Genetic Targeting or Pharmacologic Inhibition of NADPH Oxidase Nox4 Provides Renoprotection in Long-Term Diabetic Nephropathy


*Diabetic Complications Division, Juvenile Diabetes Research Foundation Danielle Alberti Memorial Centre for Diabetic Complications, Baker IDI Heart & Diabetes Institute, Melbourne, Victoria, Australia; †Department of Medicine, Monash University, Melbourne, Victoria, Australia; ‡Human Epigenetics Laboratory, Baker IDI Heart & Diabetes Institute, Melbourne, Victoria, Australia; §Department of Nephrology and Hypertension, Kawasaki Medical School, Kurashiki, Japan; ‖Department of Pharmacology, Cardiovascular Research Institute Maastricht, Faculty of Medicine, Health & Life Science, Maastricht, The Netherlands; ¶Genkyotex SA, Geneva, Switzerland; **Ottawa Hospital Research Institute, Ottawa, Ontario, Canada; and ††Institute of Cardiovascular and Medical Sciences, University of Glasgow, Glasgow, United Kingdom

ABSTRACT

Diabetic nephropathy may occur, in part, as a result of intrarenal oxidative stress. NADPH oxidases comprise the only known dedicated reactive oxygen species (ROS)–forming enzyme family. In the rodent kidney, three isoforms of the catalytic subunit of NADPH oxidase are expressed (Nox1, Nox2, and Nox4). Here we show that Nox4 is the main source of renal ROS in a mouse model of diabetic nephropathy induced by streptozotocin administration in ApoE−/− mice. Deletion of Nox4, but not of Nox1, resulted in renal protection from glomerular injury as evidenced by attenuated albuminuria, preserved structure, reduced glomerular accumulation of extracellular matrix proteins, attenuated glomerular macrophage infiltration, and reduced renal expression of monocyte chemoattractant protein-1 and NF-κB in streptozotocin-induced diabetic ApoE−/− mice. Importantly, administration of the most specific Nox1/4 inhibitor, GKT137831, replicated these renoprotective effects of Nox4 deletion. In human podocytes, silencing of the Nox4 gene resulted in reduced production of ROS and downregulation of proinflammatory and profibrotic markers that are implicated in diabetic nephropathy. Collectively, these results identify Nox4 as a key source of ROS responsible for kidney injury in diabetes and provide proof of principle for an innovative small molecule approach to treat and/or prevent chronic kidney failure.


CKD is a major complication of diabetes. Furthermore, diabetes remains the most common cause of end stage renal failure and need for kidney transplantation. The underlying mechanisms responsible for diabetic nephropathy remain to be fully defined. Therefore, effective and mechanism-based therapies are not available. It has been hypothesized that diabetes mellitus causes renal oxidative stress, that is, increased levels of reactive oxygen species (ROS), resulting in glomerular damage. Accordingly, oxidative stress is increasingly considered to be a major risk factor for diabetic nephropathy, and strategies to mitigate oxidative stress have emerged as a potential therapeutic approach. However, the precise role of oxidative stress in the development and progression of diabetic nephropathy remains to be elucidated.

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H.H.H.W.S. and K.A.J.-D. contributed equally to this work.

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Correspondence: Dr. Karin Jandeleit-Dahm, Diabetes Complications Division, Baker IDI Heart & Diabetes Research Institute, PO Box 6492 St Kilda Road, Melbourne, Victoria 8008, Australia. Email: karin.jandeleit-dahm@bakeridi.edu.au

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contributor to the development and progression of diabetic nephropathy. Various renal sources of ROS have been suggested to be relevant in the diabetic kidney. These include auto-oxidation of glucose, advanced glycation, glycolysis, glucose-6-phosphate dehydrogenase, sorbitol/polyol pathway flux, hexosamine pathway flux, mitochondrial respiratory chain, xanthine oxidase, uncoupled nitric oxide synthase, and NADPH oxidases. Among these sources, NADPH oxidases are suggested to play a pivotal role in the development and progression of renal injury in animal models of type 1 and type 2 diabetic nephropathy and hence represent a potentially important novel target. NADPH oxidases are the only enzymes known to be solely dedicated to ROS generation. Seven isoforms of their catalytic subunit exist (Nox1–5, Duox1 and 2). Nox isoforms depend to varying degrees on additional subunits. Among these isoforms, Nox1, Nox2, and Nox4 are expressed in the renal cortex. In streptozotocin-induced diabetic nephropathy, expression of Nox4, Nox2, and another subunit, p22phox, are all upregulated. With respect to Nox2, our own studies in streptozotocin-induced diabetic Nox2 knockout (KO) mice have shown increased susceptibility to infections and 100% mortality at week 20 of diabetes. We thus did not consider Nox2 blockade a priority in this study addressing strategies to reduce diabetic nephropathy.

Nox4, originally termed Renox, is highly expressed in renal tissues. The role of Nox4 in diabetic nephropathy remains controversial. Nox4 downregulation by systemic administration of antisense oligonucleotides, albeit for a short period of only 2 weeks, reduced renal and glomerular hypertrophy and attenuated the increased expression of fibronectin in renal cortex and glomeruli in streptozotocin-induced diabetic rats. However, the Nox4 antisense oligonucleotide may not be absolutely specific for Nox4. Furthermore, other authors have suggested either no effect or a protective role of Nox4 in diabetic nephropathy or in other models of renal fibrosis.

Here we report for the first time a direct comparison of the long-term effects of Nox1 and Nox4 deletion in the development and progression of diabetic nephropathy, by directly comparing renal injury in streptozotocin-induced diabetic Nox1−/−ApoE−/− and Nox4−/−ApoE−/− double KO mice and their respective wild-type (WT) control mice. In addition, the genetic deletion studies were complemented by a pharmacologic intervention study using the currently most specific Nox inhibitor, GKT137831. Key findings in the in vivo studies were confirmed in vitro using human podocytes.

RESULTS

Metabolic Parameters

First, we investigated the effects of Nox1 and Nox4 deletion as well as GKT137831 treatment on metabolic control in diabetic mice. Induction of diabetes was associated with reduced body weight, elevated plasma glucose, and glycated hemoglobin levels in diabetic Nox4+/+ApoE−/−, Nox1−/−ApoE−/−, and ApoE−/− mice compared with their respective nondiabetic controls. Diabetic animals also showed a significant elevation in serum cholesterol, triglyceride, and LDL levels compared with their respective nondiabetic controls. Neither genetic deletion of Nox4 or Nox1 had any effect on the diabetes-induced changes in body weight, glycemic control, or lipid parameters (Table 1). Furthermore, no changes in metabolic parameters were seen with pharmacologic Nox inhibition using GKT137831 in ApoE−/− mice for 20 weeks (Table 2). In addition, systolic BP was similar in all groups. The kidney weight/body weight ratio was significantly increased in diabetic mice. This tended to be attenuated in diabetic Nox4+/−ApoE−/− mice compared with diabetic Nox4−/−ApoE−/− mice (P = 0.08) and was significantly reduced in GKT137831-treated diabetic ApoE−/− mice compared with untreated diabetic ApoE−/− mice (P < 0.05). However, the kidney weight/body weight ratio was unchanged in diabetic Nox4−/−ApoE−/− mice compared with diabetic Nox1+/+ApoE−/− mice (Tables 1 and 2).

Renal Function Parameters

Albuminuria is a key feature of diabetic nephropathy. Therefore, we investigated the effect of Nox1 or Nox4 deletion on albuminuria development and compared the effects to treatment with the Nox inhibitor, GKT137831, in diabetic ApoE−/− mice. Albuminuria tended to be reduced after 10 weeks of diabetes in Nox4+/−ApoE−/− mice compared with diabetic Nox4−/−ApoE−/− mice, but this effect did not reach statistical significance (Figure 1A). However, after 20 weeks of diabetes, albuminuria was significantly attenuated in diabetic Nox4−/−ApoE−/− mice compared with diabetic Nox4+/−ApoE−/− mice (P < 0.05) (Figure 1A). Similarly to deleting Nox4, GKT137831 treatment of diabetic ApoE−/− mice protected against development of albuminuria after 10 and 20 weeks of diabetes (Figure 1C). In contrast, albuminuria was unaffected in diabetic Nox1−/−ApoE−/− mice (Figure 1B). Similar effects were also observed when the data were expressed as the urinary albumin/creatinine ratio after 10 and 20 weeks of diabetes (Figure 1, D–F).

Renal Structural Assessment

Diabetic nephropathy is associated with structural abnormalities including glomerulosclerosis and specifically mesangial expansion. Indeed, glomerulosclerosis and mesangial area expansion were significantly increased after 20 weeks of diabetes in Nox4+/−ApoE−/− mice compared with nondiabetic Nox4+/−ApoE−/− mice. In diabetic Nox4−/−ApoE−/− mice, the development of glomerulosclerosis and the degree of mesangial expansion were significantly attenuated compared with diabetic Nox4+/−ApoE−/− mice after 20 weeks of diabetes (Figure 2, A and B). These renoprotective structural changes were not observed in diabetic Nox1−/−ApoE−/− mice compared with diabetic Nox1+/+ApoE−/− mice (Figure 2, C and D).
Table 1. General and metabolic parameters after 20 weeks of study in control and diabetic Nox4+/+ApoE−/− and Nox4−/−ApoE−/− mice and in control and diabetic Nox1+/−ApoE−/− and Nox1−/−ApoE−/− mice (n=8–15 per group)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nox4+/+ApoE−/−</th>
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<th>Nox4−/−ApoE−/−</th>
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<th>Nox1+/−ApoE−/−</th>
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<td>Diabetes</td>
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<td>Diabetes</td>
<td>Control</td>
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<td>Body weight (g)</td>
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<td>25±0.8a</td>
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<td>Kidney weight/body weight</td>
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<td>0.94±0.05a</td>
<td>0.61±0.02</td>
<td>0.82±0.01a</td>
<td>0.62±0.02</td>
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<td>Systolic BP (mmHg)</td>
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<td>110±7.0</td>
<td>93±5.4</td>
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<td>104±4</td>
<td>106±4</td>
<td>100±3</td>
<td>101±2</td>
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<td>Plasma glucose (mmol/L)</td>
<td>10.4±0.6</td>
<td>25.0±2.2a</td>
<td>11.2±0.6</td>
<td>24.3±1.3a</td>
<td>13.1±0.9</td>
<td>26.2±2.3a</td>
<td>12.7±0.4</td>
<td>29.6±1.4a</td>
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<td>Glycated hemoglobin (%)</td>
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<td>15.4±0.9a</td>
<td>7.8±0.9b</td>
<td>18.9±1.2a</td>
<td>4.8±0.4</td>
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<td>Total cholesterol (mmol/L)</td>
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<td>8.2±0.4</td>
<td>16.3±1.8a</td>
<td>7.6±0.6</td>
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<td>Triglycerides (mmol/L)</td>
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<td>2.3±0.5a</td>
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<td>HDL (mmol/L)</td>
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<td>LDL (mmol/L)</td>
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<td>9.7±1.2a</td>
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<td>11.7±1.2a</td>
<td>5.4±0.5</td>
<td>6.9±1.0a</td>
<td>5.0±0.4</td>
<td>10.0±1.2a</td>
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</table>

Data are the mean±SEM.

*P<0.05 versus respective control Nox4+/+ApoE−/− or Nox4−/−ApoE−/− or control Nox1+/−ApoE−/− and Nox1−/−ApoE−/− mice.

bP<0.05 versus control Nox4+/+ApoE−/− mice.

cP<0.05 versus diabetic Nox1−/−ApoE−/− mice.

Table 2. General and metabolic parameters after 20 weeks of study in control and diabetic ApoE−/− mice, with and without treatment with GKT137831 (n=8–15 per group)

<table>
<thead>
<tr>
<th>Parameter</th>
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<td></td>
<td>Control</td>
<td>Diabetes</td>
</tr>
<tr>
<td>Body weight (g)</td>
<td>31±0.5</td>
<td>25±0.7a</td>
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<tr>
<td>Kidney weight/body weight</td>
<td>0.60±0.01</td>
<td>0.95±0.05a</td>
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<tr>
<td>Systolic BP (mmHg)</td>
<td>105±3.0</td>
<td>113±4.7</td>
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<tr>
<td>Plasma glucose (mmol/L)</td>
<td>11.8±0.4</td>
<td>24.8±1.0a</td>
</tr>
<tr>
<td>Glycated hemoglobin (%)</td>
<td>5.0±0.3</td>
<td>17.4±0.9a</td>
</tr>
<tr>
<td>Total cholesterol (mmol/L)</td>
<td>6.7±0.5</td>
<td>13.3±1.9a</td>
</tr>
<tr>
<td>Triglycerides (mmol/L)</td>
<td>1.2±0.1</td>
<td>3.2±0.7a</td>
</tr>
<tr>
<td>HDL (mmol/L)</td>
<td>1.6±0.2</td>
<td>2.0±0.3</td>
</tr>
<tr>
<td>LDL (mmol/L)</td>
<td>4.6±0.3</td>
<td>9.8±1.4a</td>
</tr>
</tbody>
</table>

Data are the mean±SEM.

*P<0.05 versus respective control ApoE−/− and ApoE−/− plus GKT137831.

bP<0.05 versus diabetic ApoE−/− mice.

Treatment of diabetic ApoE−/− mice with the Nox inhibitor GKT137831 for 20 weeks was also associated with attenuation of glomerular injury, as assessed by the glomerulosclerosis index (Figure 2E) and mesangial area (Figure 2F). These results suggest that genetic deletion of Nox4 and Nox inhibition with GKT137831 in diabetic ApoE−/− mice confer renoprotective effects with respect to structural parameters. No such effect was seen with deletion of Nox1. Furthermore, there was an increase in the tubulointerstitial area in diabetic ApoE−/− mice (Supplemental Figure 1). Indeed, the Nox inhibitor, GKT137831, significantly attenuated the tubulointerstitial area (Supplemental Figure 1, C and D). There was a similar trend seen in diabetic Nox4−/−ApoE−/− mice (P=0.07) (Supplemental Figure 1, A and B).

Nox4 Expression

Induction of diabetes was associated with increased gene expression of Nox4 as well as Nox1 and Nox2 in renal cortex (Supplemental Figure 2A). In addition, Nox4 gene expression was also increased in the tubular fraction of the renal cortex of diabetic mice (Supplemental Figure 2C). Furthermore, there was an increase in both glomerular and tubular Nox4 protein expression, as assessed by immunofluorescence (Supplemental Figure 2, B and D). By contrast, there was no significant Nox4 expression in the Nox4 KO mice in the absence or presence of diabetes.

Extracellular Matrix Proteins

We next examined glomerular collagen IV and fibronectin accumulation, which are known to be associated with glomerulosclerosis and mesangial expansion in diabetic nephropathy. Consistent with the findings on glomerulosclerosis and mesangial expansion, collagen IV protein accumulation was significantly increased in the glomeruli after 20 weeks of diabetes in Nox4+/+ApoE−/− mice compared with nondiabetic Nox4+/+ApoE−/− controls. Importantly, the increase in collagen IV expression was attenuated in Nox4−/−ApoE−/− mice (Figure 3A). In contrast, this reduction in collagen IV expression was not observed in Nox1−/−ApoE−/− mice compared with diabetic Nox1−/−ApoE−/− mice (Figure 3B). Furthermore, Nox inhibition with GKT137831 in diabetic ApoE−/− mice for 20 weeks was associated with a significant attenuation of the diabetes-induced increased expression of collagen IV (Figure 3C). Similarly, fibronectin protein accumulation was increased in the glomeruli of mice after 20

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weeks of diabetes, and this was prevented in mice with deletion of Nox4 (Figure 4A) but not with deletion of Nox1 (Figure 4B). Again, GKT137831 treatment of diabetic ApoE/−/− mice for 20 weeks resulted in attenuated diabetes-induced increased expression of fibronectin (Figure 4C).

We previously showed that renal vascular endothelial growth factor (VEGF) expression is increased in experimental diabetes and is associated with albuminuria. Indeed, we observed that VEGF expression was higher in the glomeruli of diabetic Nox4+/+ApoE/−/− mice compared with nondiabetic controls, and this was attenuated in diabetic Nox4−/−ApoE/−/− mice (Figure 5A). Furthermore, GKT137831 treatment of diabetic ApoE/−/− mice for 20 weeks was also associated with decreased expression of VEGF in the glomeruli of diabetic ApoE/−/− mice (Figure 5B).

Together, these results suggest that genetic deletion of Nox4, but not of Nox1, protects mice from renal functional and structural changes associated with diabetic nephropathy via
effects on glomerulosclerosis, mesangial expansion, collagen IV, and fibronectin accumulation. Treatment of diabetic ApoE−/− mice with the specific Nox inhibitor GKT137831 for 20 weeks resulted in similar renoprotection as observed in Nox4-deficient ApoE−/− mice, which provides a proof of concept for Nox inhibition as a novel therapeutic strategy for diabetic nephropathy.

Renal Superoxide and ROS Levels
There is increasing evidence that renal injury in diabetes is associated with increased formation of ROS. Indeed, nitrotyrosine, a marker of nitrite and oxidative stress, was increased in glomeruli after 20 weeks of diabetes in Nox4+/+ ApoE−/− and ApoE−/− mice. Importantly, diabetic Nox4−/− ApoE−/− mice and GKT137831-treated diabetic ApoE−/− mice showed reduced nitrotyrosine accumulation in the glomeruli compared with diabetic Nox4+/+ ApoE−/− and non-treated diabetic ApoE−/− mice, respectively (Figure 6A, A and C). In line with our above-described observations, no reduction of nitrotyrosine was observed in diabetic Nox1−/− ApoE−/− mice compared with diabetic Nox1+/+ ApoE−/− mice (Figure 6B).

We also measured superoxide generation in the renal cortex using the dihydroethidium/HPLC method (Figure 7, A, C, and...
E)\textsuperscript{14,24} as well as ROS levels in the cytosolic and mitochondrial fractions of the renal cortex using L-012–derived chemiluminescence (Figure 7, B, D, and F). Diabetes was associated with increased renal superoxide levels in the renal cortex (Figure 7, A, C, and E). In addition, diabetes was associated with increased ROS levels in both the cytosolic and mitochondrial compartments (Figure 7, B, D, and F). Diabetic ApoE\textsuperscript{−/−} mice with genetic Nox4 deficiency did not show the diabetes-induced increase in superoxide (Figure 7A) or ROS formation in either intracellular compartment (Figure 7B). Similar results were obtained in diabetic ApoE\textsuperscript{−/−} mice treated with GKT137831 for 20 weeks (Figure 7, E and F). Again, this effect on reducing superoxide and ROS levels was not seen in Nox1-deficient diabetic mice (Nox1\textsuperscript{−/−}/ApoE\textsuperscript{−/−} mice) (Figure 7, C and D). These results suggest that renoprotection observed with Nox4 deletion and pharmacologic Nox inhibition is associated with reduced renal ROS formation. The results further support the view that Nox4, but not Nox1, is a pathologically relevant source of ROS in diabetic nephropathy.

**Macrophage Infiltration**

Diabetes is associated with recruitment and retention of macrophages in glomeruli.\textsuperscript{25} Accordingly, expression of the macrophage marker F4/80 in glomeruli of diabetic mice after 20 weeks of diabetes was increased in diabetic Nox4\textsuperscript{+/+}/ApoE\textsuperscript{−/−} and ApoE\textsuperscript{−/−} mice compared with their nondiabetic controls. Again, this parameter was attenuated in diabetic Nox4\textsuperscript{−/−}/ApoE\textsuperscript{−/−} mice (Figure 8A) and in diabetic ApoE\textsuperscript{−/−} mice treated with GKT137831 (Figure 8C). In contrast, expression of F4/80 in glomeruli of diabetic Nox1\textsuperscript{−/−}/ApoE\textsuperscript{−/−} mice was not different from diabetic Nox1\textsuperscript{+/y}/ApoE\textsuperscript{−/−} mice (Figure 8B).

**Human Podocyte In Vitro Studies**

Podocytes are considered to be centrally involved in regulation of the glomerular filtration barrier and development of proteinuria.\textsuperscript{26} We therefore investigated the effects of hyperglycemia and TGF-\(\beta\)1, which are both key features of the diabetic milieu, on ROS formation and markers of diabetes-related injury in a human differentiated podocyte cell line as previously described (Supplemental Figure 3).\textsuperscript{27} Under nonpermissive conditions, the podocytes undergo growth arrest, display the typical arborized pattern of foot process extensions, and express markers of mature podocytic differentiation including nephrin, synaptopodin, and Wilms’ tumor-1 (Supplemental Figure 4).

Incubation of human podocytes in high glucose–containing medium (25 mM, \textit{i.e.}, similar glucose concentrations to those
observed in the serum of our streptozotocin-treated mice) resulted in increased mRNA levels of Nox4 (Figure 9A). The addition of TGF-β to this hyperglycemic milieu further amplified the increase in Nox4 gene expression and to a lesser extent also increased Nox5, but not Nox1, Nox2, or their cytosolic regulator, p47phox. The iso-osmotic control mannitol did not result in changes in any Nox isoform levels (Figure 9A). Furthermore, Nox4 protein was expressed in these podocytes, as assessed by immunofluorescence (Supplemental Figure 5).

We next infected human podocytes with a lentiviral Nox4 short hairpin RNA (shRNA) expression construct. This resulted in a decrease in Nox4 gene expression of approximately 70% (Supplemental Figure 6). Nox4 shRNA treatment of the podocytes did not change the mRNA levels of Nox1, Nox2, or Nox5 (Supplemental Figure 6). Importantly, the high glucose– and TGF-β1–induced increase in ROS production was reduced in Nox4 knockdown cells to ROS levels seen in podocytes in normal glucose or in cells that had not been treated with TGF-β1 (Figure 9, B and D).

High glucose alone increased the gene expression of the extracellular matrix (ECM) proteins, collagen IV, and fibronectin as well as VEGF, whereas the effect on α-smooth muscle actin (α-SMA) did not reach statistical significance (Figure 9C). The addition of TGF-β significantly increased gene expression of collagen IV, fibronectin, VEGF, and α-SMA (Figure 9E). Silencing of Nox4 by infecting the podocytes with a Nox4 shRNA led to a decrease in both glucose– and TGF-β–induced increased expression of collagen IV, fibronectin, VEGF, and α-SMA compared with cells infected with nontargeted control constructs (Figure 9, C and E).

Inflammatory Parameters: Monocyte Chemoattractant Protein-1 and NF-κB

We further investigated the effect of Nox4 deletion on the NF-κB/monocyte chemoattractant protein-1 (MCP-1) axis, a pathway that has been implicated in the development of diabetic nephropathy. Consistent with the results observed with respect to macrophage infiltration into the kidney (Figure 4).
progression of diabetic nephropathy. This evidence is based on the first direct comparison of Nox4 or Nox1 deletion in ApoE\(^{-/-}\) mice. We used ApoE\(^{-/-}\) mice because streptozotocin-induced diabetes in ApoE\(^{-/-}\) mice is a well characterized model of advanced renal injury with prominent ECM accumulation.\(^{28,29}\) Importantly, we translated these findings into a potential clinical therapy by showing that Nox inhibition in diabetic ApoE\(^{-/-}\) mice using a pharmacologic strategy resulted in a similar degree of renoprotection to that observed with deletion of Nox4.

Previous studies have already suggested a role for Nox-derived ROS in the development and progression of diabetic nephropathy but these experiments were short term and/or investigated only a single Nox isoform.\(^{4-6,19}\) With respect to pharmacologic intervention, previous studies relied on nonspecific inhibitors of ROS formation, such as apocynin, a drug that has also been reported to interfere with Rho kinase.\(^{30,31}\) Therefore, we postulate that this longer-term study is potentially more relevant with respect to clinical target validation.

In this study, we were able to combine observations of a renoprotective effect of genetically deleting Nox4 with pharmacologic inhibition of Nox using the most specific compound currently available, GKT137831. In diabetic ApoE\(^{-/-}\) mice, Nox4 deletion or treatment with GKT137831 attenuated various parameters of glomerular injury, including albuminuria, and glomerular structural changes, including ECM accumulation. Furthermore, the diabetes-induced increase in tubulointerstitial area was significantly attenuated using the novel Nox inhibitor GKT137831. In addition, macrophage infiltration was reduced in diabetic Nox4 KO mice and these changes occurred in association with attenuation of the expression of the chemokine MCP-1 and the key proinflammatory transcription factor, NF-κB. In addition, these renoprotective effects were associated with reduced renal cortical superoxide generation and a decrease in both cytosolic and mitochondrial ROS levels as well as reduced nitrotyrosine accumulation within glomeruli. In contrast, genetic deletion of Nox1 in ApoE\(^{-/-}\) mice did not attenuate renal ROS generation and failed to prevent glomerular injury in diabetic mice.

Consistent with other studies using type 1 and type 2 diabetic models,\(^{11,12,32}\) we observed increased Nox4 mRNA in the renal cortex of diabetic mice. One must exert due caution in interpreting results with respect to Nox4 protein expression because there is currently no fully validated monospecific Nox4 antibody available. In the context of

**DISCUSSION**

This study provides evidence that Nox4-derived, but not Nox1-derived, ROS are causatively linked to the development and

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**Figure 5.** Genetic deficiency of Nox4 and pharmacologic Nox inhibition attenuate increased VEGF expression in glomeruli of diabetic ApoE\(^{-/-}\) mice. Immunostaining for VEGF in glomeruli of control and diabetic Nox4\(^{+/+}\)ApoE\(^{-/-}\) and Nox4\(^{-/-}\)ApoE\(^{-/-}\) mice after 20 weeks (A) and control and diabetic ApoE\(^{-/-}\) mice with and without treatment with GKT137831 for 20 weeks (B) (n=6–8 per group). Data are the mean±SEM. *P<0.05 versus respective control Nox4\(^{+/+}\)ApoE\(^{-/-}\) and Nox4\(^{-/-}\)ApoE\(^{-/-}\) mice (A) or control ApoE\(^{-/-}\) and ApoE\(^{-/-}\) plus GKT137831 mice (B); †P<0.05 versus diabetic Nox4\(^{+/+}\)ApoE\(^{-/-}\) (A); ‡P=0.08 versus diabetic ApoE\(^{-/-}\) mice (B). Cont, control; Diab, diabetic; GKT, GKT137831.
these limitations, we identified increased immunoreactivity to Nox4 in diabetic ApoE<sup>-/-</sup> mice, particularly in the glomerulus, a phenomenon not observed in Nox4 KO mice. These findings are similar to those reported in shorter-term studies by other groups.19

A previous study by Gorin et al. suggested that short-term downregulation of Nox4 by systemic administration of antisense oligonucleotides attenuated renal and glomerular hypertrophy as well as reduced the increase in fibronectin expression that is commonly seen in the diabetic kidney.19 This group has recently further explored the link between Nox4 and ECM production and has shown that Nox4 can be modulated by the matrix metalloproteinase, ADAM (a disintegrin and metalloproteinase)-17.33

Babelova et al.20 investigated the role of Nox4 in various models of renal injury, including a model of streptozotocin-induced diabetes, albeit in C57BL/6 and not in ApoE<sup>-/-</sup> mice. Consequently, and in contrast to our findings, those authors did not observe upregulation of Nox4<sup>20</sup> and Nox4 deficiency did not attenuate nephropathy. However, C57BL/6 mice are relatively resistant to the development of typical morphologic features of diabetic nephropathy.34 These differences in the duration of the experimental model and the mouse strains utilized may explain the conflicting results of that study with our and other studies.11,19,32

Given the importance of podocytes not only in albuminuria but also in morphologic manifestations of diabetic nephropathy, and to translate our findings from mice to a human context, we performed in vitro studies using human podocytes. In line with the in vivo observations using mice, Nox4 and to a lesser extent Nox5 were upregulated in response to high glucose and this upregulation was further amplified in the presence of TGF-β1 exposure, both key features of the diabetic milieu.35,36 Both silencing of Nox4 and Nox inhibition with GKT137831 reduced ROS levels in human podocytes, and this was associated with attenuation of critical pathways linked to renal fibrosis, including gene expression of collagen IV, fibronectin, connective tissue growth factor, and α-SMA. These findings confirm a previous report in which Nox4 was shown to play an important role in hyperglycemia-induced ROS formation in mouse podocytes37; however, our study importantly confirms and extends these findings to human cells and emphasizes the effect of Nox4 on prosclerotic pathways.

The effects of Nox4-derived ROS formation on VEGF expression, a growth factor expressed by renal cells including
Figure 7. Genetic deficiency of Nox4, but not of Nox1, and pharmacologic Nox inhibition attenuate increased renal superoxide and ROS formation in diabetic ApoE−/− mice. Superoxide production in renal cortex (A, C, and E) and ROS production in cytosolic and mitochondrial fractions of the renal cortex (B, D, and F) in control and diabetic Nox4+/+ApoE−/− and Nox4−/−ApoE−/− mice (A and B), control and diabetic Nox1+/yApoE−/− and Nox1−/−ApoE−/− mice after 20 weeks (C and D), or control and diabetic ApoE−/− mice with and without treatment with GKT137831 for 20 weeks (E and F) (n=5–6 per group). Superoxide data (A, C, and E) are shown as the ratio of 2HE (nanomoles) to DHE (micromoles). With respect to ROS measurements, results were expressed relative to control Nox4+/+ApoE−/− mice (B), control Nox1+/yApoE−/− mice (D), or control (untreated) ApoE−/− mice (F), which was arbitrarily assigned a value of 100. Data are the mean±SEM. *P<0.05 versus respective control Nox4+/+ApoE−/− or control Nox1+/yApoE−/− mice or control ApoE−/− mice; †P<0.05 versus diabetic Nox4+/+ApoE−/− or diabetic ApoE−/− mice. 2HE, 2 hydroethidium; Cont, control; Diab, diabetes; DHE, dihydroethidium; GKT, GKT137831; RLU, relative light unit.
podocytes, were also confirmed by our in vivo studies of diabetic nephropathy. Both Nox4 deletion and inhibition of Nox with GKT137831 were associated with attenuation of the diabetes-induced increase in VEGF expression in glomeruli, and this was also associated with reduced proteinuria. Furthermore, in our in vitro studies, GKT137831 treatment attenuated podocyte VEGF expression in a hyperglycemic milieu. Importantly, this is likely to be Nox4 dependent because downregulation of Nox4 in human podocytes was also associated with attenuation of VEGF expression. Consistent with our findings, other researchers reported a link between VEGF with Nox4 in the retina, where Nox4 was associated with vascular permeability, as well as similar findings in a stroke model.

Diabetic nephropathy is considered to be at least in part an inflammatory disorder in which progressive glomerular injury is associated with macrophage infiltration. Consistent with this view, induction of diabetes in our study was associated with a significant increase in accumulation of macrophages within the glomeruli. These changes were attenuated in diabetic Nox4-deficient mice and in diabetic ApoE−/− mice treated with the Nox inhibitor GKT137831 but not in diabetic Nox1−/− mice. A link between Nox4 and inflammation was previously suggested, albeit in a nonrenal context. Specifically, Nox4 downregulation using a small interfering RNA approach attenuated the LPS-induced proinflammatory response in human endothelial cells. Consistent with these effects of Nox4 deletion on renal macrophage infiltration, we observed reduced expression of the key proinflammatory transcription factor NF-κB as well as the well characterized NF-κB–dependent chemokine MCP-1 on the gene and protein level in the renal cortex. Complementary in vitro studies in human podocytes confirmed that high glucose–induced upregulation of the NF-κB subunit, p65, and MCP-1 could be prevented by silencing of Nox4.

Block et al. suggested that Nox4 is present in the mitochondria, and that silencing of mitochondrial Nox4 is associated with reduced mitochondrial oxidative stress and injury. Thus, we examined ROS formation in not only the cytosolic fraction but also the mitochondrial fraction of the renal cortex. Indeed, we demonstrated reduced mitochondrial as well as cytosolic ROS generation in the renal cortex of diabetic Nox4-deficient mice. GKT137831 treatment of diabetic ApoE−/− mice caused similar reductions in mitochondrial ROS.

Figure 8. Genetic deficiency of Nox4, but not of Nox1, and pharmacologic Nox inhibition attenuates macrophage infiltration in glomeruli of diabetic ApoE−/− mice. Immunostaining for F4/80 in glomeruli of control and diabetic Nox4+/−/ApoE−/− and Nox4−/−/ApoE−/− mice (A) or in control and diabetic Nox1+/−/ApoE−/− and Nox1−/−/ApoE−/− mice after 20 weeks (B), or control and diabetic ApoE−/− mice with and without treatment with GKT137831 for 20 weeks (C) (n=6–8 per group). Data are the mean±SEM. *P<0.05 versus respective control Nox4+/−/ApoE−/− and Nox4−/−/ApoE−/− mice (A), control Nox1+/−/ApoE−/− and Nox1−/−/ApoE−/− mice (B), or control ApoE−/− and ApoE−/− plus GKT137831 mice (C); *P<0.05 versus diabetic Nox4+/−/ApoE−/− (A) or diabetic ApoE−/− mice (C). Cont, control; Diab, diabetes; GKT, GKT137831.

Figure 9. Silencing of Nox4 attenuates high glucose–as well as high glucose plus TGF-β1–mediated ROS formation and gene expression of profibrotic markers in human podocytes. (A) Nox4 and Nox5, but not Nox1, Nox2, or p47phox mRNA levels were upregulated in human podocytes by diabetic stimuli. Analysis of Nox isoform mRNA levels and the cytosolic regulator, p47phox, in cultured differentiated human podocytes in NG (5 mM) or HG (25 mM) and in the presence or absence of TGF-β1 (5 ng/ml, 2 days). Mannitol (20 mM/L+5 mM d-glucose) served as an osmotic control. Data are the mean ± SEM. *P<0.05 versus NG; #P<0.05 versus HG. (B and C) Analysis of ROS production (B) and RT-PCR (C) for collagen IV, fibronectin, VEGF and α-SMA in differentiated human podocytes transfected with shRNA specific for Nox4 and then grown in NG (5 mM) or HG (25 mM) for 2 days. Results for ROS production are expressed relative to nontarget plus NG, which was arbitrarily assigned a value of 100 (B). Data are the mean ± SEM (n=6/group). ∧P<0.05 versus nontarget plus NG; §P<0.05 versus nontarget plus HG. (D and E) Analysis of ROS production (D) and RT-PCR (E) for collagen IV, fibronectin, VEGF and α-SMA in differentiated human podocytes transfected with shRNA specific for Nox4 and then grown in the presence or absence of TGF-β1 (5 ng/ml) for 4 hours for ROS production (D) and 2 days for RT-PCR (E). Data are the mean ± SEM (n=6/group). †P<0.05 versus nontarget, ‡P<0.05 versus non-target plus TGF-β1. HG, high glucose; NG, normal glucose; RLU, relative light unit.
generation. These findings strengthen the view that Nox4 is not only a cytosolic but also a mitochondrial source of ROS, at least in the diabetic kidney. Other groups have shown that alterations in the electron transport chain are a major source of mitochondrial ROS in the setting of hyperglycemia.42,43 However, our findings extend these results by demonstrating that Nox4 may be an alternative or additional target to reduce mitochondrial oxidative stress, particularly in the kidney.

The role of Nox1 in diabetic nephropathy has not been clearly delineated previously. Nox1 is expressed in the renal cortex, including in glomeruli of the normal kidney, albeit at almost undetectable levels. Increased renal expression of Nox1 has been reported in hypertension-associated forms of renal disease such as in models of angiotensin II infusion and in Dahl salt-sensitive hypertensive rats.44,45 These findings are relevant because activation of the renin-angiotensin system in the diabetic kidney has been shown to promote renal injury.66,47 Angiotensin II induces upregulation of Nox1.48 Therefore, it has been postulated that Nox1 could play an important role in the development and progression of diabetic nephropathy.44,45 However, in our study, Nox1 deletion was not associated with an improvement in diabetes-related renal injury. Thus, our findings argue against a critical role for Nox1 in diabetic nephropathy but Nox1 may be more important, as recently suggested, in diabetes-associated macrovascular disease.49

We focused our study on Nox1 and Nox4 and did not specifically address Nox2, which was previously shown to not play a key role in diabetic nephropathy.50 Furthermore, Nox2 deletion was reported to be associated with increased susceptibility to infections in the context of diabetes mellitus.14 Nevertheless, one cannot exclude a potential role for partial Nox2 inhibition but the lethality of severe Nox2 deficiency in hyperglycemic states is likely to narrow the therapeutic window of such an approach. There are also increasing data to suggest a role for another Nox isoform, Nox5, in pathologic ROS generation.7,51 However, because Nox5 is not present in rats and mice, we were not able to delineate the contribution of this particular Nox isoform in our in vivo models. Nevertheless, in human podocytes, Nox5 was upregulated upon treatment with diabetes-related stimuli, such as high glucose and TGF-β1. Thus, we cannot exclude an additional role for Nox5 in human diabetic nephropathy.

To test the possibility to clinically translate our experimental studies, we administered GKT137831 to diabetic ApoE−/− mice. This Nox inhibitor has been suggested to have dual efficacy on Nox1 and Nox4. It has been shown to provide end-organ protective effects, albeit in the liver.22,52 Importantly, in our study, treatment of diabetic ApoE−/− mice with GKT137831 mimicked the effects of Nox4 deletion on glomerular injury, albuminuria, ROS production, ECM accumulation, and macrophage infiltration. Thus, the renoprotective effects of GKT137831 are likely to be mediated by Nox4 rather than Nox1 inhibition. In line with our study results, another Nox inhibitor, GKT136901, was recently reported to be renoprotective in a model of type 2 diabetes, the db/db mouse. This renoprotective effect was associated with reduced albuminuria and urinary excretion of thiobarbituric acid–reactive substances as well as attenuation of renal extracellular signal-regulated protein kinase 1/2 phosphorylation.8 The initial antialbuminuric effect observed in that study was not sustained after 16 weeks of diabetes. It is possible that the longer lasting antialbuminuric effect seen in our study may be related to a difference in potency between the two compounds or more likely related to the mode of administration of the Nox inhibitor. The drug was mixed in the food in the previous study,8 whereas the drug was administered by gavage in this study.

In conclusion, compelling evidence is provided that Nox4, but not Nox1, is a major pathologic source of ROS in a long-term model of insulin-deficient diabetes leading to relatively advanced diabetic nephropathy. Our experiments have identified Nox4 as an attractive mechanism-based therapeutic target for the treatment of diabetic nephropathy. Furthermore, we provide proof of principle that this mechanism can be translated into a novel pharmacologic therapy with important future clinical implications. Therefore, our study strengthens the need to develop Nox4-specific inhibitors that can be used for prevention and treatment of this major diabetic complication.

**CONCISE METHODS**

**Animals**

Diabetes-induced renal functional changes and morphologic kidney damage were studied in diabetic Nox4+/−/ApoE−/−, Nox4−/−/ApoE−/− double KO, Nox1−/−/ApoE−/−, Nox1−/−/ApoE−/− double KO, and ApoE−/− male mice and compared with respective nondiabetic control mice. Nox1−/−/ApoE−/− mice were generated as previously described.53,54 To generate the double KO mice, Nox4 KO mice41 were crossed for 10 generations with the ApoE−/− mouse strain (Animal Resources Centre, Murdoch, WA, Australia). Initially we mated ApoE−/− (F) with Nox4−/− (M) mice to produce heterozygotes in the F1 generation (Nox4+/−/ApoE−/−). From the F2 generation we set up Nox4−/−/ApoE−/− × Nox4−/−/ApoE−/− and Nox4−/−/ApoE−/− × Nox4−/−/ApoE−/−, which produced the F3 generation including the WT Nox4+/+/ApoE−/− and double KO Nox4−/−/ApoE−/− mice. From that generation, we mated male and female Nox4−/−/ApoE−/− mice and are now at the 16th generation.

Diabetes was induced in 6-week-old mice by five daily intraperitoneal injections of streptozotocin (Sigma-Aldrich, St Louis, MO), at a dose of 55 mg/kg in citrate buffer, with control mice receiving citrate buffer alone. None of the animals with diabetes required supplemental insulin to maintain body weight or to prevent ketosis. A subgroup of diabetic and nondiabetic ApoE−/− mice were treated with the Nox inhibitor, GKT137831, administered daily by gavage at a dose of 60 mg/kg per day for 20 weeks commencing with the last injection of streptozotocin. GKT137831, a member of the pyrazolopyridinedione family, is a specific inhibitor of both Nox4 and Nox1 isoforms (K_i in the range of 100–150 nM in cell-free assays of ROS production). It has no ROS scavenging activity when tested at a concentration of 10 μM.52,55
After 20 weeks, animals were anesthetized by sodium pentobarbital intraperitoneally (100 mg/kg body weight) (Euthalal; Sigma-Aldrich, Castle Hill, NSW, Australia). The kidneys were rapidly dissected, weighed, and snap-frozen or processed to paraffin for subsequent analysis. All animal studies were approved by the Alfred Medical Research & Education Precinct Animal Ethics Committee under guidelines of the National Health and Medical Research Council of Australia. All animals were housed at the Precinct Animal Centre of the Baker IDI Heart & Diabetes Institute. During the study, animals had unrestricted access to water and food and were maintained on a 12-hour light/dark cycle in a pathogen-free environment on standard mouse chow (Specialty Feeds, Perth, WA, Australia). All animals were housed at the Precinct Animal Centre of the Baker IDI Heart & Diabetes Institute. During the study, animals had unrestricted access to water and food and were maintained on a 12-hour light/dark cycle in a pathogen-free environment.

Measurement of Metabolic Parameters

At 10 and 20 weeks after induction of diabetes, mice were placed individually into metabolic cages (Iffa Credo, L’Arbresle, France) for 24 hours. Urine was collected for subsequent analysis. Blood glucose was measured serially using a glucometer (Accutrend; Boehringer Manheim Biochemistry, Manheim, Germany). Glycated hemoglobin was measured by HPLC (CLC330 GHb Analyzer; Primus, Kansas City, MO) in lysates of erythrocytes separated from whole blood.56 Systolic BP was assessed using a computerized noninvasive tail-cuff method.57 Mice were familiarized with the equipment with readings taken by an experienced technician in conscious mice at the end of the 20-week study. Urinary albumin concentration was measured at 10 and 20 weeks after the induction of diabetes, using a mouse albumin ELISA quantitation kit (Bethyl Laboratories, Montgomery, TX).

Urinary creatinine concentrations were measured by HPLC as previously described.56,58 The urinary albumin/creatinine ratios were calculated.

In Vivo Gene Expression Analyses

Total RNA was extracted after homogenizing renal cortex (Polytech PT-MR2100; Kinematica, Littau/Lucerne, Switzerland) in TRIzol reagent (Invitrogen Australia, Mt Waverly, VIC, Australia) as previously described.56 Gene expression using probes and primers as described in Supplemental Table 1 for Nox1, Nox2, Nox4, MCP-1, and NF-κB p65 were analyzed quantitatively and relative to the expression the housekeeping gene 18S (18S ribosomal RNA TaqMan Control Reagent kit) using the TaqMan system (ABI Prism 7500; PerkinElmer, Foster City, CA).14,56 Results were expressed relative to nondiabetic ApoE–/– mice, which were arbitrarily assigned a value of 1.

Histologic Assessment

Three-micrometer kidney sections were stained with periodic acid–Schiff for measurement of glomerulosclerotic injury and mesangial expansion. Mesangial area was analyzed (percentage of glomerular area) from digital pictures of glomeruli (20 glomeruli per kidney per animal) using Image-Pro plus 6.0 software (Media Cybernetics, Bethesda, MD), as previously described.56,58 Glomerulosclerotic injury was graded based on the severity of glomerular damage, including mesangial matrix expansion, hyalinosis with focal adhesion, capillary dilatation, glomerular tuft occlusion, and sclerosis, as previously described.12,29,59 Twenty glomeruli per kidney were assessed in a blinded fashion.

Immunohistochemistry

Renal paraffin sections (4-μm) were stained for collagen IV (1:600, rabbit polyclonal anti-collagen IV; Abcam, Cambridge, MA), fibronectin (1:800, polyclonal rabbit anti-fibronectin; Dako Cytomation, Glostrup, Denmark), nitrotyrosine (1:100, rabbit polyclonal anti-nitrotyrosine; Millipore, Billerica, MA), F4/80 (1:50, rat monoclonal; Millipore, Upstate Biotechnology, Lake Placid, NY). Briefly, sections were dewaxed, hydrated, and quenched with 3% H2O2 in Tris-buffered saline (TBS) to inhibit endogenous peroxidase activity. Sections for collagen IV and fibronectin were digested with 0.4% pepsin (Sigma-Aldrich) in 0.01 M HCl at 37°C. This was followed by incubation with 0.5% milk diluted in TBS to block nonspecific binding. Subsequently, sections were incubated with the primary antibody overnight at 4°C followed by avidin/biotin blocking. Sections for nitrotyrosine were incubated with 10% normal horse serum in TBS instead of 0.5% milk before incubation with the primary antibody. Similarly, sections for F4/80 were incubated with protein blocking agent (Dako CSA Kit) before incubation with the primary antibody.
antibody anti-F4/80 overnight at 4°C and staining was also amplified further by Dako Catalyzed Signal Amplification Kit, according to the manufacturer’s instructions. Thereafter, biotinylated anti-rabbit Ig (1:500) for collagen IV, fibronectin, nitrotyrosine, and biotinylated anti-rat Ig (1:200) for F4/80 (Vector Laboratories, Burlingame, CA) were applied as the secondary antibody, followed by horseradish peroxidase–conjugated streptavidin (VECTASTAIN Elite ABC Staining Kit; Vector Laboratories). Peroxidase conjugates were subsequently visualized using 3,3’-diaminobenzidine tetrahydrochloride (Sigma-Aldrich) in 0.08% H2O2/TBS. For VEGF immunostaining, a Dako ARK Peroxidase for Mouse Primary Antibodies protocol was followed. Sections were dewaxed, hydrated, and incubated with peroxidase block followed by incubation with biotinylated primary anti-VEGF antibody for 1 hour at room temperature and incubation with streptavidin peroxidase. Peroxidase conjugates were subsequently visualized using 3,3’-diaminobenzidine substrate chromogen.

Finally, sections were counterstained with Mayer’s hematoxylin, dehydrated, and mounted. All sections were examined under a light microscope (Olympus BX-50; Olympus Optical, Tokyo, Japan) and digitized with a high-resolution camera. For the quantification of the proportional area of staining, 20 glomeruli (×400) were analyzed using Image-Pro plus 6 (Media Cybernetics). All assessments were performed in a blinded manner. Six or eight kidneys were investigated in each group.

**MCP-1 ELISA**

The concentration of MCP-1 was identified in the protein extracts obtained from the renal cortex for each group (n=5–6 per group) by

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**Figure 11.** Genetic targeting of Nox4 attenuates diabetes-induced increased expression of proinflammatory markers MCP-1 and NF-κB p65 in vitro and in vivo. (A and B) RT-PCR analysis of (A) MCP-1 and (B) NF-κB p65 in human podocytes transfected with shRNA specific for Nox4 and then grown in NG (5 mM) or HG (25 mM) for 2 days. Data are the mean±SEM (n=6/group). *P<0.05 versus nontarget plus NG; †P<0.05 versus nontarget plus HG. (C and D) RT-PCR analysis of (C) MCP-1 and (D) NF-κB p65 in renal cortex of control and diabetic Nox4+/−ApoE−/− and Nox4−/−ApoE−/− mice after 20 weeks. Data are the mean±SEM (n=6/group). ‡P<0.05 versus control Nox4+/−ApoE−/− and Nox4−/−ApoE−/− mice. (E and F) Measurement of MCP-1 by ELISA in protein extracts of renal cortex of (E) control and diabetic Nox4+/−ApoE−/− and Nox4−/−ApoE−/− mice or in (F) control and diabetic Nox1+/−ApoE−/− and Nox1−/−ApoE−/− mice after 20 weeks, (n=5–6/group) or in (G) control and diabetic ApoE−/− mice with and without treatment with GKT137831 for 20 weeks, (n=5–6/group). Data are the mean±SEM. †P<0.05 versus respective control Nox4+/−ApoE−/− and Nox4−/−ApoE−/− mice (E) or control Nox1+/−ApoE−/− and Nox1−/−ApoE−/− mice (F) or control ApoE−/− and ApoE−/− plus GKT137831 mice (G); ‡P<0.05 versus diabetic ApoE−/− mice (G). Cont, control; Diab, diabetes; GKT, GKT137831; HG, high glucose; NG, normal glucose.
in the instructions of an ELISA kit (1:3; R&D Systems, Kirrawee, NSW, Australia). The ELISA results were expressed relative to the protein concentration.

**Measurements of Superoxide and ROS Production in Renal Cortex**

Renal superoxide levels were measured in frozen kidney cortex using HPLC calibrated to measure dihydroethidium by a previously established method. Furthermore, ROS levels were measured in frozen kidney cortex. Briefly, renal cortex was homogenized in Krebs buffer, and cytosolic and mitochondrial fractions were prepared by differential centrifugation as previously described. Cytosolic and mitochondrial isolates were assayed in duplicate in clear 96-well plates and prewarmed Krebs-HEPES supplemented with L-012 (Wako Chemicals, Richmond, VA) at a concentration of 100 μM added to each well in the dark and incubated at 37°C for 10 minutes. After incubation, plates were read in a luminometer (MicroLumat Plus; Berthold Technologies, Pforzheim, Germany) and luminescence was measured with a single measuring time of 1 second and cycle time of 111 seconds for 20 minutes at 37°C. Buffer blank was subtracted from each reading. A bicinchoninic acid protein assay (Pierce/Thermo Scientific, Scoresby, VIC, Australia) was performed (samples 1:10 in PBS) according to the kit instructions and results were expressed relative to the total protein concentration (in milligrams).

**In Vitro Experiments**

Conditionally immortalized human podocytes were used for the in vitro study. Podocytes were grown in RPMI with 10% FCS and 1× ITS media supplement (Sigma-Aldrich), which contains 1.0 mg/ml insulin from bovine pancreas, 0.55 mg/ml human transferrin, and 0.5 μg/ml sodium selenite in a humidified incubator, 5% CO2 at 33°C. Approximately 60% confluent cells were transferred to 2% FBS media and incubated at 37°C for 2 weeks. Under these conditions, the podocytes undergo growth arrest, display the typical arborized pattern of foot process extensions (Supplemental Figure 3), and express markers of mature podocytic differentiation in vivo, including Wilms' tumor-1 and nephrin (Supplemental Figure 4). Cells were then cultured in RPMI with 5 mmol/L glucose or 25 mmol/L glucose in the presence or absence of TGF-β1 (5 ng/ml; R&D Systems, Minneapolis, MN) with or without GKT137831 (10 μM) dissolved in 0.1% DMSO and incubated for 48 hours at 37°C.

**shRNA to Nox4**

The knockdown of Nox4 was performed in human podocyte using MISSION shRNA expressing lentivirus vectors (Sigma-Aldrich) as previously described. The sequence targeting Nox4 knockdown corresponds to 5'-GCTGTATATTGATGGTCCTTT-3' (TRCN0000046089). Cells transduced with the MISSION nontarget shRNA control vector particles (Sigma-Aldrich) were used as controls. The undifferentiated podocytes were seeded at 1×10⁶ cells per dish in a 100-mm dish and infected by the lentivirus particles in the presence of 8 μg/ml polybrene, followed by selection in puromycin (1 μg/ml; Sigma-Aldrich) for 4 days. The knockdown efficiency in the cells was verified by RT-PCR and was approximately 70% for Nox4. Nontarget and Nox4-shRNA–infected cells were then cultured in RPMI with 5 mmol/L glucose or 25 mmol/L glucose or in the presence or absence of TGF-β1 (5 ng/ml) and incubated for 48 hours at 37°C. At the end of each experiment, cells were harvested and RNA was extracted by the TRizol method and cDNA was synthesized for quantitative RT-PCR.

**In Vitro Gene Expression Analyses**

Gene expression was analyzed by real-time RT-PCR, using the TaqMan system based on real-time detection of accumulated fluorescence (ABI Prism 7500; PerkinElmer). Fluorescence for each cycle was quantitatively analyzed by an ABI Prism 7500 Sequence Detection System (PerkinElmer). To control for variation in the amount of DNA that was available for PCR in the different samples, gene expression of the target sequence was normalized in relation to the expression of an endogenous control 18S ribosomal RNA (18S rRNA TaqMan Control Reagent Kit, ABI Prism 7500; PerkinElmer). Triplicate experiments were performed, with six replicates each. Results were expressed relative to control (untreated) cells, which was arbitrarily assigned a value of 1. Human probe and primer sequences used for quantitative RT-PCR are shown in Supplemental Table 2.

**Measurement of ROS In Vitro**

Fully differentiated normal, nontarget, and Nox4-shRNA infected human podocytes were trypsinized and resuspended in 200 μl RPMI media at a density of 10⁶ cells per well of a white 96-well microplate (PerkinElmer) and incubated at 37°C for 24 hours. Normal human podocytes were then cultured with or without GKT137831 (10 μM) for 2 hours and then treated with or without TGF-β1 (5 ng/ml) for 4 hours at 37°C. However, nontarget and Nox4-shRNA–infected cells were cultured in normal glucose (5 mM) or in high glucose (25 mM) for 2 days or in the presence or absence of TGF-β1 (5 ng/ml) for 4 hours at 37°C. Each well was washed with Krebs-HEPES, and 100 μl of Krebs-HEPES supplemented with L-012 (100 μM) (Wako Chemicals) was subsequently added and incubated at 37°C for 10 minutes. After incubation, plates were read on a luminometer (Berthold Technologies).

**Statistical Analyses**

All parameters were analyzed by one-way ANOVA using GraphPad Prism 5 software (GraphPad Software, Inc., La Jolla, CA) for multiple comparisons of the means or analyzed by the two-tailed unpaired Mann–Whitney U test when required. A P value<0.05 was considered statistically significant. Results are expressed as the mean±SEM, unless otherwise specified.

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