Glomerular Ultrafiltration in Normal and Preeclamptic Pregnancy

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Abstract. GFR and renal plasma flow (RPF) decrease in preeclampsia, a serious hypertensive complication of pregnancy. Serial data derived in late pregnancy (LP) and >5 mo postpartum (PP) in 13 healthy controls and 10 preeclamptic women (13 and 5, respectively) returning PP for theoretical analysis of neutral dextran sieving curves (θD), are presented and are used to calculate the key determinants of glomerular ultrafiltration. Normal LP hyperfiltration was associated with increases in RPF and the ultrafiltration coefficient (Kf), as well as in the nondiscriminatory shunt pathway (ω0) and the SD of pore size (S). Preeclamptic LP showed the largest ω0 and S values, indicating a loss of size-selectivity, accompanying reduced Kf and RPF, both of which are implicated in the relative hypofiltration. Despite a 100-fold increase in urinary albumin excretion (UAЕ), LP preeclamptic θD values were reduced for the equivalent neutral dextran (36Å), providing indirect evidence for a loss of glomerular barrier charge-selectivity. All the determinants of GFR and all modeled parameters were comparable across both groups PP, strong evidence that preeclamptic glomerular dysfunction resolves.

Preeclampsia, a major cause of maternal and fetal morbidity and mortality, is a multisystem disorder affecting, among others, the hepatic, hematologic, and renal systems. The latter include decreases in renal plasma flow (RPF) and GFR as well as proteins in that may be in the nephrotic range. Impaired RPF and disordered glomerular barrier integrity could both contribute to hypofiltration (1). One goal of our study was to determine the relative contributions of each in preeclampsia; the other being the quantification of glomerular barrier parameters in relation to proteinuria. Renal hemodynamics were analyzed using clearance of PAH and inulin, while fractional dextran clearances (θD), combined with mathematical modeling, provided glomerular sieving data, including estimation of the ultrafiltration coefficient (Kf) and glomerular porosity. Preeclamptic and healthy women were studied in late pregnancy (LP) and again 5 mo postpartum (PP).

Materials and Methods

Subjects

Thirteen normotensive, healthy white women with no family history or evidence of renal or cardiovascular disease were studied during LP (36 to 38 wk) and again at least 5 mo PP. Ten untreated preeclamptic primigravidae were also studied in LP, of which 5 returned PP. All met the criteria of the International Society for the Study of Hypertension in Pregnancy (ISSHP) for preeclampsia (de novo hypertension >140/90 mmHg; proteinuria >500 mg/24 h) (2). When PP, none were hypertensive, ingesting oral contraceptives, taking medication or breast-feeding. All gave informed written consent to protocols approved by the Joint Ethics Committee of Newcastle and North Tyneside Health Authority and the Universities of Newcastle upon Tyne and Northumbria at Newcastle.

Protocols

On the study morning, each subject ate a light carbohydrate breakfast but avoided tea and coffee. A 24-h urine collection was completed before the morning of the study, from which total protein excretion (TPE) was calculated. With the subject seated in a temperature-controlled room, basal blood tests were taken (full blood count, urea, and electrolytes). A priming infusion of 48 ml of dextran (10% Dextran-40 in 0.9% saline; Baxter Healthcare, UK), 10 ml of inulin (Inutest; Fresenius Kabi, Austria), and 2 ml of p-aminohippurate (PAH; 20% PAH; Merck, Sharp & Dohme) was administered over 10 min followed by a sustaining infusion (10% dextran; 5% inulin, and 2% PAH) at 1 ml/min (3). After an hour to allow equilibration, the volunteer voided and then three 20-min urine collections were made and blood sampled in the mid-period (clearances 1, 2, and 3). Water was ingested to replace preceding urinary losses. BP was measured at 30 min intervals (Datascope).

GFR and RPF were calculated from the mean of three inulin and PAH clearances (1, 2, and 3). The renal PAH extraction rate in pregnancy was assumed to be 0.85 (4). The clearances of neutral dextrans (θD) were measured in clearance period 3. Analytical procedures and across-batch coefficients of variation (CV) for inulin, PAH, total serum protein, TPE, urinary albumin excretion (UAЕ), and dextran have been described elsewhere, as have the formulae used in all the calculations (5). Dextran separation, for radii ranging from 31 to 65Å, was undertaken using gel permeation chromatography with a

Received July 3, 2001. Accepted October 4, 2002.

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1046-6673/1403-0648

Journal of the American Society of Nephrology

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DOI: 10.1097/01.ASN.0000051724.66235.E0
refractive index detector where the integrator divided the chromatogram into 38 integrations per ml of elution volume, with no interference from protein(s) or inulin. Calibration with five standards (6.7, 11.7, 27.0, 42.8, and 78.8 kD) was undertaken every 3 wk, and the 42.8 kD standard was used daily. Further details of chromatography and integration using online analysis programs (PCGCP software) are described in a previous publication (5).

Renal Hemodynamic Measurements

Afferent glomerular oncotic pressure \( (\pi_A) \) was derived from total serum protein concentration \( (C) \) in g/dl using the following formula (6):

\[
(1) \quad \pi_A = 2.1C + 0.16C^2 + 0.009C^3
\]

Filtration fraction \( (FF) \) is calculated from GFR/RPF. The relationship between GFR and its determinants was examined using the following formula:

\[
(2) \quad GFR = K_f (\Delta P - \pi_{GC})
\]

\( \pi_{GC} \) is the glomerular oncotic pressure and can be approximated by taking a mean of afferent \( (\pi_A) \) and efferent \( (\pi_E) \) glomerular oncotic pressures (7). This provides an underestimate of \( K_f \) because \( \pi_{GC} \) is calculated assuming a linear increase in protein concentration between the afferent and efferent ends of the glomerulus, which is not the case. Methods of estimating \( \pi_{GC} \) are detailed elsewhere (7). \( \pi_E \) is approximated using the following formula:

\[
(3) \quad \pi_E = \pi_A/(1 - FF)
\]

Dextran Sieving Analysis and Heteroporous Membrane Modeling

Dextran-40, a polymer of anhydroglucose encompassing a wide range of molecular weights, is neither secreted nor reabsorbed by the renal tubule with urinary concentration reflecting transglomerular passage, thus providing glomerular size-selectivity data. Mathematical modeling combines fractional dextran sieving data \( (\theta_d) \) with \( \pi_A \) and renal hemodynamic measurements at an assumed transglomerular hydrostatic pressure difference \( (\Delta P) \), enabling otherwise inaccessible ultrafiltration parameters to be estimated. Two theoretical models of glomerular function were utilized (7,8,9,10). Each model represents the glomerular capillary wall as a heteroporous membrane characterized by two pore parameters. The isoporous + shunt model assumes that the capillary wall is perforated by a series of restrictive pores of identical radius \( (r_0) \) with a parallel shunt pathway \( (\alpha_0) \) that fails to restrict the passage of large molecules. The log-normal model represents the capillary wall as being perforated by a single continuous population of pores with a log-normal distribution of radii, characterized by a mean pore radius \( (U) \) and SD \( (S) \). Both models take into account the effect of GFR determinants on convective and diffusive transmembrane transport of neutral dextrans and require input values for GFR, RPF, \( \pi_A \), and \( \Delta P \).

It is important to emphasize that \( \Delta P \) cannot be measured directly in humans, and an assumed range (37 to 43 mmHg) similar to that found in micropuncture studies of rat pregnancy (11) was assigned. These choices for \( \Delta P \) are arbitrary, but, bearing in mind glomerular physiology, the actual value of \( \Delta P \) must be greater than \( \pi_{GC} \) for filtration to occur and is likely to be significantly less than systemic arterial pressure.

Each model estimates changes in \( \pi_{GC} \), volume flows, and fluxes along the glomerular capillary, allowing computation of a series of theoretical \( \theta_d \) curves, each with values for capillary wall porosity \( (r_0 \) and \( \alpha_0 \) or \( U \) and \( S) \) and \( K_f \). The closeness of fit between measured and theoretical \( \theta_d \) curves is judged by calculating the sum of \( \chi^2 \) for the range of dextran sizes between 31 and 65Å. For each assumed \( \Delta P \) value, the theoretical \( \theta_d \) curve with the closest fit to the measured \( \theta_d \) curve identifies the predicted parameters of porosity and \( K_f \). The pitfalls and merits of each of these models are discussed elsewhere (9).

Statistical Analyses

Each woman acted as her own nonpregnant control. Differences in \( \theta_d \) curves were assessed by first splitting each curve into four bands (31 to 39, 41 to 49, 51 to 59, and 61 to 65Å), and differences among band areas were assessed across test occasions. The significance of changes in GFR, RPF, \( \pi_A \), and \( \theta_d \) band area were estimated using an ANOVA for repeated measurements, and significance of differences between each stage of the study was estimated using paired or unpaired \( t \) tests as appropriate. Wilcoxon rank sum testing was used to assess differences in TPE and UAE. Data are expressed as mean ± SEM. All \( P \)-values are two-tailed, and results considered significant for \( P < 0.05 \).

Results

Hemodynamics and Renal Function

Renal hemodynamic data are shown in Table 1. In normal pregnancy, significant increases in GFR, RPF, and FF were evident (\( P < 0.001 \), \( P < 0.001 \), \( P = 0.02 \), respectively), all such changes being absent in preeclampsia.

Urinary Protein and Albumin Excretion

Before the infusion study, in normal LP, TPE did not exceed 300 mg/24 h on any test occasion. As expected, TPE was

Table 1. Normal and preeclamptic group serial changes in renal haemodynamic and functional (mean ± SEM, \( n = 13 \))

<table>
<thead>
<tr>
<th></th>
<th>GFR (ml/min)</th>
<th>RPF (ml/min)</th>
<th>FF (%)</th>
<th>MAP (mmHg)</th>
<th>( \pi_A ) (mmHg)</th>
<th>( \pi_E ) (mmHg)</th>
<th>( U_{Na} ) (μmol/min)</th>
<th>UAE median (interquartile range) µg/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal LP</td>
<td>158 ± 15</td>
<td>849 ± 50</td>
<td>18.6 ± 1.1</td>
<td>86 ± 3</td>
<td>18.90 ± 0.4</td>
<td>25.24 ± 0.9</td>
<td>0.172</td>
<td>6.1 (4.4 to 10.6)</td>
</tr>
<tr>
<td>Preeclampsic LP</td>
<td>105 ± 6</td>
<td>781 ± 38ms</td>
<td>13.5 ± 1.0b</td>
<td>111 ± 1d</td>
<td>17.52 ± 0.7ms</td>
<td>19.80 ± 0.5b</td>
<td>0.218 ± 0.038ms</td>
<td>1817 (1128 to 3455)d</td>
</tr>
<tr>
<td>Normal PP</td>
<td>92 ± 5</td>
<td>585 ± 27</td>
<td>15.7 ± 0.5</td>
<td>82 ± 7</td>
<td>24.53 ± 0.2</td>
<td>29.33 ± 0.9</td>
<td>0.156</td>
<td>8.0 (4.2 to 9.9)</td>
</tr>
<tr>
<td>Preeclampsic PP</td>
<td>108 ± 5</td>
<td>679 ± 46</td>
<td>15.3 ± 1.0</td>
<td>80 ± 6</td>
<td>22.58 ± 0.4</td>
<td>26.66 ± 0.4</td>
<td>0.240 ± 0.027</td>
<td>18.3 (N/A)</td>
</tr>
</tbody>
</table>

* LP, late pregnancy; PP, postpartum; SCR, serum creatinine; GFR, glomerular filtration rate; RPF, renal plasma flow; FF, filtration fraction; MAP, mean arterial pressure; \( \pi_A \), afferent oncotic pressure; \( \pi_E \), efferent glomerular oncotic pressure; UAE, urinary albumin excretion.

Preeclamptic LP versus Normal LP: ns, not significant; \( b P < 0.05 \); \( c P < 0.01 \); \( d P < 0.001 \); Other significant differences are highlighted in the text.
significantly higher in preeclamptic LP (mean, 2.0 g/24 h; interquartile range, 1.6 to 3.1 g/24 h; \( P < 0.0001 \)) with UAE rates (measured during collection period 3) 300 times higher than normal LP but returning to normal PP. Although quantification of UAE in a 20-min collection period is subject to timing and collection errors, there was a moderate correlation between this UAE and 24 h TPE (\( r = 0.4322 \)).

**Renal Handling of Neutral Dextrans**

Compared with normal LP, measured \( \theta_0 \) for radii 31 to 63 Å were reduced in preeclampsia (Figure 1). These reductions were statistically significant for bands 31 to 39 Å (\( P < 0.0001 \)) and 41 to 49 Å (\( P < 0.01 \)). This is in marked contrast to the PP data in which \( \theta_0 \) values were almost identical between groups.

**Theoretical Analysis of Ultrafiltration Parameters: Normal Group**

\( K_f \) values were increased in LP except at the lowest assumed \( \Delta P \) (Table 2). The log-normal model predicted reduced LP mean pore size \( U \), offset by an increase in \( S \) (the variance around the mean). The isoporous + shunt model predicted similar \( r_0 \) values in LP and PP but with the shunt \( \omega_0 \) almost doubled in LP. \( \chi^2 \) values were consistently low, with the isoporous + shunt model providing the closest overall fit to the measured \( \theta_0 \) data.

**Theoretical Analysis of Ultrafiltration Parameters: Preeclamptic Group**

\( K_f \) was reduced by 50% in preeclamptic LP returning to normal PP (Table 3). The log-normal model predicted reduced \( U \), combined with the largest \( S \). Although the isoporous + shunt model predicted \( r_0 \) increases in preeclamptic LP compared with PP, \( r_0 \) remained reduced compared with normal pregnancy. Preeclamptic LP revealed an almost twofold increase in \( \omega_0 \), which normalized PP. Once again, the isoporous + shunt model outperformed the log-normal model, with \( \chi^2 \) testing giving the best fit on each occasion.

**Discussion**

We have shown that the normal pregnancy increments in GFR and RPF were not evident in preeclampsia, thus endorsing our previous work (3,5) that in normal LP GFR increments are RPF-driven with contributions from both decreased \( \pi_a \) and increased \( K_f \). In preeclamptic LP, there was a 50% reduction in \( K_f \), and GFR values were almost identical to those PP. The proteinuria correlates with a loss of glomerular barrier size selectivity and almost certainly reduced charge selectivity too.

It is important to acknowledge that theoretical modeling of glomerular permeselectivity makes major assumptions (7,9), and circumspection is mandatory when interpreting results. Both theoretical models were, however, in close agreement (Tables 2 and 3), each predicting gestational increases in those parameters linked to clearance of larger dextrans (a widening of the pore distribution \( S \) and an increase in the nondiscriminating shunt \( \omega_0 \)), maximal in preeclamptic LP. Compared with PP values, \( K_f \) was increased in normal LP contrasting with the 50% reduction seen in preeclampsia. Although the inability to measure \( \Delta P \) in humans precludes a precise estimate of \( K_f \), the inferred reduction in preeclampsia was so great that there was little doubt that glomerular ultrafiltration would be compromised.

Of particular interest are the similarities of these results to nonpregnant human nephrotic syndrome (12), where \( K_f \) reductions were proportional to structural changes on renal biopsy

**Table 2.** Predicted values of \( K_f \) and porosity using theoretical models in normal late pregnancy (36 to 38 wk) and postpartum (>5 mo) (mean ± SEM)^a^

<table>
<thead>
<tr>
<th>Assumed ( \Delta P ) (mmHg)</th>
<th>Derived ( K_f ) (ml · min⁻¹ · mmHg⁻¹)</th>
<th>( r_0 ) (Å)</th>
<th>( \omega_0 )</th>
<th>Sum of ( \chi^2 )</th>
<th>( U ) (Å)</th>
<th>± S (Å)</th>
<th>Sum of ( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Pregnancy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>11.20</td>
<td>63.19</td>
<td>0.0050</td>
<td>1.271</td>
<td>56.25</td>
<td>1.064</td>
<td>1.328</td>
</tr>
<tr>
<td>40</td>
<td>8.94</td>
<td>62.66</td>
<td>0.0063</td>
<td>1.116</td>
<td>56.30</td>
<td>1.152</td>
<td>1.536</td>
</tr>
<tr>
<td>43</td>
<td>7.475</td>
<td>63.02</td>
<td>0.0064</td>
<td>1.238</td>
<td>56.37</td>
<td>1.152</td>
<td>1.598</td>
</tr>
<tr>
<td>Postpartum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>12.99</td>
<td>62.58</td>
<td>0.0024</td>
<td>1.350</td>
<td>57.36</td>
<td>1.130</td>
<td>1.025</td>
</tr>
<tr>
<td>40</td>
<td>7.93</td>
<td>62.94</td>
<td>0.0030</td>
<td>1.015</td>
<td>58.43</td>
<td>1.121</td>
<td>1.184</td>
</tr>
<tr>
<td>43</td>
<td>6.04</td>
<td>63.00</td>
<td>0.0036</td>
<td>1.110</td>
<td>58.63</td>
<td>1.119</td>
<td>1.310</td>
</tr>
</tbody>
</table>

^a^ \( \Delta P \), transglomerular hydrostatic pressure difference; \( K_f \), ultrafiltration coefficient pressure; \( r_0 \) and \( \omega_0 \), predicted values using isoporous + shunt model for pore radius and shunt contribution, respectively; \( U \) and \( S \), predicted values using log-normal model for mean pore radius and standard deviation of pore radius about the mean, respectively.

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Table 3. Predicted values of $K_f$ and porosity in preeclamptic late pregnancy (36 to 38 wk) and postpartum (>5 mo) (mean ± SEM)\(^a\)

<table>
<thead>
<tr>
<th>Assumed $\Delta P$ (mmHg)</th>
<th>Derived $K_f$ (ml · min(^{-1} \cdot ) mmHg(^{-1}))</th>
<th>$r_0$ (Å)</th>
<th>$\omega_0$</th>
<th>Sum of $\chi^2$</th>
<th>$U$ (Å)</th>
<th>$\pm S$ (Å)</th>
<th>Sum of $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preeclamptic</td>
<td>37</td>
<td>5.48</td>
<td>61.66</td>
<td>0.0061</td>
<td>0.6954</td>
<td>52.70</td>
<td>1.180</td>
</tr>
<tr>
<td>Late pregnancy</td>
<td>40</td>
<td>4.64</td>
<td>61.68</td>
<td>0.0071</td>
<td>0.7287</td>
<td>52.82</td>
<td>1.179</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>4.02</td>
<td>61.68</td>
<td>0.0075</td>
<td>0.9527</td>
<td>52.88</td>
<td>1.179</td>
</tr>
<tr>
<td>Preeclamptic</td>
<td>37</td>
<td>10.34</td>
<td>60.89</td>
<td>0.0035</td>
<td>0.7902</td>
<td>54.73</td>
<td>1.145</td>
</tr>
<tr>
<td>Postpartum</td>
<td>40</td>
<td>8.06</td>
<td>60.92</td>
<td>0.0042</td>
<td>0.9182</td>
<td>54.87</td>
<td>1.144</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>6.60</td>
<td>60.92</td>
<td>0.0048</td>
<td>1.001</td>
<td>55.07</td>
<td>1.142</td>
</tr>
</tbody>
</table>

\(^a\) $\Delta P$, transglomerular hydrostatic pressure difference; $K_f$, ultrafiltration coefficient; $r_0$ and $\omega_0$, predicted values using isoporous+shunt model for pore radius and shunt contribution, respectively; $U$ and $S$, predicted values using log-normal model for mean pore radius and standard deviation of pore radius, respectively.

associated with reduced glomerular hydraulic permeability to water ($k$), ascribable to reduced filtration slit frequency.

Reduced $K_f$ with significant proteinuria appears paradoxical; structural changes hindering the ultrafiltration of water might reasonably be expected to equally retard the transmural passage of proteins. Drumond et al. (12) proposed two possible explanations, and each could be applied to our data. First, broadened epithelial foot processes capable of reducing $k$ may, in a small proportion, lead to complete disruption of the slit diaphragms, allowing for a high loss of protein across small pockets of the glomerular wall while contributing only small increases to the net flux of water. Increases in $\omega_0$ would reflect such a change, as seen in preeclamptic LP. Second, reduced charge selectivity could increase proteinuria despite a reduced area available for ultrafiltration.

We could locate no other antenatal estimates of $K_f$ in preeclampsia. The only other work we are aware of to date are those from Lafayette et al. (13). These investigators undertook morphometric analysis of glomeruli by biopsy postpartum both in healthy gravidas and those with preeclampsia, studies performed immediately post-caesarean section under regional anesthesia after volume loading. From their renal hemodynamic measurements, there was an approximately 40% reduction in preeclamptic GFR, with no difference in RBF compared with the control group. SNGFR was reduced by approximately 40% or approximately 23% depending on estimated reductions in $k$, resulting from subendothelial fibrinoid deposits. Their hypothetical preeclamptic $K_f$ values were approximately 44% lower than similarly derived control values (4.8 versus 8.6 ml/min per mmHg, respectively) and were in close agreement with our modeled LP $K_f$ values (4.64 versus 8.94 ml/min per mmHg) at an assumed $\Delta P$ of 40 mmHg. Whether such reductions in $K_f$ can be held solely responsible for glomerular hypofiltration is a matter of controversy, as it ignores the profound depression of RBF consistently seen in preeclampsia (1,14) and again confirmed by this investigation.

Our $\theta_D$ data were derived for dextran of radii up to 65Å (Figures 1 and 2), beyond which the number of molecules that breach the glomerular filtration barrier are so limited that measured $\theta_D$ approaches zero. Nevertheless, the large radii dextran $\theta_D$ values (>55Å) are crucial for modeling, exerting a significant influence on derived values for $S$ and $\omega_0$ (8,15,16). In the normal group, there were no statistically significant differences between $\theta_D$ curves on any test occasion. In preeclamptic LP, there were significant reductions in the $\theta_D$ of smaller dextrans (33 to 37Å), which, when compared with normal LP, were even greater and seen for all dextran molecules, reaching significance across the range 31 to 49Å (Figure 2). The subsequent return to almost identical $\theta_D$ curves in both groups PP (with normalization of $K_f$ values and $S$ and $\omega_0$) provides strong evidence for reestablishment of glomerular barrier integrity by 5 mo PP.

Reduced preeclamptic $\theta_D$ is compatible with increased protein excretion because $\theta_D$ curves, while providing detailed size-selectivity data, provide limited information about the actual amount of dextran excreted. Also, the majority of proteins, such as albumin, are anionic and repelled by the negatively charged glomerular barrier. Proteinuria arising from reduced charge-selectivity will not, therefore, be revealed by the clearance rates of neutral dextran. Such changes in barrier charge are implicated in diabetic nephropathy (17), minimal change, and membranous glomerulonephritis (16,18) and have been confirmed by biopsy studies in early-onset preeclampsia (19). Our data indirectly support proteinuria due to a loss of charge-selectivity, as preeclamptic LP UAE was increased 30-fold to 100-fold, whereas $\theta_D$ at the equivalent neutral dex-

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**Figure 2.** Mean postpartum (>5 mo) fractional dextran clearance ($\theta_D$) for normal ($n = 13$) and preeclamptic ($n = 5$) subjects.
tran radii (36 Å) was reduced (P < 0.01). This leaves loss of glomerular barrier charge selectivity as the major if not the only explanation for high LP preeclamptic UAE in the presence of reduced θp and similar GFR.

In conclusion, this study confirms that normal gestational increases in renal hemodynamics are blunted in preeclampsia and that the reductions in both RPF and Kf can be implicated in the reduced GFR. The glomerular barrier parameters, ω0, and S, which increase in normal pregnancy, were even larger in preeclampsia, concomitant with increased protein excretion. All changes appear to resolve by 5 mo PP, suggesting that glomerular barrier integrity is fully restored.

Acknowledgments

We gratefully acknowledge Elizabeth A. Shiells, Maureen Kirkley, and Fiona Harding for their skilled analytical work. The studies were supported throughout by Sport Aiding Research for Kids (SPARKS) and Northern Counties Kidney Research Fund. Parts of this work were presented in abstract form at the annual meeting of the American Society of Nephrology, Toronto, Canada, October 2000.

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