Original Article

Nephron number determines susceptibility to renal mass reduction-induced CKD in Lewis and Fisher 344 rats: implications for development of experimentally induced chronic allograft nephropathy

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Abstract

Background. The Fisher 344 (F344) rat kidney transplanted to a Lewis rat recipient is a common model of chronic renal allograft nephropathy (CAN); however, CAN does not develop when the Lewis kidney is grafted into a F344 recipient. In this study we investigated whether a difference in nephron number/glomerular volume exists between the strains that could contribute to a greater susceptibility to development of kidney disease in the F344.

Methods. Separate animals, male F344 and Lewis rats, were subjected to either sham surgery or right uni-nephrectomy and infarction of 2/3 of the left kidney, to produce a 5/6 ablation/infarction injury (5/6 A/I). Serial urinary protein excretions were measured, a terminal 24-h creatinine clearance was obtained and rats were killed 11 weeks after surgery and kidneys were harvested for pathology. Glomerular volumes were measured in the sham controls of each strain. Glomerular number was counted in separate, normal rats of each strain.

Results. The normal F344 had ~30% fewer glomeruli than Lewis rats that were larger in volume. The sham F344 had similar creatinine clearance and glomerular structure to the Lewis shams, although BP and urine protein excretion were higher. After 5/6 A/I the F344 developed more severe proteinuria and structural kidney damage. When factored for kidney weight, the F344 rats exhibited a greater compensatory hyperfiltration in response to 5/6 A/I, compared to Lewis.

Conclusions. The F344 strain is more vulnerable to development of progressive kidney damage due to 5/6 A/I, compared to the Lewis. This is likely due to the lower nephron number/greater glomerular volume of the F344 that may also account for the greater susceptibility to CAN exhibited by this strain.

Keywords: creatinine clearance; 5/6 renal ablation/infarction; glomerulosclerosis; proteinuria; rat strain

Introduction

Nephron number endowed during fetal development determines later susceptibility to hypertension and chronic kidney disease (CKD), and genetic background is a major determinant of nephron number [1–4]. When few functional glomeruli are present they tend to hypertrophy, thus increasing volume, and increased glomerular volume predicts later development of hypertension and progressive renal disease [5,6]. Thus, glomerular number is likely to influence the development of any specific CKD.

The most widely used experimental model of chronic renal allograft rejection is the Fisher 344 (F344) kidney to the Lewis rat recipient transplantation model [7,8]. This represents a relatively mild immunological ‘mismatch’, and if acute rejection is suppressed with short-term immunosuppression, the chronic rejection and subsequent chronic allograft nephropathy (CAN) develop slowly over several months. Interestingly, when the Lewis rat kidney is grafted into the F344 recipient the kidney transplants do not develop CAN [8]. This highlights the importance of alloantigen-independent factors in the development of CAN.

There are alloantigen-independent donor-related factors that can impact on late allograft function, which can also influence the rate of progression of other forms of chronic kidney disease (CKD), including nephron volume and number [1–3,9–12]. In this study we investigated (1) the glomerular number/volume in the normal kidney of the two strains and (2) the relative vulnerability of F344 and Lewis rats to an alloantigen-independent model of CKD, produced by right uni-nephrectomy and infarction of 2/3 of the left kidney (5/6 A/I).
Subjects and methods

Inbred male F344 (RT1v1, from Harlan Sprague-Dawley, Indianapolis, n = 19) and male Lewis (RT1, from Harlan Sprague-Dawley, Indianapolis, n = 17) were purchased at 10–12 weeks of age. All animals were maintained on standard rat chow and water ad libitum. Sham surgery and 5/6 ablation/infarction (A/I) were performed on rats of each strain as follows: the A/I surgery involved lateral flank incision to remove the right kidney and ligate branches of the left renal artery to infarct ∼2/3 of the left kidney mass. A/I and sham surgery (without removal of renal mass) were done under general anesthesia (using a 1:1 mixture of A/I and sham surgery (without removal of renal mass) were done under general anesthesia (using a 1:1 mixture of 1:1 mixture of ketamine/xylazine). Blood pressure (BP) was measured under anesthesia via aorta just prior to killing; then blood was withdrawn, and tissues were perfused with PBS and harvested. Plasma creatinine was determined as above and BUN was measured using a Sigma kit (640-A).

Results

At ∼12–14 weeks of age, in the baseline state the body weight (BW) and kidney weight (KW) of the F344 rats were significantly less than those of the Lewis rats while the KW/BW ratio was similar (Table 1). Over the 11-week observation period both rat strains showed increases in BW and KW in the sham control group, with the F344 BW increase being greater than that in the Lewis, P < 0.05 (Table 2). The mean BP was higher in the F344 versus Lewis rats (P < 0.005) although BUN and Ccr (total and factored for kidney weight) were not different between the F344 versus Lewis rats (Table 2). The mean BP was higher in the F344 versus Lewis rats (P < 0.001). There is no difference in the percentage of sclerosed glomeruli in the young adult sham rats of each strain (Table 2; and the overall glomerular injury scale was similar in Lewis and F344 shams, P < 0.05). This is due to the development of functional remnant 1/6 kidney (scar tissue removed) shown to have a significant reduction in glomerular injury.

Table 1. Summary of body weight (BW) and kidney weight (KW) in the F344 and Lewis sham (S) and 5/6 A/I (A/I) rats

<table>
<thead>
<tr>
<th>Strain</th>
<th>BW, g baseline</th>
<th>BW, g 11 weeks</th>
<th>KW, g right</th>
<th>KW, g left</th>
<th>KW/BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>F344 S</td>
<td>208 ± 2</td>
<td>329 ± 6</td>
<td>1.17 ± 0.07</td>
<td>1.12 ± 0.04</td>
<td>0.0036 ± 0.0002</td>
</tr>
<tr>
<td>F344 A/I</td>
<td>201 ± 6</td>
<td>297 ± 10</td>
<td>0.72 ± 0.02</td>
<td>1.46 ± 0.08</td>
<td>0.0036 ± 0.0002</td>
</tr>
<tr>
<td>P value</td>
<td>ns</td>
<td>ns</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>ns</td>
</tr>
<tr>
<td>Lewis S</td>
<td>240* ± 2</td>
<td>351* ± 6</td>
<td>1.45* ± 0.06</td>
<td>1.24* ± 0.04</td>
<td>0.0041 ± 0.0002</td>
</tr>
<tr>
<td>Lewis A/I</td>
<td>240* ± 2</td>
<td>348* ± 7</td>
<td>1.02* ± 0.02</td>
<td>1.85* ± 0.07</td>
<td>0.0043* ± 0.0003</td>
</tr>
<tr>
<td>P value</td>
<td>ns</td>
<td>ns</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Significant difference from respective Fisher 344 group, P < 0.05.

For shams the right kidney harvested at sacrifice is compared to the sacrifice BW.

For 5/6 A/I rats the right kidney harvested at the time of surgery is compared to the baseline BW.
significant and similar hypertrophy in F344 (103 ± 9%) and Lewis (81 ± 9%) rats 11 weeks after surgery (Table 1).

In response to 5/6 A/I, the F344 rats developed significant proteinuria, first being evident ~6 weeks after reduction of renal mass (Figure 1). In contrast, the 5/6 A/I Lewis rats had no change in urine protein excretion over the 11-week period. BUN and Pcr increased after 11 weeks of 5/6 A/I and in the Lewis this value was reduced after A/I. There were no significant changes in kidney weight, there was no change after A/I in F344 but was lower in the A/I rats of each strain versus respective shams.

In the F344 with A/I was even greater (±) damage compared to the Lewis A/I rat versus Lewis sham <5% in the Lewis A/I rats. There was a marked increase in overall injury in the Lewis A/I rat versus Lewis sham (<0.005). The total percentage of sclerosed glomeruli was higher in the F344 versus Lewis in the remnant. There were marked compensatory increases in GFR (estimated from 24 h Ccr) in the remnant in both strains but to greater absolute values (Table 2) compared to Lewis.

The arterial BP did not change with 5/6 A/I in either F344 or strain differences in the Ccr/gKW in either shams or A/I. There were no measure-ments of glomerular haemodynamics in the present study, but it is likely that the greater the compensatory hyperfiltration response to nephron loss, the more marked the

Discussion

The main finding in this study is that the F344 rat develops more severe CKD in response to 5/6 A/I than the Lewis rat, and that this is associated with fewer nephrons and greater glomerular volume in the vulnerable, F344 strain. Since the F344 and Lewis rats are commonly used to produce an experimental model of CAN, this ‘mismatch’ in nephron number between donor (F344) and the Lewis recipient is likely to contribute to the development of CAN.

There are many alloantigen-independent donor-related factors that can influence the long-term survival of a renal transplant [14], and nephron number seems to be a major determinant. Brenner and Milford originally hypothe-sized that when nephron under-dosing occurs in a renal transplant, i.e. where nephron supply is inadequate for the recipient demand, this contributes importantly to development of CAN [15]. Experimental support was obtained in the F344 to Lewis allograft model where graft survival correlated directly with transplanted nephron number, and in the presence of two, rather than a single donor kidney, CAN was virtually absent [10,16]. Also, the appearance of CAN with a single transplanted kidney was delayed when the second native kidney was retained for 8 weeks post-transplant, and only developed after removal of the native kidney [10]. In the present study we report that the F344 has ~30% fewer glomeruli with greater volume than the Lewis rat, and since the F344 is the usual donor, this is likely to accelerate the development of CAN in this allograft model. Indeed, the nephron excess in the Lewis is the likely expla-nation why CAN does not develop when a Lewis donor kidney is grafted into a F344 recipient [8].

Nephron number also influences the rate of progression of other forms of CKD [1–3]. In this study we observed that the nephron-deficient F344 exhibited much more rapid progression of CKD compared to Lewis rats when subjected to an alloantigen-independent model of CKD produced by right uni-nephrectomy and infarction of 2/3 of the left kidney. There were marked compensatory increases in GFR (estimated from 24 h Ccr) in the remnant in both strains but the Ccr factored for viable kidney remnant remained unchanged in F344 while falling in the Lewis. This, together with the fewer number of nephrons in the F344, implies proportionally greater compensatory increases in SNGFR in F344 than Lewis in the remnant. There were no measure-ments of glomerular haemodynamics in the present study, but it is likely that the greater the compensatory hyperfiltration response to nephron loss, the more marked the

### Table 2. Indices of kidney function, structure (percentage of glomeruli sclerosed, GS) and blood pressure (BP) in the F344 and Lewis sham and 5/6 A/I rats

<table>
<thead>
<tr>
<th></th>
<th>Per (mg/dl)</th>
<th>BUN (mg/dl)</th>
<th>Ccr (ml/min)</th>
<th>Ccr (ml/min/gKW)</th>
<th>BP (mmHg)</th>
<th>GS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F344 S</td>
<td>0.59 ± 0.04</td>
<td>17 ± 1</td>
<td>4.1 ± 0.6</td>
<td>1.85 ± 0.29</td>
<td>103 ± 2</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>F344 A/I</td>
<td>1.07 ± 0.13</td>
<td>47 ± 5</td>
<td>2.4 ± 0.3</td>
<td>1.71 ± 0.30</td>
<td>107 ± 5</td>
<td>56 ± 3</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.01</td>
<td>&lt;0.001</td>
<td>&lt;0.05</td>
<td>ns</td>
<td>ns</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Lewis S</td>
<td>0.41* ± 0.01</td>
<td>21 ± 2</td>
<td>5.4 ± 0.4</td>
<td>2.04 ± 0.19</td>
<td>75* ± 3</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>Lewis A/I</td>
<td>0.68* ± 0.03</td>
<td>32* ± 2</td>
<td>3.2 ± 0.3</td>
<td>1.37 ± 0.41</td>
<td>84* ± 4</td>
<td>29* ± 2</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.001</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.05</td>
<td>ns</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*Significant difference from respective Fisher 344 group, P < 0.05.

**Fig. 1.** The 24-h urinary total protein excretion (U_{protV}) in the baseline state (Week 0) and following either 5/6 renal mass reduction by ablation/infarction (A/I) or sham surgery, in F344 and Lewis, male rats.

*denotes a significant (P < 0.05) change from baseline.
afferent arteriolar vasodilation and consequent glomerular hypertension are, a primary risk factor for progression of CKD [4].

As shown here, a lower nephron number correlates with greater volume of the individual glomeruli. In the present study the total glomerular filtration area (nephron number × individual glomerular volume) was approximately equal in F344 and Lewis despite the lower nephron number and higher glomerular volume in the F344 (42.3 and 45.2 mm³ respectively). The original hypothesis by Brenner, Garcia and Anderson [4] suggested that there was an inverse relationship between the total glomerular filtration surface area and risk of hypertension and progression. However, increased glomerular volume is a risk factor for progression of CKD [17], and it now appears that many small glomeruli are preferable to fewer larger glomeruli and that the larger the individual glomerular volume, the greater is the tendency to develop hypertension and progressive renal disease [5,6]. The mechanism by which increased glomerular volume causes renal damage is likely due to increases in intramural tension as glomerular volume (diameter) increases [17]. Thus glomerular hypertrophy and glomerular hypertension act synchronously to exacerbate development of CKD.

There are many factors that determine nephron number, some of which are likely to be genetically mediated. There are several examples of inbred rat strains that exhibit a low nephron number and susceptibility to CKD, such as F344 (present study) and the Munich Wistar Frompter [18]. Conversely, Wistar Furth rats have a high nephron number and are resistant to several forms of CKD compared to Sprague-Dawley [1,2]. In man, there is clear evidence that a low nephron number associates with hypertension and CKD. There is an astounding almost 10-fold variation in the nephron number in man of various ethnic origins, but there is no clear evidence of any genetic association. What is clear is that early developmental events program the kidney for nephron number and that a hostile uterine environment leading to fetal malnutrition is associated with a reduced nephron number and a later susceptibility to hypertension and CKD [19,20].

In summary, this study provides another example of an association between an inborn nephron deficit and susceptibility to later development of CKD. This study has particular relevance to the experimental renal transplant literature since the donor kidney widely used in the rodent model of CAN is derived from the F344 rat, which has a low nephron number. We recognize the complexity of the processes leading to CAN but consider that the nephron number makes a significant contribution to the non-immunological causes of CAN.

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Conflict of interest statement. None declared.

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