Glomerular Hemodynamics in Persistent Renovascular Hypertension in the Rat

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SUMMARY We studied the glomerular hemodynamics and activity of the tubuloglomerular feedback system (TGFS) in Wistar rats with persistent hypertension 60 days after removal of the clipped kidney in the Goldblatt (two-kidney, one clip) hypertension model. Ten hypertensive rats (HBP) were compared with 12 normotensive ones (NBP). Micropuncture studies revealed that values for the single nephron glomerular filtration rate (SNGFR), glomerular plasma flow (Q_A), and afferent oncotic pressure (P_A) were similar in both groups, whereas glomerular capillary pressure (P_GC) and effective filtration pressure (EFP) were higher in the HBP group (p < 0.05). A slight but insignificant increase in afferent resistance was present in the HBP group. A positive correlation was found between mean arterial pressure and stop flow pressure (SFP) (r = 0.64, p < 0.05) but not with SNGFR, suggesting a reduction in the ultrafiltration coefficient in hypertensive rats. This was further supported by studies of the activity of the TGFS, which demonstrated that interrupting flow to the macula densa was followed by a smaller increment in SNGFR in HBP, in spite of a similar rise in SFP. The mechanism responsible for decreasing glomerular permeability is unknown but could be related to structural changes in glomerular capillary or to an increase in intrarenal angiotensin II, as has been demonstrated previously in this model. It is suggested that these adaptations occurring in the kidney exposed to hypertension can contribute to the maintenance of elevated arterial pressure after removing the stenotic kidney. (Hypertension 5 (supp V): V-110-V-114, 1983)

KEY WORDS • persistent renovascular hypertension • afferent resistance • Kf • tubuloglomerular feedback sensitivity • contralateral kidney resetting

Renovascular hypertension frequently persists after arterial stenosis has been corrected. This is usually the case in patients with long-standing hypertension in whom nephrosclerosis is present in the contralateral kidney. In rats with Goldblatt hypertension (two-kidney, one clip), a similar situation has been described, characterized by persistence of elevated blood pressure after removal of the clipped kidney. This has been related to alterations in the contralateral kidney, because blood pressure becomes normal when the stenotic kidney is revascularized and the contralateral kidney is removed. The nature of these alterations is unknown. However, various functional changes have been described in the contralateral kidney during earlier stages of hypertension, before removal of the stenotic kidney. These include increased afferent resistance, reduced glomerular capillary permeability coefficient (Kf), as well as impaired tubuloglomerular feedback activity with concomitant loss of autoregulation. At least from a theoretical point of view, these functional adaptations could also contribute to the maintenance of hypertension if they persist after nephrectomy of the clipped kidney.

We undertook the present study to evaluate the hemodynamic determinants of single nephron glomerular filtration rate (SNGFR) and the sensitivity of the tubuloglomerular feedback system (TGFS) in rats with persistent renovascular hypertension.

Methods

Production of the Experimental Model

Systemic hypertension was produced in 22 male Wistar rats weighing 150 g, by applying a silver clip (0.2 mm i.d.) to the left renal artery. Sixty days later, the left kidney was removed. Blood pressure was mea-
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ure before the clip was placed and before nephrectomy. Micropuncture studies were performed 60 days after nephrectomy of the clipped kidney.

Systolic blood pressure was measured in the tail with the rats awake, using a programmed electro-sphygmomanometer and an MK-IV physiograph from Narco Bio Systems (Houston, Texas). Rats were allowed free access to water and received a standard rat pellet diet throughout the experiments.

Micropuncture

Anesthesia was induced with Inactin (100 mg/kg i.p.). Following tracheostomy, rats were prepared in routine fashion for micropuncture, as described previously. Briefly, the jugular vein, femoral artery, and bladder were catheterized with PE-50 tubing; the right kidney was exposed through a flank incision, placed in a lucite holder, and packed with thin-flowing silicone (Xantopren, Bayer) and the surface covered with Ringer's solution. The femoral artery catheter was used for periodic blood sampling and monitoring of the mean arterial pressure (MAP) with a transducer (Model P23 Db, Statham Instruments, Gould Division Inc. Hato Rey, Puerto Rico) connected to a direct writing recorder (Model 7712, Hewlett Packard, Waltham, Massachusetts). During the operation, rats received a continuous infusion of plasma (1% of body weight) with the rats awake, using a programmed electro-sphygmomanometer and an MK-IV physiograph from Narco Bio Systems (Houston, Texas). Rats were allowed free access to water and received a standard rat pellet diet throughout the experiments.

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In all experiments, glomerular hemodynamics were measured as follows: exactly timed (3-minute) samples of fluid were collected from the proximal tubules after inserting an oil block in six nephrons for determining flow rate, inulin concentration, and calculation of SNGFR. Coincident with these tubular fluid collections, three or four samples of femoral arterial blood were obtained in each period for determination of systemic arterial hematocrit (Hct) and inulin concentration in plasma. In addition, two or three samples of urine from the bladder were collected for determination of flow rate and inulin concentration, for calculation of the whole kidney glomerular filtration rate (GFR). Additional proximal tubules were punctured for measuring free flow (FFP) and stop flow pressures (SFP) with a continuous recording, servo null micropipette transducer, using pipettes with an outer tip diameter of 6–8 μm containing 1 M NaCl. The hydraulic output of the servo system was coupled electronically to a second channel of the Hewlett Packard recorder by means of a pressure transducer. These measurements were obtained in all rats except in one from the HBP group.

To estimate the colloid osmotic pressure in the glomerular capillaries, protein concentration (C) was measured in plasma from the femoral arterial blood, and in plasma obtained by puncturing the surface efferent arterioles ("star vessel"). Colloid osmotic pressure (C) was calculated according to the equation of Landis and Pappenheimer. Values for C, and thus C, from the femoral arterial plasma were taken as representative of values of C and C for the afferent end of the glomerular capillary network. The estimates of pre- and postglomerular plasma protein concentrations permitted calculation of the single nephron filtration fraction (SNFF) and the initial glomerular capillary plasma flow rate (QG) using equations given elsewhere. Since the profile of C along the glomerular capillary is not linear, Kf and effective filtration pressure were calculated with the differential equation given by Blantz et al., under the condition of constant hydrostatic pressure along the glomerular capillaries. Tubuloglomerular feedback was evaluated with the following methodology.

Measurement of Proximal and Distal Single Nephron Glomerular Filtration Rate (SNGFR)

A micropipette with an outer tip diameter of 6–8 μm containing a 1% lissamine green solution was inserted into a proximal convolution to allow visualization of the proximal and distal segments of the same nephron. After placement of an oil block, fluid was collected, first from the distal segment and later from the proximal tubule, to determine SNGFR in the same nephron. Small amounts of the dye solution were injected to insure complete collections. In each animal, four nephrons were studied in this fashion.

Measurement of Stop Flow Pressure With and Without Perfusion to the Macula Densa

For this manipulation, a dye-filled pipette was inserted into the proximal tubule to localize the distal segment. A high density grease block was then injected one or two convolutions down in the proximal tubule, the servo pipette was inserted proximal to the block, and the perfusion pipette was placed distal to the block in the proximal tubule. The composition of the perfusate was Na, 140 mEq/liter, Cl 103 mEq/liter, HCO3, 40 mEq/liter, K 3 mEq/liter, and lissamine green 0.1%. Stop flow pressure was measured during conditions of zero flow to the macula densa and a flow greater than 40 nl/min. Three or four nephrons were studied with this technique in each animal.

Analysis

The volume of fluid collected from an individual proximal tubules was estimated from the length of the fluid column in a constant bore capillary tube of known internal diameter. The concentration of inulin in the tubular fluid was measured usually in triplicate by the microfluorescence method of Vureck and Pegram. Inulin concentrations in plasma and urine were determined by the macroanthrone method of Davidson et al. Protein concentrations were determined in efferent arteriolar and femoral arterial blood plasma, usually in duplicate, using the fluorometric method of Viets et al.

Results are expressed as means ± standard error. Student's t test was used for statistical analysis.
Results

Renal artery stenosis produced sustained hypertension after a few days in all rats. Systolic blood pressure rose from 101 ± 4 to 171 ± 6 mm Hg at 2 months. Nephrectomy of the clipped kidney normalized blood pressure in 12 rats (NBP), and 10 remained hypertensive (HBP). During the hypertensive stage, there was no difference in systolic pressure between HBP and NBP (173 ± 10 vs 170 ± 7 mm Hg).

Values for SNGFR, QA, and \( P^p \) were similar in both groups (table 1). SNGFR and QA were elevated as expected 2 months after unilateral nephrectomy. Persistence of high blood pressure was associated with an increment in SFP, glomerular capillary pressure (\( P_{GC} \)), and mean effective glomerular filtration pressure (EFP). All these differences were statistically significant \( (p < 0.05) \).

Afferent resistance was increased in most of the rats of the HBP group. However, the difference between mean values \((2.11 \pm 0.24 \text{ vs } 1.53 \pm 0.26 \text{ dyn-sec-cm}^{-3}\)\) did not reach statistical significance \( (p < 0.0625) \) because of individual variability.

Table 1. Hemodynamic Determinants of Glomerular Filtration in Rats with Normal Blood Pressure (NBP) and High Blood Pressure (HBP) After Nephrectomy of the Clipped Kidney

<table>
<thead>
<tr>
<th></th>
<th>NBP (n = 12)</th>
<th>HBP (n = 10)</th>
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<tbody>
<tr>
<td>Mean arterial pressure (MAP) (mm Hg)</td>
<td>105.8 ± 2.8</td>
<td>135.9 ± 2.9†</td>
</tr>
<tr>
<td>Glomerular filtration rate (nl/min)</td>
<td>1.45 ± 0.18</td>
<td>1.57 ± 0.17</td>
</tr>
<tr>
<td>Single nephron glomerular filtration rate (SNGFR) (nl/min)</td>
<td>51.5 ± 5.6</td>
<td>56.9 ± 8.9</td>
</tr>
<tr>
<td>Single nephron plasma flow ( (Q_A) ) (nl/min)</td>
<td>208.5 ± 41.9</td>
<td>205.0 ± 23.0</td>
</tr>
<tr>
<td>Single nephron blood flow (nl/min)</td>
<td>436.7 ± 90.0</td>
<td>368.0 ± 40.2</td>
</tr>
<tr>
<td>Filtration fraction</td>
<td>0.27 ± 0.02</td>
<td>0.29 ± 0.02</td>
</tr>
<tr>
<td>Afferent oncotic pressure ( (\Pi_{A}) ) (mm Hg)</td>
<td>16.7 ± 1.8</td>
<td>17.0 ± 0.7</td>
</tr>
<tr>
<td>Efferent oncotic pressure ( (\Pi_E) ) (mm Hg)</td>
<td>25.3 ± 1.4</td>
<td>28.5 ± 0.9*</td>
</tr>
<tr>
<td>Free flow pressure (FFP) (mm Hg)</td>
<td>10.6 ± 0.7</td>
<td>10.6 ± 0.3</td>
</tr>
<tr>
<td>Stop flow pressure (SFP) (mm Hg)</td>
<td>25.7 ± 0.9</td>
<td>29.4 ± 1.1†</td>
</tr>
<tr>
<td>Glomerular capillary pressure ( (P_{GC}) ) (mm Hg)</td>
<td>41.6 ± 2.4</td>
<td>46.3 ± 1.1*</td>
</tr>
<tr>
<td>Mean effective filtration pressure ( (EFP) ) (mm Hg)</td>
<td>29.2 ± 1.3</td>
<td>12.9 ± 0.9†</td>
</tr>
<tr>
<td>Hydrostatic pressure ( (\Delta P) ) (mm Hg)</td>
<td>31.4 ± 2.2</td>
<td>35.7 ± 0.9*</td>
</tr>
<tr>
<td>Afferent resistance ( (AR) ) (dyn-sec-cm(^{-5}))</td>
<td>1.53 ± 0.26</td>
<td>2.11 ± 0.24</td>
</tr>
<tr>
<td>Permeability coefficient ( (Kf) ) (nl/sec/mm Hg)</td>
<td>0.11 ± 0.02</td>
<td>0.08 ± 0.01</td>
</tr>
</tbody>
</table>

HBP vs NBP, †p < 0.05.
HBP vs NBP, †p < 0.025.

The values for Kf showed no difference between groups, even though in the HBP group, similar values of SNGFR were associated with higher levels of \( P_{GC} \) and SFP, suggesting that glomerular permeability was actually reduced.

To further evaluate the relationship between SFP and SNGFR and possible alterations in Kf in the hypertensive rats, values of MAP, SNGFR, and SFP were analyzed individually for each rat from both groups. As shown in figure 1, SNGFR did not rise in rats with a higher MAP despite an increasing stop flow pressure \( (r = 0.64, p < 0.05) \). These data suggest that persistence of hypertension after nephrectomy of the clipped kidney is associated with a decrease in glomerular permeability, which is more apparent with greater degrees of hypertension.

The tubuloglomerular feedback system (TGFS) was studied in nine of 12 NBP and seven of 10 HBP rats. The activity of this system was evaluated by the changes in SNGFR and FFP induced by interrupting tubular flow to the macula densa. The magnitude of these changes reflected the activity of the system which is directly influenced by the level of systemic MAP.4 Results are shown in table 2.

Stop flow pressure increased when perfusion to the macula densa was stopped in both groups. All increments were significant, and no difference in the magnitude of the changes was apparent between groups. Similarly, SNGFR measured in the distal tubule was decreased compared to estimates based on collections of fluid made from the proximal tubule when the flow distal to the collection site was interrupted. However, the magnitude of the changes was strikingly different between the groups. In the NBP group, in which MAP was 105.8 ± 2.8 mm Hg, a marked increment in SNGFR \((23.4 ± 5.6 \text{ nl/min}, p < 0.01) \) was observed.
TABLE 2. Tubuloglomerular Feedback System Activity Estimated as SFP and SNGFR with and without Distal Perfusion in Rats with Normal Blood Pressure (NBP) and High Blood Pressure (HBP) after Nephrectomy of the Clipped Kidney

<table>
<thead>
<tr>
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<th>NBP</th>
<th>HBP</th>
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<tr>
<td>Stop flow pressure (SFP) (mm Hg)</td>
<td></td>
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<tr>
<td>without distal perfusion</td>
<td>25.0 ± 0.9</td>
<td>28.1 ± 1.1</td>
</tr>
<tr>
<td>with distal perfusion</td>
<td>21.7 ± 1.4*</td>
<td>22.6 ± 1.1*</td>
</tr>
<tr>
<td>Δ</td>
<td>3.3 ± 1.2</td>
<td>5.6 ± 2.1</td>
</tr>
<tr>
<td>Single nephron glomerular filtration rate (SNGFR) (nl/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>proximal</td>
<td>62.6 ± 9.5</td>
<td>49.5 ± 5.8</td>
</tr>
<tr>
<td>distal</td>
<td>39.2 ± 6.0*</td>
<td>37.6 ± 5.2*</td>
</tr>
<tr>
<td>Δ</td>
<td>23.4 ± 5.6*</td>
<td>11.0 ± 3.8</td>
</tr>
</tbody>
</table>

*p < 0.05, with distal perfusion vs without distal perfusion.
†p < 0.05, NBP vs HBP.

In contrast, the HBP group, the rise in SNGFR was considerably smaller (11.0 ± 3.8), in spite of a much higher level of systemic MAP (135.9 ± 2.9 mm Hg), indicating a decreased sensitivity of the tubuloglomerular feedback system.

Discussion

The aim of our study was to characterize the glomerular hemodynamics in a model of persistent renovascular hypertension after nephrectomy of the clipped kidney. A slight increase in the afferent resistance, normal GFR in spite of increased stop flow pressure (SFP), and a decrease in the TGFS sensitivity were associated with this form of hypertension. Increased afferent resistance has previously been shown in the earlier stages of this model and in other models of experimental hypertension except those that are salt-dependent. The increase in afferent resistance with elevated MAP suggests that it occurs in response to autoregulation. However, it could also be secondary to structural damage associated with a reduction in the arterial lumen, as has been previously demonstrated by different methods (microspheres, scanning microscopy) in other experimental models. The finding in the hypertensive group that the rise in SFP was not followed by a concomitant increase in SNGFR suggests a reduction in glomerular permeability. However, the difference in Kf values between groups did not reach statistical significance, but the observed correlation between individual values of MAP and SFP indicates that, at least in the more hypertensive rats, a decreased glomerular permeability could be present. On the other hand, when we analyzed the response to interruption of flow to the macula densa; the increase in SNGFR in the hypertensive rats was significantly less, in spite of a similar increase in SFP, further supporting a coexistent reduction in glomerular capillary permeability. The reduced Kf could be due to structural alterations in the capillary wall that diminish permeability. In different forms of hypertension, including human, thickening of the basal membrane has been demonstrated in early stages, Steiner et al. and Schweitzer et al. have suggested that the increase in capillary pressure that appears early in the course of hypertension could be the cause of this change in capillary permeability. However, in other models of hypertension in which capillary pressure increases even more, Kf is reported to be normal or even increased. A reduction in Kf could also result from mesangial contraction by reducing the effective filtration area. Recently, Schor et al. have suggested that angiotensin II is the final pathway by which vasoactive substances regulate Kf through mesangial contraction. Our model has been characterized as associated with activation of the renin-angiotensin system (RAS), and decreased values of Kf in early stages. In late stages, as in our study, plasma values of angiotensin II are normal but hypertension responds to inhibition of the RAS with converting-enzyme inhibitor. Moreover, Mendelsohn has recently shown that the contralateral kidney has a normal or increased concentration of angiotensin II in spite of concomitant renin depletion. These data would suggest that the decrease and maintenance of low values of Kf could be secondary to a persistent generation of local angiotensin II.

Independent of its mechanism, this alteration becomes particularly important because in conditions of filtration pressure disequilibrium, as occurred in our rats, SNGFR is highly dependent on Kf and rather independent of flow rate or transcapillary hydraulic pressure. Under such conditions, a high filtration pressure is required to overcome the reduction in Kf in order to maintain GFR at normal levels.

In our study, the sensitivity of the TGFS was evaluated by the changes induced in SNGFR by interrupting flow to the macula densa (proximal vs distal SNGFR). However, the differences observed in the NBP group (23.4 nl/min, 63%) and HBP group (11 nl/min, 29%) appear to be considerably greater than those previously reported in normal two-kidney rats (6 nl/min, 24%). One possible explanation for this discrepancy is that, in our rats there was considerable hypertrophy of the remaining kidney that resulted in a 65% increase of basal (distal) SNGFR, under these conditions it is possible that the same changes in pressure and flow could lead to greater changes in filtration rate.

Independent of absolute values, our results demonstrated a clear difference between the NBP and HBP groups, indicating that persistent hypertension was associated with diminished sensitivity of the tubuloglomerular feedback system. This finding has been shown previously in earlier stages of Goldblatt II hypertension. The mechanism responsible is unknown, but it has been proposed that lack of angiotensin II and/or vascular damage of the afferent arteriole could be the causal factor. Recent studies by Mendelsohn and Ploth et al. would tend to discard the first possibility. On the other hand, demonstration that structural alterations in the afferent arteriole were not associated with a loss of TGFS sensitivity in other experimental mod-
els"\textsuperscript{5} militates against the second one. An additional possibility is that this alteration resulted from a decreased glomerular capillary permeability coefficient. Previous studies by Ichikawa et al.,\textsuperscript{23} have demonstrated that the response to TGFS is partly mediated by modifications in Kf. Accordingly, if Kf is reduced, the same change in filtration pressure will induce a smaller change in SNGFR. In our study, interrupting flow to the macula densa in the HBP group was followed by a smaller rise in SNGFR, in spite of a similar increment in stop flow pressure.

In summary, persistent renovascular hypertension was associated with slightly increased afferent resistance, diminished glomerular capillary permeability, and hyporesponsiveness of TGFS. All these alterations seem to reset the kidney in such a way that increased filtration pressure is required to maintain the GFR at normal levels. At the same time, these adaptations of renal function can contribute to perpetuate elevated systemic arterial pressure.

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