Roles of Oxidative Stress and AT1 Receptors in Renal Hemodynamics and Oxygenation in the Postclipped 2K,1C Kidney

William J. Welch, Margarida Mendonca, Shakil Aslam, Christopher S. Wilcox

Abstract—The spontaneously hypertensive rat (SHR) exhibits angiotensin II (Ang II)–dependent oxidative stress and reduced efficiency of renal oxygen usage (Q\textsubscript{O2}) for tubular sodium transport (T\textsubscript{Na}). We tested the hypothesis that oxidative stress determines the reduced T\textsubscript{Na}:Q\textsubscript{O2} ratio in the clipped kidney of the early 2-kidney, 1-clip (2K,1C) Ang II–dependent model. One week after sham operation (Sham) or clip placement, 2K,1C rats received for 2 weeks either a vehicle, the superoxide dismutase mimetic tempol (Temp), or candesartan (Cand). Oxidative stress was assessed from excretion of 8-isoprostaglandin F\textsubscript{2α} (PGF\textsubscript{2α}) and malondialdehyde (MDA) and renal oxygenation from pO\textsubscript{2} in the renal cortex and from the ratio of calculated T\textsubscript{Na} and Q\textsubscript{O2} values. The mean arterial pressure (MAP) of Sham (113±6 mm Hg) was increased in 2K,1C vehicle-treated rats (148±4 mm Hg), but both Temp and Cand restored MAP to Sham levels. The excretions of 8-iso-PGF\textsubscript{2α} and MDA were higher in 2K,1C vehicle-treated rats compared with Sham and were normalized by Temp. The pO\textsubscript{2} of Sham (42±2 mm Hg) was lower in 2K,1C vehicle-treated animals (28±2 mm Hg). This was restored to Sham values by Temp (36±3 mm Hg) but not by Cand (28±2 mm Hg). The T\textsubscript{Na}:Q\textsubscript{O2} of Sham (12.9±1.6) was reduced in 2K,1C vehicle-treated rats (9.7±2.8) and was restored to Sham values by Temp (13.7±2.5) but not by Cand (7.5±1.6). We conclude that the correction of oxidative stress in the 2K,1C model partially corrects renal cortical hypoxia and inefficient utilization of O\textsubscript{2} for Na\textsuperscript{+} transport, independent of the fall in blood pressure.

Key Words: hypertension, renovascular ■ Goldblatt hypertension ■ renal artery ■ nitric oxide

Renal oxygen consumption (Q\textsubscript{O2}) is closely related to the energy required for sodium transport (T\textsubscript{Na}). Classic studies have established that variations in sodium delivery and hence, transport, over a broad range are matched by proportionate changes in Q\textsubscript{O2}. Prevention of glomerular filtration reduced Q\textsubscript{O2} to a low but measurable value, identified as the O\textsubscript{2} required for basal kidney metabolism. However, across a broad range of glomerular filtration rates (GFRs), Q\textsubscript{O2} rose linearly with the GFR above the basal level. This defines the normal rate at which O\textsubscript{2} is consumed to satisfy the energy requirements for T\textsubscript{Na} (15 to 25 μmol of Na\textsuperscript{+} transported per μmol of O\textsubscript{2} consumed).

Recent studies have reported that the T\textsubscript{Na}:Q\textsubscript{O2} ratio is variable. Laycock and associates\textsuperscript{3} showed that the T\textsubscript{Na}:Q\textsubscript{O2} in the dog kidney was reduced by ≈50% during inhibition of nitric oxide (NO) synthase with 1-nitroarginine. We showed a similar reduction in T\textsubscript{Na}:Q\textsubscript{O2} in kidneys from spontaneously hypertensive rats (SHR).\textsuperscript{4} The SHR is a model of reduced renal NO bioactivity associated with increased superoxide radical (O\textsubscript{2}--).\textsuperscript{5} There is a complex interrelation between NO, O\textsubscript{2}--., and Po\textsubscript{2} or O\textsubscript{2} usage in the tissues. In pulmonary arteries and vascular smooth muscle cells, both chronic hypoxia and hyperoxia can enhance O\textsubscript{2}-- levels.\textsuperscript{6,7} Increased O\textsubscript{2}-- interacts with NO, which reduces its bioactivity and produces peroxynitrite. Nevertheless, we detected a reduced renal cortical pO\textsubscript{2} in the SHR, which we attributed to inefficient utilization of O\textsubscript{2} for T\textsubscript{Na}, as a consequence of functional NO deficiency during oxidative stress. We found also that the renal cortical hypoxia and reduction in Po\textsubscript{2} in the SHR could be corrected by prolonged administration of the angiotensin receptor antagonist candesartan (Cand) but not by equally effective antihypertensive therapy with agents that do not block the renin-angiotensin system. Moreover, we found that Cand also restored NO bioactivity in the SHR kidney.\textsuperscript{8} Angiotensin II (Ang II) stimulates the expression of NADPH oxidase.\textsuperscript{9,10} We concluded that the reduced NO bioactivity and inefficient utilization of O\textsubscript{2} in the SHR kidney could have been secondary to oxidative stress. The present study was designed to test this hypothesis in the early phase of 2-kidney, 1-clip (2K,1C) Goldblatt hypertension. The 2K,1C is a pathophysiological model of Ang II–dependent hypertension, which suppresses function in the clipped kidney in response to the fall in blood pressure.
to the induced renal artery stenosis. One week after the renal artery clip was placed, rats were treated with the superoxide dismutase mimetic tempol (Temp) to reduce $O_2^-$ or with Cand to lower blood pressure equivalently.

**Methods**

These studies were performed under guidelines recommended by the National Institutes of Health and were approved by the Georgetown University Animal Care and Use Committee. Young male Sprague-Dawley rats (80 to 100 g) were anesthetized with isoflurane (0.5% to 1.5%). A silver clip (0.2 mm) was placed around the left renal artery (2K,1C). Sham animals (Sham) were prepared similarly without clip placement. One week thereafter, the 2K,1C rats received for 2 weeks vehicle (Veh, n = 5), Temp (10 mg · kg$^{-1}$ · min$^{-1}$ added to drinking water, n = 8), or Cand (10 mg · kg$^{-1}$ · d$^{-1}$ added to drinking water, n = 9). On day 13 of drug administration, the rats were placed in metabolic cages for a 24-hour urine collection. Whole-body oxidative stress was assessed from the excretion of 8-isoprostaglandin $F_{2\alpha}$ (8-iso-PGF$F_{2\alpha}$) and malondialdehyde (MDA) from both kidneys. 8-iso-PGF$F_{2\alpha}$ was measured by an ELISA (Cayman Chemical, Ann Arbor, Mich) on extracted 24-hour samples. MDA was measured by chemical concentration of thiobarbituric acid-reactive substances.

On the following day, rats were anesthetized with Inactin (100 mg/kg IP; Research Biochemicals Inc) and prepared for measurements of mean arterial pressure (MAP), renal function, and renal plasma flow; FF, filtration fraction; Cand, Candesartan; and Temp, tempol.

### Table 1. MAP and Renal Function in the Left Kidney

<table>
<thead>
<tr>
<th>Group</th>
<th>BW, g</th>
<th>MAP, mm Hg</th>
<th>KW, g</th>
<th>GFR, ml/min/g</th>
<th>RPF, ml/min/g</th>
<th>FF, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sham (n = 9)</td>
<td>234±12</td>
<td>105±5</td>
<td>1.10±0.03</td>
<td>1.02±0.09</td>
<td>3.2±0.2</td>
<td>34±2</td>
</tr>
<tr>
<td>2K,1C Vehicle (n = 7)</td>
<td>216±11</td>
<td>148±4</td>
<td>0.97±0.05$^*$</td>
<td>0.61±0.09$^*$</td>
<td>1.8±0.2$^*$</td>
<td>37±1</td>
</tr>
<tr>
<td>2K,1C Cand (n = 8)</td>
<td>212±10</td>
<td>112±6$^\ddagger$</td>
<td>0.77±0.07$^\ddagger$</td>
<td>0.51±0.11$^\ddagger$</td>
<td>2.0±0.4$^\ddagger$</td>
<td>28±1$^\ddagger$</td>
</tr>
<tr>
<td>2K,1C Tempol (n = 7)</td>
<td>241±9</td>
<td>118±7$^\ddagger$</td>
<td>1.01±0.05</td>
<td>0.89±0.08$^\ddagger$</td>
<td>2.4±0.4$^\ddagger$</td>
<td>36±1</td>
</tr>
</tbody>
</table>

$^*$P < 0.05, $^\ddagger$P < 0.01, $^\ddagger\ddagger$P < 0.001 compared with Sham; $^\ddagger\ddagger\ddagger$P < 0.001 compared with vehicle.

MAP indicates mean arterial pressure; BW, body weight; KW, kidney weight; GFR, glomerular filtration rate; RPF, renal plasma flow; FF, filtration fraction; Cand, Candesartan; and Temp, tempol.

Statistics were assessed by ANOVA, with a post hoc Dunnett’s test to determine differences. Significance was determined at P < 0.05.

### Results

All rats grew at normal rates. The body weights at the end of treatment did not differ between groups (Table 1). MAP measured under anesthesia was higher (P < 0.001) in 2K,1C, Veh compared with Sham and was normalized by both Temp and Cand. The clipped kidney weight was lower in 2K,1C Veh and Cand compared with Sham but was not different from Sham in 2K,1C Temp. The right (uncropped) kidney weight was not different among groups. However, the ratio of left to right kidney weight was decreased in 2K,1C Veh compared with Sham and normalized in 2K,1C Temp rats (Table 1). This ratio was further increased in 2K,1C Cand.

As shown in Table 1, the GFR, factored by kidney weight, was reduced in the postclip kidney of 2K,1C Veh compared with Sham. The low GFR associated with clipping was increased significantly in 2K,1C by Temp but not by Cand. Compared with Sham, the RPF was lower in 2K,1C Veh and was not changed by Temp or Cand. The filtration fraction was similar to Sham in 2K,1C Veh and 2K,1C Temp. However, the filtration fraction was reduced by Cand.

As shown in Figure 1, the excretion of 8-iso-PGF$F_{2\alpha}$ was higher (P < 0.05) in 2K,1C Veh compared with Sham. Treatment with Temp (P < 0.05) or Cand (P < 0.05) reduced 8-iso-PGF$F_{2\alpha}$ excretion to a level comparable to those in Sham. The excretion of MDA also was higher (P < 0.05) in 2K,1C Veh compared with Sham. However, whereas Temp reduced this (P < 0.05) to a level comparable to that in Sham, Cand had no effect. Because the urine samples represent excretion from both kidneys, these values may not reflect the true level of oxidative stress in the clipped kidney.

O$_2$ extraction, as shown by the difference in renal arterial and venous oxygen content, was elevated significantly in 2K,1C Veh. This was not changed by Temp or Cand (Table 2). However, O$_2$ extraction in the 2K,1C Temp group was not different from Sham. There were no differences in O$_2$ usage between groups. Changes in T$_Na$ reflected the pattern of changes in GFR.

The O$_2$ efficiency for Na$^+$ transport in the clipped kidney is shown in Figure 2. The T$_Na$:O$_2$ of Sham was 12.9±1.6 (μmol of Na$^+$ transported per μmol of O$_2$ consumed). This was reduced in 2K,1C Veh 9.7 to 1.8 (P < 0.01) because of a sharp fall in T$_Na$ with relative preservation of O$_2$. The ratio was restored to Sham values in 2K,1C given Temp (13.7±2.5).
because the reduction in T Na was matched by an equivalent reduction in Q O2. However, the T Na:Q O2 of 2K,1C given Cand was reduced even further (7.5±1.6).

The pO2 in the inner and outer cortex of the clipped kidney is shown in Figure 3. In Sham animals, the pO2 in the outer and inner cortex averaged 42±2 and 33±2 mm Hg, respectively. The pO2 in the outer cortex was reduced by 31% and in the inner cortex by 60% in 2K,1C Veh. Whereas 2K,1C rats given Temp had pO2 values equivalent to those in Sham in the outer cortex, these were reduced in the inner cortex. The pO2 was not improved by Cand compared with Veh 2K,1C. Indeed, there was a further reduction in pO2 in the inner cortex to 11±3 mm Hg.

Discussion

The main new findings from this study are that the clipped kidney of the early 2K,1C model has an increased use of O2 in relation to T Na associated with a sharp reduction of pO2 in the outer cortex and especially the inner cortex. These abnormalities are largely prevented by Temp, which also prevented the whole-body oxidative stress associated with the clipping. Although Temp treatment led to a normal blood pressure in the 2K,1C rats, the defects in oxygenation were not corrected by equivalent reduction in blood pressure by Cand. Indeed, Cand led to a further decline in T Na in the inner cortex to 11±3 mm Hg.

Because NO and O2 compete, the relation between NO and O2 affects both vascular tone and O2 consumption.13,14 NO at physiological levels can compete with O2 for the respiratory chain in mitochondria. Thus, low levels of NO after inhibition of NO synthase enhance O2 usage and reduce the levels of oxygen in various tissues, including the kidney. Decreased bioactive NO is found in the kidney in the SHR, which is a model of oxidative stress. In this setting, the low NO in the juxtaglomerular apparatus (JGA) can be ascribed to interaction with O2, because NO bioactivity increased 6-fold after local microper-

<table>
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<th>Table 2. Oxygen Extraction and Consumption in the Left Kidney</th>
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<tr>
<td>Group</td>
</tr>
<tr>
<td>Sham (n=9)</td>
</tr>
<tr>
<td>2K,1C Vehicle (n=7)</td>
</tr>
<tr>
<td>2K,1C Cand (n=8)</td>
</tr>
<tr>
<td>2K,1C Tempol (n=7)</td>
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</tbody>
</table>

(A-V)O2 indicates the difference between oxygen content in the femoral artery and that in the renal vein; T Na, sodium transported; and Q O2, oxygen consumption.

*P<0.05, †P<0.001 compared with Sham; ‡P<0.001 compared with vehicle.

Figure 1. Mean±SEM values for 24-hour excretion of 8-isoprostaglandin F2α (8-isoPGF2α, left) and malondialdehyde (MDA) (right). Veh indicates vehicle; Cand, candesartan; Temp, tempol.

Figure 2. Mean±SEM calculated values for tubular sodium transport relative (T Na) to renal oxygen usage (Q O2) in the left kidney. Veh indicates vehicle; Cand, candesartan; Temp, tempol.
fusion of Temp to metabolize $O_2$•−.5 Thus, we propose that the reduced $T_{Na}:Q_{O2}$ and the reduced pO2 of the SHR kidney might be secondary to NO deficiency owing to interaction with $O_2$•−. However, we cannot rule out additional effects of Temp in the development of renovascular hypertension. Because kidney size was not reduced in this group, it is plausible that the beneficial effects are related to more complete perfusion of the kidney during this typically ischemic phase of this model. However, this effect may also be related to superoxide dismutase activity, because Temp promotes longer bioactivity of NO and would help to maintain stable blood flow.

Further evidence is derived from the results of prolonged blockade of Ang II type I receptors with Cand. Cand corrected oxidative stress, restored NO bioactivity in the JGA, and normalized renal $T_{Na}:Q_{O2}$ and renal pO2 levels in SHR.4 Therefore, we elected to study the relation between oxidative stress and oxygenation more directly in the present series in a model of extreme Ang II action in the clipped kidney of 2K,1C rats. Previous studies in the 2K,1C pig15 and rat16 showed that increased oxidative stress was associated with high renin levels in the early phase. We have consistently observed low pO2 in the cortex of hypertensive kidneys, which also demonstrate high oxidative stress and deficient NO. However, direct supporting evidence of this relation is currently unavailable. The finding that Temp corrected oxidative stress, reduced renal cortical pO2, and reduced renal oxygen usage for $T_{Na}$ provides direct evidence linking defective renal oxygenation to oxidative stress. Because $T_{Na}:Q_{O2}$ may be dependent on available $O_2$, the effect on superoxide and NO production may suggest that this parameter is linked to redox capacity within the kidney.

Studies in patients with renovascular hypertension due to unilateral renal artery stenosis show enhanced markers for oxidative stress and decreased renal excretion of NO metabolites associated with endothelial dysfunction.17 All of these parameters are normalized after correction of the hypertension by renal angioplasty. Our study suggests that the beneficial effect of angioplasty is not due to the reduction in blood pressure, because our previous study detected no benefit from nonspecific antihypertensive treatment in the SHR model and no benefits in the present study in 2K,1C hypertension with Cand. In another study of patients with unilateral renal artery stenosis, O2 saturation was consistently lower in the blood draining from the contralateral compared with the poststenotic kidney.18 The authors related the enhanced renal O2 uptake to a reduced filtration fraction, leading to a lower level of Na+ reabsorption. However, neither $T_{Na}$ nor $Q_{O2}$ could be assessed in this study. We did not measure the O2 content of the contralateral kidney in our study. Nevertheless, the O2 content of the postclipped kidney was already reduced sharply (Table 2). Therefore, if the contralateral kidney has an even lower renal venous O2 content, as anticipated from this clinical study, then it must likely also have profound defects of oxygenation.

Because treatment trials of angioplasty of the stenotic renal artery in human renovascular hypertension have been quite disappointing, attention has focused on the use of angiotensin-converting enzyme inhibitors or angiotensin receptor blockers. However, although these drugs can reduce blood pressure quite effectively, they can cause a further loss of GFR and size in the poststenotic kidney. This has limited enthusiasm for their use in this condition. The results in this model of acute 2K,1C hypertension may not be fully applicable to chronic renovascular hypertension in humans. Nevertheless, blocking of the angiotensin AT1 receptor in the 2K,1C model reduced the GFR and size of the postclipped kidney. In contrast, we observed that scavenging superoxide with Temp not only corrected hypertension but also normalized the GFR and the relative size of the 2 kidneys. Importantly, the angiotensin receptor blocker led to a further deterioration in $T_{Na}:Q_{O2}$ and to a profound fall in pO2 in the deep cortex to values as low as 11 mm Hg, whereas these parameters of oxygenation were improved by Temp. This suggests that treatment aimed at correction of oxidative stress could have advantages over current therapy for renovascular hypertension.

In summary, we found that in renovascular hypertension generated by clipping of the left renal artery, oxidative stress was increased both systemically and in the kidney. In the clipped kidney, GFR, RBF, and the efficient use of oxygen were reduced, concomitant with hypertension. Correction of hypertension by Cand did not improve renal function or oxygen efficiency in the clipped kidney. Reduction of hypertension by Temp led to normalized renal function and oxygen efficiency in the clipped kidney. The renal tissue pO2 in both the outer and inner cortex of the left kidney was also reduced by clipping. The tissue pO2 was unaffected by Cand but was normalized by Temp. We conclude that suppression of oxidative stress in this model partially corrects renal cortical hypoxia and inefficient usage of O2 for sodium transport.

Perspectives

This study extends the observations that many of the physiological consequences of elevated Ang II are mediated by superoxide. Renal function and the efficient use of oxygen in
the kidney are both suppressed during high superoxide conditions of renovascular hypertension. This suggests that the levels of oxygen in the kidney are dependent on the utilization of oxygen for the work of sodium transport. Therefore, the relation of oxygen with the important metabolites NO and superoxide may be partially dependent on energy requirements. This represents novel regulation of a potentially potent vasoactive family.

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References
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