impair intrarenal vascular, glomerular, and tubular function and increase the activity of growth factors and inflammatory mediators, eventuating in renal structural damage. However, whether these detrimental effects are exacerbated in atherosclerotic RAS by a cross talk between HC and hypoperfusion remains to be defined. In particular, their interaction to affect intrarenal hemodynamics and function in vivo has been difficult to assess because of lack of...
reliable, noninvasive techniques capable of studying the kidney distal to RAS.

Electron-beam computed tomography (EBCT) provides accurate, reproducible, simultaneous, and noninvasive quantifications of single-kidney volume, perfusion, glomerular filtration rate (GFR), and segmental tubular function, which are difficult to obtain using other methods. Hence, the present study was designed to investigate the effects of HC+RAS on the stenotic kidney in vivo and to test whether early chronic HC+RAS induces more pronounced increases in oxidative stress and renal hemodynamic, functional, and structural impairment than hypoperfusion or HC alone.

Methods

All procedures were approved by the Institutional Animal Care and Use Committee. Twenty-seven domestic pigs (57 to 67 kg; Pork Partners, Stewartville, Minn) were studied after a 12-week treatment. Seven pigs (normal) were fed a normal diet, and 7 others (HC) received an atherogenic diet of 2% cholesterol and 15% lard (TD-93296, Harlan-Teklad). In 6 others (RAS), a local-irritant coil placed in the left renal artery at baseline induced gradual development of unilateral RAS, as previously described, followed by a 12-week normal diet. In 7 others (HC+RAS), a 12-week HC diet and RAS were initiated simultaneously.

The degree of RAS was subsequently measured by quantitative renal angiography, and blood samples were collected from the inferior vena cava and renal veins bilaterally for measurement of plasma renin activity (PRA). In vivo EBCT flow studies were then performed for assessment of basal regional renal perfusion, renal blood flow (RBF), GFR, and tubular function and were repeated during suprarenal infusion of acetylcholine (ACh) and sodium nitroprusside (SNP) to test endothelium-dependent and -independent responses, respectively.

In vitro studies were subsequently performed to obtain plasma lipid profiles (Roche), PRA (New England Nuclear), and serum creatinine (spectrophotometry). Plasma oxidation was assessed spectrophotometrically by the lag time, malondialdehyde content, and relative electrophoretic mobility of LDL (indicating its propensity for oxidation), as well as plasma levels of the endogenous antioxidant vitamins E and C by HPLC. Activities of the radical scavenger enzymes catalase, glutathione peroxidase, copper zinc superoxide dismutase (CuZn-SOD), and manganese SOD (Mn-SOD) were determined spectrophotometrically in shock-frozen renal tissue and normalized for protein content by the Lowry method.

Renal morphology and protein expression in each pig was examined in representative 5-μm-thick formalin-embedded or shock-frozen sections. Renal morphology was examined in sections stained with hematoxylin-eosin, periodic acid–Schiff, and trichrome. Immunohistochemistry examined protein expression of endothelial eNOS (inducible) and iNOS NO synthase, the fibrogenic transforming growth factor (TGF)-β, nuclear factor (NF)-κB, and nitrotyrosine, the footprint for peroxynitrite formation in vivo.

EBCT Studies

Animals were anesthetized with 0.5 g ketamine and xylazine IM, intubated, and mechanically ventilated. Anesthesia was maintained intravenously with a mixture of ketamine (0.2 mg · kg⁻¹ · min⁻¹) and xylazine (0.03 mg · kg⁻¹ · min⁻¹). This was followed by placement of intravascular catheters in the suprarenal aorta and right atrium for administration of vasoactive substances and contrast media, respectively. The arterial guide also served for renal angiography and monitoring mean arterial pressure.

Animals were then transferred to the EBCT (C-150, Imatron Inc). After a 1-hour recovery, hemodynamic parameters were recorded and blood samples collected. A baseline EBCT flow study was then performed as previously detailed, after a right atrial bolus injection (0.5 mL/kg) of iopamidol (Squibb Diagnostics). After a 15-minute recovery, a 15-minute randomized infusion of either ACh (4.5 g · kg⁻¹ · min⁻¹) or SNP (5.5 nmol · L⁻¹ · kg⁻¹ · min⁻¹) was initiated. After hemodynamic stabilization, EBCT studies were repeated. Finally, a volume study was performed for measurement of cortical and medullary volumes.

Pigs were subsequently euthanized with sodium pentobarbital (100 mg/kg IV) (Fort Dodge Laboratories). Kidneys were sectioned and immediately shock-frozen in liquid nitrogen and stored at −80°C or preserved in formalin.

Immunohistochemistry

Immunostaining for eNOS, nitrotyrosine, and TGF-β was performed in frozen cross sections as described previously. The Vectastain Elite ABC Kit (Vector Laboratories) was used according to the vendor’s instructions. Monoclonal antibodies to mouse eNOS (Transduction Laboratories, 1:500), nitrotyrosine residues (Cayman, 1:20), or TGF-β (MAB1835, R&D Systems, 1:100), served as primary antibodies.

Immunostaining for iNOS and NF-κB was performed on deparaffinized renal cross sections. Polyclonal (iNOS, Affinity Bioreagents, 1:500) and monoclonal (NF-κB, Santa Cruz Biotechnology Inc, 1:50) primary antibodies were used. The secondary antibody, IgG Envision Plus (Dako), was followed by staining with the Vector NovaRED substrate kit (Vector Laboratories), and slides were counterstained with hematoxylin.

Data Analysis

Manually traced regions of interest were selected in EBCT images in the aorta, renal cortex, medulla, and papilla, and their densities were sampled. Time-density curves were generated and fitted with extended γ-variable curve fits, and the area enclosed under each segment of the curve and its first moment were calculated by use of curve-fitting parameters. These were used to calculate renal regional perfusion (mL · min⁻¹ · g tissue⁻¹), intratubular fluid concentration (ITC, an index of tubular fluid reabsorption), single-kidney GFR, and RBF by previously validated methods.

Histology sections were examined with a computer-aided image-analysis program. In each representative slide, immunostaining was quantified in 15 to 20 fields and expressed as percentage of staining of total surface area, and the results from all fields were averaged. Glomerular score (percentage of sclerotic glomeruli) and arteriolar media-to-lumen ratio were assessed by standard techniques.

Statistical Analysis

Results are shown as mean±SEM. Comparisons within groups were performed by use of paired Student’s t test, and among groups by ANOVA, with the Bonferroni correction for multiple comparisons, followed by unpaired Student’s t test. Interaction between HC and RAS was tested in HC, RAS, and HC+RAS with 2-way ANOVA. Statistical significance was accepted for P<0.05.

Results

Total and LDL cholesterol levels were elevated in HC and HC+RAS compared with normal and RAS pigs (Table 1). Mean arterial pressure (Table 1) and the degree of RAS (79.2±6.9% versus 68.7±9.1%, P=0.4) were not different between the RAS and HC+RAS groups. There were no significant differences among the groups in mean arterial pressure and heart rate response to ACh or SNP (P=0.6 for both). Plasma creatinine increased significantly in HC, RAS, and HC+RAS (P=0.01 each), but PRA did not (Table 1), as typical for chronic renovascular hypertension. PRA lateralized to the stenotic kidney in 1 of 6 RAS and 2 of 7 HC+RAS pigs.

Basal Renal Hemodynamics and Function

Basal renal volume, RBF, and GFR were not different between the stenotic RAS and HC+RAS kidneys and were
TABLE 1. Systemic Characteristics, Redox Status, and Tissue Activities of Radical Scavengers in Normal, HC, RAS, and HC+RAS Pigs

<table>
<thead>
<tr>
<th></th>
<th>Normal (n=7)</th>
<th>HC (n=7)</th>
<th>RAS (n=6)</th>
<th>HC+RAS (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cholesterol, mmol/L</strong></td>
<td>1.67±0.16</td>
<td>9.65±1.26*</td>
<td>1.92±0.16</td>
<td>8.34±0.54†</td>
</tr>
<tr>
<td><strong>LDL, mmol/L</strong></td>
<td>0.58±0.12</td>
<td>7.24±1.06*</td>
<td>1.08±0.13</td>
<td>6.76±0.64†</td>
</tr>
<tr>
<td><strong>MAP, mm Hg</strong></td>
<td>101.8±4.4</td>
<td>105.0±4.0</td>
<td>121.6±9.0*</td>
<td>121.9±4.3*</td>
</tr>
<tr>
<td><strong>PRA, ng·mL⁻¹·h⁻¹</strong></td>
<td>0.51±0.31</td>
<td>0.36±0.08</td>
<td>0.28±0.06</td>
<td>0.75±0.41</td>
</tr>
<tr>
<td><strong>Creatinine, μmol/L</strong></td>
<td>129.9±6.2</td>
<td>160.6±7*</td>
<td>165±11.5*</td>
<td>182.1±21.2*</td>
</tr>
<tr>
<td><strong>Redox status: plasma</strong></td>
<td></td>
<td></td>
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<tr>
<td>Vitamin C, μmol/L</td>
<td>94±2.54</td>
<td>85±2.9*</td>
<td>87.7±1.44*</td>
<td>76.7±2.5†‡</td>
</tr>
<tr>
<td>Vitamin E, μmol/L</td>
<td>60.5±2.8</td>
<td>51.5±1.9*</td>
<td>62.8±1.3‡</td>
<td>44.3±2.1†‡</td>
</tr>
<tr>
<td>LDL lag time, min</td>
<td>83.7±3.0</td>
<td>73.8±2.5*</td>
<td>82.6±1.4‡</td>
<td>68.8±1.9†‡</td>
</tr>
<tr>
<td>LDL MDA, mmol/L·mg⁻¹</td>
<td>6.6±0.4</td>
<td>8.5±0.2*</td>
<td>7.1±0.2‡</td>
<td>9.2±0.2†‡</td>
</tr>
<tr>
<td>LDL REM, mm</td>
<td>10.9±0.3</td>
<td>12.4±1.3*</td>
<td>10.7±1.3‡</td>
<td>12.5±0.3†‡</td>
</tr>
<tr>
<td><strong>Redox status: tissue, μmol/mg protein</strong></td>
<td></td>
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<tr>
<td>Glutathione peroxidase</td>
<td>86.5±2.5</td>
<td>86.6±2.2</td>
<td>66.1±1.7†</td>
<td>59.7±2.1†‡</td>
</tr>
<tr>
<td>Catalase</td>
<td>23.5±1.3</td>
<td>21.6±1.2</td>
<td>16.9±1.0‡</td>
<td>14.5±0.6†‡</td>
</tr>
<tr>
<td>Mn-SOD</td>
<td>3.2±0.1</td>
<td>3.2±0.1</td>
<td>2.6±0.1*</td>
<td>1.9±0.1†‡</td>
</tr>
<tr>
<td>CuZn-SOD</td>
<td>8.1±0.2</td>
<td>8.0±0.2</td>
<td>7.3±0.1*</td>
<td>6.7±0.2†‡</td>
</tr>
</tbody>
</table>

MAP indicates mean arterial pressure; MDA, malondialdehyde; and REM, relative electrophoretic mobility. Values are mean±SEM.

*P<0.05 vs normal; †P<0.05 vs RAS; ‡P<0.05 vs HC.

Response to ACh and SNP

Cortical perfusion was also lower in RAS and HC+RAS, whereas medullary perfusion was lower only in HC+RAS. Basal ITC was not different between normal and HC, whereas in RAS it was significantly higher in the proximal tubule and Henle’s loop, suggesting increased fluid resorption. In HC+RAS, however, ITC was significantly lower along the nephron than in all other groups (Figure 1a), suggesting impaired tubular fluid reabsorption.

**TABLE 2. Basal Single-Kidney Hemodynamics and Function in Normal, HC, RAS, and HC+RAS Pigs**

<table>
<thead>
<tr>
<th></th>
<th>Normal (n=7)</th>
<th>HC (n=7)</th>
<th>RAS (n=6)</th>
<th>HC+RAS (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume, mL</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cortex</td>
<td>100.4±6.2</td>
<td>95.1±5.7</td>
<td>55.2±15.3*</td>
<td>75.2±4.1†</td>
</tr>
<tr>
<td>Medulla</td>
<td>45.4±2.3</td>
<td>41.8±6.9</td>
<td>24.7±6.6‡</td>
<td>30.3±3.3†‡</td>
</tr>
<tr>
<td>Renal blood flow, mL/min</td>
<td>534.0±49.1</td>
<td>499.5±44.5</td>
<td>266.9±99.9*</td>
<td>364.7±54.5*</td>
</tr>
<tr>
<td>Glomerular filtration rate, mL/min</td>
<td>70.8±4.3</td>
<td>60.3±3.1</td>
<td>31.8±11.1*</td>
<td>50.4±3.5*</td>
</tr>
<tr>
<td><strong>Perfusion, mL·min⁻¹·g⁻¹</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cortex</td>
<td>4.11±0.33</td>
<td>4.36±0.43</td>
<td>3.27±0.62†</td>
<td>3.31±0.33†‡</td>
</tr>
<tr>
<td>Medulla</td>
<td>2.63±0.33</td>
<td>3.13±0.66</td>
<td>2.91±0.17</td>
<td>2.34±0.34†‡</td>
</tr>
<tr>
<td>Papilla</td>
<td>2.38±0.33</td>
<td>2.59±0.55</td>
<td>1.99±0.43</td>
<td>2.42±0.76</td>
</tr>
</tbody>
</table>

Values are mean±SEM.

*P<0.05 vs normal; †P<0.05 vs HC, ‡P<0.05 vs RAS.
In normal animals, SNP increased RBF (to 641.5 ± 58.8 mL/min, *P < 0.05 vs normal and HC, †P < 0.05 vs RAS, b and d, Change in RBF in response to ACh and SNP, *P < 0.05 vs baseline, c, Change in GFR in response to ACh, *P < 0.05 vs baseline, †P < 0.05 vs normal.

Redox Status
HC animals showed a decrease in circulating vitamins C and E, whereas RAS pigs had lower levels of vitamin C, and in HC+RAS, both vitamin levels were lowered further compared with all other groups (Table 1). In HC but not RAS, systemic LDL showed increased oxidizability (shortened lag time and increased LDL-malondialdehyde and LDL-relative electrophoretic mobility). Nevertheless, this was accentuated in HC+RAS compared with HC alone (Table 1). Tissue activities of radical-scavenger enzymes were significantly lower in RAS than with normal but were unchanged in HC. Notably, in stenotic HC+RAS kidneys, the decrease in scavenging activity was significantly greater than in each group alone (Table 1).

Renal Histology
Compared with normal, HC kidneys showed mild and focal interstitial fibrosis with associated tubular atrophy. RAS kidneys showed more extensive regions of focal interstitial fibrosis and tubular atrophy, with patchy lymphocytic infiltrates localized to regions of tubular atrophy and isolated sclerotic glomeruli. HC+RAS kidneys, however, showed multifocal interstitial fibrosis with associated tubular atrophy. Globally, sclerotic glomeruli were identified, primarily within the regions of interstitial fibrosis and tubular atrophy (Figure 2a). Focal lymphocytic infiltrates were identified within the expanded interstitial regions. Mild and focal perivascular fibrosis was noted (Figure 2b). The media-to-lumen ratio and glomerular score were increased in all stenotic kidneys (Table 3).

These findings were accompanied in HC by enhanced glomerular, vascular, and/or tubular immunostaining of trichrome, iNOS, nitrotyrosine, TGF-β, and NF-κB, which were further increased in RAS and HC+RAS compared with HC (Table 3, Figures 2 and 3). Moreover, trichrome, iNOS, nitrotyrosine, and NF-κB immunostaining was further significantly increased in HC+RAS compared with all other groups. No differences in eNOS expression were observed (Figure 3a), although it tended to be decreased in HC. All measures of oxidative stress, proximal and Henle’s loop ITC, and immunostaining of trichrome, iNOS, nitrotyrosine, and NF-κB showed significant interactive effects between HC and RAS (ANOVA, *P < 0.05).

Discussion
This study demonstrates that coexistence of early HC and hypoperfusion is associated with greater renal functional and structural impairment, especially in the tubular and glomerular systems, compared with each condition alone. This was accompanied by pronounced increases in both systemic and tissue oxidative stress and proinflammatory and early progrowth changes in the stenotic kidney, which might be involved in progression of renal injury that characterizes atherosclerotic RAS.

Figure 1. a, Basal intratubular concentration in normal (n = 7), HC (n = 7), RAS (n = 6), and HC+RAS (n = 7) pigs. *P < 0.05 vs normal and HC, †P < 0.05 vs RAS. b and d, Change in RBF in response to ACh (b) and SNP (d). *P < 0.05 vs baseline, c, Change in GFR in response to ACh. *P < 0.05 vs baseline, †P < 0.05 vs normal.
Atherosclerotic RAS is increasingly being identified in patients with ESRD, and clinical studies consistently demonstrate unfavorable outcomes compared with other causes of RAS suggesting that additional mechanisms contribute to the deleterious effect of hypoperfusion on the kidney and augment renal injury. Atherosclerosis or HC and renal hypoperfusion might interact in several common pathophysiological pathways to disrupt the balance among intrarenal vasactive factors that regulate vascular tone and tissue growth. Acceleration of vascular, tubular, and glomerular injury may be mediated by inhibition of NO-mediated vasodilatation, activation of angiotensin II, increased generation of ROSs, LDL oxidation, and modulation of cell growth and proliferation. This cascade, which is shared by many forms of renal disease, may lead to vasoconstriction, glomerulosclerosis, and fibrosis and impair renal function and structure.

The EBCT technique allowed unique measurement of concomitant hemodynamics and function of the intact single kidney distal to RAS. The degree of stenosis, which was slightly (albeit not significantly) greater in RAS than HC/RAS, might have resulted in somewhat but insignificantly lower renal volume, RBF, and GFR in RAS, all of which were decreased in both groups compared with normal and HC. Interestingly, basal ITC and GFR and tubular responses to challenge were significantly more impaired in HC/RAS, indicating that concurrent HC promoted functional renal injury. This was particularly obvious in the renal tubules, which showed in vivo decreased basal filtrate concentration capacity, a measure of intrinsic renal damage, and blunted response to challenge. GFR failure to respond to challenge may also indicate an early pathophysiological mechanism that can accompany altered tubular reabsorption. Conversely, renovascular dysfunction was not substantially augmented by concurrent HC. These in vivo findings were supported by morphological examination of the stenotic HC/RAS kidney, which revealed a marked increase in tubulointerstitial accompanied by less pronounced glomerular injury and milder vascular changes. Similarly, alterations in iNOS, NF-κB, and TGF-β expression, suggestive of inflammation and fibrosis, were localized principally to the tubulointerstitial and, to a lesser degree, glomerular and vascular compartments.

**TABLE 3. Morphological Evaluation and Immunostaining in Normal, HC, RAS, and HC+RAS Kidneys**

<table>
<thead>
<tr>
<th></th>
<th>Normal (n=7)</th>
<th>HC (n=7)</th>
<th>RAS (n=6)</th>
<th>HC+RAS (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glomerulosclerosis</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>4.3±0.8*</td>
<td>4.7±1.2*†</td>
</tr>
<tr>
<td>Media-lumen ratio</td>
<td>0.24±0.00</td>
<td>0.26±0.01*</td>
<td>0.61±0.07†</td>
<td>0.64±0.04†</td>
</tr>
<tr>
<td>Trichrome</td>
<td>3.0±0.2</td>
<td>6.6±0.8*</td>
<td>11.7±0.8†</td>
<td>15.6±0.6‡‡</td>
</tr>
<tr>
<td>iNOS</td>
<td>2.6±0.7</td>
<td>9.0±0.9*</td>
<td>15.2±0.9†</td>
<td>17.9±0.4‡‡</td>
</tr>
<tr>
<td>Nitrotyrosine</td>
<td>7.6±0.3</td>
<td>8.7±0.2*</td>
<td>9.2±0.3†</td>
<td>10.4±0.5‡‡</td>
</tr>
<tr>
<td>TGF-β</td>
<td>5.4±0.4</td>
<td>7.1±0.3*</td>
<td>9.5±0.3†</td>
<td>9.3±0.2†</td>
</tr>
<tr>
<td>NF-κB</td>
<td>0.3±0.1</td>
<td>1.4±0.4*</td>
<td>3.6±1.1†</td>
<td>6.4±0.8‡‡</td>
</tr>
</tbody>
</table>

Values are % of renal area, mean±SEM. 
*P<0.05 vs normal; †P<0.05 vs HC; ‡P<0.05 vs RAS.

Figure 2. Representative immunostaining of glomerular (a, ×10) and arteriolar (b, ×20) trichrome, TGF-(c, ×10), and NF-κB (d, ×20) in normal, HC, RAS, and HC+RAS kidneys showing increased interstitial and perivascular fibrosis, tubular atrophy, and NF-κB immunoreactivity in HC+RAS kidneys.
This concordance of in vivo and in vitro findings may also suggest a potential role for ITC as an index of tubular integrity and function. The renal tubules are distinctly vulnerable to renal circulatory compromise and hypoxic injury, and renal susceptibility to hypoperfusion is aggravated by insults that increase medullary vulnerability to hypoxia, especially models combining multiple insults. Indeed, medullary perfusion was significantly decreased in HC+/RAS. In chronic conditions, intrarenal hypoperfusion injury progresses to encompass the entire kidney. The proximal tubule, and particularly its S3 segment, is also highly susceptible to injury, and the decreased ITC observed in both the proximal tubule and Henle’s loop in HC+/RAS might have represented early functional injury in these tubular segments.

Furthermore, a progressive and marked increase in iNOS expression along the nephron paralleled the increasing severity of renal disease in the HC, RAS, and HC+/RAS kidneys. The constitutive tubular expression of iNOS is enhanced in renal disease by cytokines, increased ROS activity, and peroxynitrite. Increased iNOS expression may mediate hypoxic tubular injury or alternatively might conceivably reflect a compensatory mechanism to decrease oxygen consumption during renal ischemia. Its natriuretic effects may explain the enhanced ITC response observed in HC, whereas in RAS, ITC probably increased secondary to angiotensin II–driven proximal fluid resorption that outweighed the moderately elevated iNOS expression. In HC+/RAS, however, tubular atrophy in association with pronounced tubular iNOS expression may have attenuated basal and challenged ITC.

In contrast to iNOS-derived tubular NO, renovascular dysfunction, demonstrated by similarly blunted RBF responses to both endothelium-dependent and -independent vasodilators in HC, RAS, and HC+/RAS, implied decreased bioavailability and/or responsiveness to vascular NO. This impairment, in view of unaltered eNOS expression, may result from altered eNOS activity, increased sensitivity to vasoconstrictors, or quenching of NO by ROSs, indicated in the present study by significant peroxynitrite formation. Furthermore, increased iNOS activity may also inhibit eNOS and lead to renal vasoconstriction and reduction in GFR.

The functional alterations in HC+/RAS were accompanied by marked tissue injury, increased LDL oxidizability, and decreased tissue activities of radical scavengers, denoting an amplified increase in systemic and tissue oxidative stress. Renal histology revealed considerable tubulointerstitial and, to a lesser degree, glomerular and vascular injury in the HC+/RAS kidneys, in association with increased expression of NF-κB, a transcription factor that regulates expression of numerous genes involved in inflammation and cell proliferation. Notably, immunoreactivity of TGF-β, which participates in renal injury and progression to ESRD, was similarly enhanced in RAS and HC+/RAS, suggesting that additional progrowth mechanisms probably played a role in tissue fibrosis in HC+/RAS.

Indeed, in atherosclerotic RAS patients, additional risk factors, longer duration, and chronicity could influence renal damage, and vascular injury probably progresses, because we have shown that their decrease in cortical perfusion exceeds the degree of stenosis. In the present study, media-to-lumen ratio was comparably increased in RAS and HC+/RAS and glomerulosclerosis was minimal, suggesting that the HC+/RAS model mimics a very early stage of ischemic...
nephropathy. This study used a swine model, the renal anatomy and physiology of which resemble those of humans. Diet-induced HK, a surrogate of early atherosclerosis, and our RAS model possess many characteristics of human conditions. Therefore, the HK+RAS model provides an important opportunity to explore relevant pathophysiological mechanisms triggered early in this disease process.

In summary, the present study demonstrates substantial accentuation of the impact of RAS and augmentation of early functional and tissue injury in HK+RAS distal to the stenosis in vivo and in vitro. These observations suggest a cross talk between hypoperfusion and atherosclerosis to interactively increase oxidative stress, inflammation, and tubular injury in the stenotic kidney, perpetuating a vicious circle of potentially irreversible injury. These deleterious alterations may account for the increased propensity for ESRD observed in this disease.

Acknowledgments

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References

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