Role of fibrillin-1 in hypertensive and diabetic glomerular disease

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The microfibrillar protein fibrillin-1 is a component of the mesangial matrix. Defects in fibrillin-1 predisposes individuals to vascular damage in Marfan syndrome, but the role of fibrillin-1 in kidney disease is unknown. We hypothesized that fibrillin-1 is involved in hypertensive or diabetic glomerular disease. DOCA-salt hypertension or streptozotocin (STZ) diabetes led to a significant increase in glomerular fibrillin-1 deposition. To test the functional role of fibrillin-1, DOCA hypertension and STZ diabetes were induced in mice homozygous for a mutation leading to a fivefold lower expression of fibrillin-1 (mgR/mgR). Untreated male mgR/mgR mice usually die from aortic dissection during the first 4 mo of life. All DOCA-treated mgR/mgR mice died within 2 wk after onset of DOCA treatment. DOCA-treated heterozygous (mgR/+) and their wild-type littermates displayed similar blood pressure levels, but albuminuria was significantly lower in mgR/+ than in wild-type mice after DOCA treatment. Similarly, STZ diabetic mgR/mgR and mgR/+ developed lower albuminuria than wild-type mice despite higher blood glucose levels in mgR/mgR and mgR/+ compared with wild-type mice. Blood pressure, blood glucose, and albuminuria did not differ among untreated mgR/mgR, mgR/+, and wild-type mice, respectively. In diabetic mgR/+ and mgR/mgR, but not in wild-type mice, an induction of glomerular decorin expression was observed. Thus underexpression of fibrillin-1 predisposes individuals to lethal aortic dissection in the presence of hypertension. On the other hand, albuminuria as a parameter of microvascular damage in hypertension and diabetes was ameliorated in fibrillin-1-underexpressing mice, possibly due to a compensatory upregulation of decorin. We conclude that fibrillin-1 may contribute to glomerular damage in hypertensive and diabetic kidney disease.

deoxycorticosterone acetate hypertension; fibrillin-1-underexpressing mice; glomerular damage; streptozotocin; diabetes

THE MICROFIBRIL-ASSOCIATED protein fibrillin-1 is abundant in elastic and nonelastic tissues of many organs. Fibrillin-1 is often associated with elastin but can also be found in elastin-free microfibrillar bundles (4). Mutations in the fibrillin-1 gene lead to Marfan syndrome. In addition to skeletal and eye abnormalities, patients with Marfan syndrome suffer from severe dilatation or even rupture of the aorta, which is the most common cause of premature death in Marfan patients (16). Fibrillin-1 is abundantly expressed in the wall of large arterial vessels. Recent studies revealed that the protein is also present in the extracellular matrix produced by mesangial cells in vitro and in the mesangium of the glomerular capillary tuft in vivo (26). The function of fibrillin-1 in the glomerular mesangium, however, is not known. Several case reports describing different types of glomerular disease in patients with Marfan syndrome have been published (1, 11, 17, 18, 22), but there is no evidence that this is more than a chance association. No systematic study on renal sequelae of Marfan syndrome has been performed so far.

A mutant mouse model that exhibits a fivefold underexpression of fibrillin-1 was established by Pereira et al. (15). These mice showed some hallmarks of Marfan syndrome, including cardiovascular complications due to mechanical collapse and dissecting aneurysms of the aortic wall. However, no obvious abnormal renal phenotype was observed. Moreover, previous studies from our laboratory revealed neither functional nor major structural alterations in the kidneys from these mice (8).

An expression of fibrillin-1 apparently does not disturb the development and function of a healthy kidney. This observation does not rule out the possibility that fibrillin-1 may affect the progression of glomerular injury. Here, we show that fibrillin-1 was more abundant in glomeruli of animals with hypertensive or diabetic nephropathy than in healthy glomeruli. To test the hypothesis that fibrillin-1 contributes to renal disease, we induced hypertensive or diabetic glomerular damage in fibrillin-1-underexpressing mice and their wild-type littermates.

MATERIALS AND METHODS

Animal Procedures

Male Sprague-Dawley rats were obtained from Charles River (Sulzfeld, Germany). Heterozygous fibrillin-1-underexpressing mice (strain mgR) were a generous gift from Dr. F. Ramirez (Hospital for Special Surgery, New York, NY), were kept on a mixed genetic background (129SV in C57BL/6), and were bred at our animal facilities. Fibrillin-1-underexpressing mice were genotyped by PCR using the primers 5′-CTC CTG GGG ACC TAC AAA TG-3′ and reverse: 5′-CCA GTG GTG TTT CGA CAT TG-3′); and neomycin (forward: 5′-GTG TTC CGG CTC TGA GGC CA-3′; reverse: 5′-GTC CTG ATA GGC GTC CGC CA-3′), detecting the native fibrillin-1 gene or the introduced neomycin cassette, respectively. Mice were used for experiments at the age of 10 wk. Animals were housed in a room maintained at 22 ± 2°C, exposed to a 12:12-h dark-light cycle with free access to standard chow (no. 1320, Altromin, Lage, Germany) and tap water (or 1% saline; see below). All procedures performed using animals were done in accordance with guidelines of the American Physiological Society and were approved by local government authorities (Regierung von Mittelfranken, AZ 621–2531.31–1/01 and AZ 621–2531.3–18/94).

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To determine glomerular fibrillin-1 expression patterns in diseases associated with glomerular injury, we performed a study, investigating fibrillin-1 mRNA and protein expression in glomeruli of rats with experimental DOCA-induced glomerular hypertension (DOCA hypertension) and in glomeruli of rats with streptozotocin (STZ)-induced diabetic nephropathy (STZ diabetes). Disease models were induced as described elsewhere (10, 30).

**DOCA hypertension in mice.** At an average weight of 25-30 g, male mice with a homozygous (mgR/mgR) or heterozygous (mgR/mgR) gene defect for fibrillin-1 and their wild-type (+/+) littermates underwent a right unilateral nephrectomy in deep ketamine/xylazine anesthesia. After 2 wk of recovery, 21-day-release DOCA pellets containing 50 mg DOCA (Innovative Research of America, Sarasota, FL) were implanted subcutaneously by incision of the right flank under ether anesthesia. Control animals were sham operated. After 21 days, DOCA-treated animals received a replacement pellet. All animals (DOCA and control) received isotonic saline (10 g NaCl/l) for drinking over a period of 6 wk, starting with the first day of DOCA treatment. Mice of the different genotypes were distributed randomly to salt-loading control groups (5 mgR/mgR, 15 mgR+/+, and 9 in +/+) or DOCA-salt treated groups (13 mgR/mgR, 10 mgR++, 11 in +/+). Systolic blood pressure was measured (Visitec Systems, Apex, NC) after 6 wk of treatment, mice were placed into metabolic cages, and urine was collected for 24 h for measurement of albumin-uria. The urinary albumin content was measured by an enzyme immunoassay kit (CellTrend, Luckenwalde, Germany).

**STZ diabetes in mice.** For this study, female mice were used, because our DOCA experiments in male mice had revealed that only a few male mgR/mgR mice survived only a few weeks even without induction of DOCA hypertension. Female mice with a homozygous (mgR/mgR) or heterozygous (mgR+/+) gene defect for fibrillin-1 and their wild-type (+/+) littermates were used at an average weight of 20–25 g for induction of diabetes. Diabetes was induced by intraperitoneal injection of STZ (200 mg/kg body wt, Sigma, Deisenhofen, Germany) dissolved in 0.1 M sodium citrate buffer (pH 4.5). Two days later, blood was obtained from the tail vein and diabetes was confirmed by measurement of blood glucose using a reflectance meter (Glucometer Elite II, Bayer, Leverkusen, Germany). Only mice with a consistent blood glucose >250 mg/dl were included in the study. Mice of the different genotypes were distributed randomly to control groups (4 mgR/mgR, 10 mgR+/+, and 7 +/+) or STZ-treated groups (7 mgR/mgR, 11 mgR+/+, 10 +/+). Blood glucose was followed daily (at 8:00 A.M.) for 5 wk. After 5 wk, the mice were kept in metabolic cages for determination of urinary albumin excretion [enzyme immunoassay kit (CellTrend)] for 24 h. Systolic blood pressure was measured (Visitec Systems) after 5 wk of treatment.

The animals were killed by dissecting the abdominal artery and bleeding in deep ketamine/xylazine anesthesia. After kidney weight was measured, the organs were decapsulated. Part of each kidney was immediately snap frozen in liquid nitrogen for later RNA extraction, whereas a second part was embedded in TissueTek (Sakura, Zoeterwoude, The Netherlands) and frozen in liquid nitrogen for cryostat sections. Another part was transferred to methyl-Carnoy solution (60% methanol, 30% chloroform, and 10% glacial acetic acid) for fixation. Tissues were dehydrated by bathing in increasing concentrations of methanol, followed by 100% isopropanol. For later decorin staining and in situ hybridization procedures, parts of the kidneys were fixed in 3% paraformaldehyde and dehydrated by increasing concentrations of isopropanol. After being embedded in paraffin, 3-μm sections were cut with a Leitz SM 2000 R microtome (Leica Instruments, Nussloch, Germany).

**Real-Time RT-PCR**

Renal cortical tissue (10 mg) was homogenized in 500 μl of RLT buffer reagent (Qiagen, Hilden, Germany) with an ultratrraxor for 30 s, and total RNA was extracted with RNeasy Mini columns (Qiagen) according to the standard protocol provided by the manufacturer. First-strand cDNA was synthesized with TaqMan RT reagents (Applied Biosystems, Darmstadt, Germany) using random hexamers as primers. Final RNA concentration in the reaction mixture was adjusted to 0.1 ng/μl. Reactions without RT were used as negative controls to test for genomic DNA contamination. RT products were diluted 1:1 with dH2O before the PCR procedure. PCR was performed with the ABI PRISM 7000 Sequence Detector System and SYBR Green reagents (Applied Biosystems) according to the manufacturer’s instructions. For amplification of the rat fibrillin-1 cDNA, the forward primer was 5’TGCTCTGAAAGGACCACCATGT-3’ and the reverse primer was 5’CGGGACAACAGTATGCGTTATAAC-3’. The relative amount of the specific mRNA was normalized with respect to 18S rRNA. Primers used for amplification of 18S cDNA were the following: forward primer 5’TGATTAAGTCTCCTGCTCCTTGT-3’ and reverse primer 5’CGATCCAGGGGCTCACCTA-3’. All samples were analyzed in triplicate.

**Immunohistochemistry**

Staining of cryostat sections was performed as described elsewhere (9). The primary rabbit antibody to fibrillin-1 (28) was used at a dilution 1:500. CY3-labeled anti-rabbit IgG (DAKO Diagnostica, Hamburg, Germany) was used as a secondary antibody.

For detection of glomerular collagen IV, renal sections were deparaffinized, and endogenous peroxidase activity was blocked with 3% H2O2 in methanol for 20 min at room temperature. Sections were then layered with an antibody to collagen IV (1:1,000; Southern Biotechnology Associates, Birmingham, AL) and incubated at 4°C overnight. After addition of the secondary antibody (dilution 1:500; biotin-conjugated goat anti-rabbit IgG, Dianova, Hamburg, Germany), the staining procedure was performed as described before (7). Decorin was detected with LF-113 (kindly provided by Dr. L. W. Fisher, National Institute of Dental and Craniofacial Research, National Institutes of Health, Bethesda, MD), a rabbit anti-murine decorin antibody using an alkaline phosphatase anti-alkaline phosphatase technique (19).

Expansion of glomerular fibrillin-1 or collagen IV staining was evaluated in a Leitz Aristoplan microscope (Leica Instruments) by Metaview software (Visiotron Systems, Puchheim, Germany) in every third glomerulus per cross section, and the stained area was expressed as the percentage of the total area of the glomerular tuft.

**In Situ Hybridization**

In situ hybridization for decorin was performed as described previously (19). Briefly, deparaffinized paraaffin sections were rehydrated, treated with 5 μg/ml proteinase K (Roche Diagnostics), refixed with 4% paraformaldehyde/PBS, acetylated, and incubated with prehybridization buffer in a humid chamber at 50°C for 2 h. Hybridization was performed for 16 h at 50°C in the same buffer containing a riboprobe (7.5 ng/μl). Specimens were washed twice with 2× SSC containing 50% formamide and 1% 2-mercaptoethanol followed by washing with 2× and 0.1× SSC at 50°C. The sections were blocked with 2% normal sheep serum and 0.05% Triton X-100 in 2× SSC, washed twice with buffer 1 (50 mM Tris-HCl, pH 7.5, 225 mM NaCl), and incubated with alkaline phosphatase (AP)-conjugated anti-digoxigenin Fab in a humid chamber for 2 h at 37°C. Slides were washed twice with buffer 1 and equilibrated with 100 mM Tris-HCl, pH 9.5, containing 100 mM NaCl and 50 mM MgCl2. Endogenous AP was blocked with 5 mM levamisole. The digoxigenin/anti-digoxygenin conjugates were visualized by reaction with 0.15 mg/ml 5-bromo-4-chloro-3-indolyl phosphate/0.3 mg/ml nitroblue tetrazolium (FAST BCIP/NBT, Sigma) in 100 mM Tris-HCl, pH 9.5, containing 5 mM MgCl2, for 16 h at 4°C. Slides were then dehydrated and analyzed without counterstaining. Sections were hybridized with the sense and antisense probes in parallel using identical conditions.
Indexes of Renal Damage

Paraffin-embedded sections were stained with periodic acid-Schiff’s reagent (PAS) and investigated using light microscopy. The degree of sclerosis within the glomerular tuft was determined on PAS-stained paraffin sections using a semiquantitative scoring system as described before in detail (10). The size of the glomerular area was evaluated in PAS-stained renal sections with a Leitz Aristoplan microscope (Leica Instruments) and Metaview software (Visitron Systems).

Analysis of Data

Two-way ANOVA, followed by a post hoc Newman-Keuls test with adjustment for multiple comparisons, was used to test the significance of differences between groups. A P value <0.05 was considered significant. The procedures were carried out using SPSS software (SPSS, Chicago, IL). All data are expressed as means ± SE.

RESULTS

Induction of Fibrillin-1 Expression and Deposition in Glomeruli of Kidneys with Hypertensive or Diabetic Renal Disease in Rats and Mice

DOCA-salt-treated rats had significantly higher mean arterial blood pressure than controls (154.6 ± 11.2 vs. 98.4 ± 1.7 mmHg in controls, P < 0.05). Moreover, proteinuria was pronounced in DOCA-salt-treated rats compared with controls (739 ± 119 vs. 46 ± 4 μg/day in controls, P < 0.05). Glomerular fibrillin-1 deposition was significantly increased in DOCA-salt-treated rats compared with controls (35.0 ± 4.0 vs. 16.7 ± 3.3% glomerular area stained in controls, P < 0.05). There was also a significant induction of renal fibrillin-1 mRNA expression detected in DOCA-salt treated rats. (491.5 ± 199.8 vs. 62.8 ± 11.0 relative copy numbers in

Fig. 1. Induction of renal cortical fibrillin-1 in response to DOCA-induced hypertension (A) or streptozotocin (STZ)-induced diabetes (B). A: immunofluorescent detection of fibrillin-1 in the renal cortex of control (co) and DOCA-treated mice. Right: densitometric evaluation of glomerular fibrillin-1 staining. B: immunofluorescent detection of fibrillin-1 in the renal cortex of control and STZ-diabetic mice. Right: densitometric evaluation of glomerular fibrillin-1 staining. *P < 0.05 DOCA- or STZ-treated mice vs. co.

Fig. 2. Expression levels of fibrillin-1 mRNA in wild-type mice (WT) and mice with a heterozygous (mgR/+ ) or homozygous (mgR/mgR) mutation in the fibrillin-1 gene after 5 wk of treatment with STZ. *P < 0.05 vs. STZ-treated WT.
controls, \( P < 0.001 \). In STZ-treated rats, blood glucose was significantly elevated (433.7 \pm 22.3 vs. 116 \pm 7.1 \text{ ng/100 ml} \text{ in controls, } P < 0.05). After 5 wk, diabetic animals had developed marked albuminuria (1.11 \pm 0.08 vs. 0.22 \pm 0.05 \mu g \text{ albumin/creatinine in controls, } P < 0.05). Glomerular fibrillin-1 deposition was more pronounced in the kidneys of diabetic rats than in controls (21.3 \pm 1.5 vs. 12.4 \pm 0.6 in controls, \( P < 0.05 \)). Fibrillin-1 mRNA expression in the renal cortex tended to be higher in diabetic rats (2,222.5 \pm 776.3 vs. 1,571.2 \pm 332.5 \text{ relative copy numbers in controls, not significant}).

Similar results were obtained in DOCA-salt- and STZ-treated wild-type mice. DOCA-salt treatment led to an induction of fibrillin-1 mRNA expression (421.2 \pm 49.1 vs. 258.8 \pm 45.7 \text{ relative copy numbers in controls, } P < 0.05) and in glomerular fibrillin-1 protein deposition (Fig. 1A). STZ treatment led to an induction of fibrillin-1 mRNA expression (146.4 \pm 22.8 vs. 98.0 \pm 9.9 \text{ relative copy numbers in controls, } P < 0.05) and in glomerular fibrillin-1 protein deposition (Fig. 1B).

To study the role of elevated fibrillin-1 expression during glomerular disease, we then induced both DOCA-salt hypertension and STZ diabetes in mice underexpressing fibrillin-1. Fibrillin-1 expression levels were first evaluated in untreated mice with a homozygous (mgR/mgR) or heterozygous (mgR/+\text{)} mutation in the fibrillin-1 gene vs. their wild-type siblings. In mgR/mgR mice, fibrillin-1 expression levels were about fivefold lower than in wild-type (22.5 \pm 9.0\% \text{ compared with } 100 \pm 23.7\% \text{ in wild-type}). In contrast, fibrillin-1 expression levels in mgR/+ mice were not significantly reduced compared with wild-type (87.4 \pm 21.0\%). After induction of STZ diabetes, however, the increase in fibrillin-1 expression was significantly reduced in mgR/+ mice compared with wild-type (Fig. 2). Similar results were obtained in DOCA-salt hypertensive mgR/+ mice. Fibrillin-1 expression was only 63\% of the fibrillin-1 expression of DOCA-salt hypertensive wild-type mice.

**Effects on Survival and Extent of Renal Damage after Induction of DOCA-Salt Hypertension in Fibrillin-1 Gene-Mutated Mice**

Induction of DOCA-salt hypertension in mgR/mgR mice led to the death of most animals after implantation of the first DOCA pellet (Fig. 3). Only 2 of 11 mice survived for 3 wk

**Fig. 3. Survival of WT mice and mice with a heterozygous (mgR/+\text{)} or homozygous (mgR/mgR) mutation in the fibrillin-1 gene after uninephrectomy (UNX) implantation of the first DOCA pellet (DOCA 1) and the second DOCA pellet (DOCA 2). No. of animals analyzed are in parentheses.**

**Fig. 4.** Systolic blood pressure (A), albuminuria (B), and glomerular collagen IV protein expansion (C) in NaCl-treated controls (NaCl) or DOCA-salt-treated (DOCA) WT mice and mice with a heterozygous mutation in the fibrillin-1 gene (mgR/+). *\( P < 0.05 \text{ DOCA-salt- vs. NaCl-treated mice. D: photomicrographs of periodic acid-Schiff-stained renal sections of DOCA-salt-treated WT and DOCA-salt-treated mgR/+ mice.}**
until implantation of the second pellet, but they died soon afterward, whereas wild-type mice and mgR/+ mice survived DOCA-salt treatment until the end of the experiment. Systolic blood pressure was not different in wild-type and mgR/+ mice, neither in the control nor in the DOCA-salt-treated groups after 6 wk (Fig. 4A). However, albumin excretion in DOCA-salt-treated mgR/+ mice was significantly lower than in DOCA-salt-treated wild-type littermates (Fig. 4B). DOCA-salt treatment led to an increase in urine volume and relative kidney weights in both genotypes (Table 1). Moreover, sclerotic lesions were less severe in DOCA-salt-treated mgR/+ mice compared with DOCA-salt-treated wild-type (Fig. 4D), and the increase in glomerular collagen IV expansion detected in wild-type mice after DOCA-salt treatment is blunted in mgR/+ mice (Fig. 4C).

Effects of STZ-Induced Diabetes on Renal Function in Fibrillin-1 Gene-Mutated Mice

Treatment with STZ led to an increase in food intake and urine excretion in all genotypes (Table 2). In STZ-treated mice, blood pressure was not different compared with control mice after 5 wk (Fig. 5A). Furthermore, no genotype differences in blood pressure were detected (Fig. 5A). Blood glucose was elevated in all genotypes 5 wk after injection of STZ, in mgR/+ or mgR/mgR mice even more prominently than in wild-type mice (Fig. 5B). Significant increases in matrix deposition or sclerotic lesions in the glomerulus, however, were not detected at this early time point investigated (data not shown). On the other hand, the size of the glomerular area was increased in renal sections of STZ-treated wild-type mice, whereas no increase in glomerular size was detected in STZ-treated mgR/+ or mgR/mgR mice compared with controls (Fig. 5C). Albuminuria was clearly induced in wild-type mice after STZ treatment (Fig. 5D). In mgR/+ or mgR/mgR mice, the increase in albumin excretion was significantly lower after STZ treatment than in wild-type mice (Fig. 5D). Staining for decorin in renal sections of diabetic kidneys revealed immunoreactivity in podocytes of mgR/+ or mgR/mgR mice but not in podocytes of wild-type mice (Fig. 6, A–C). To confirm these findings, in situ hybridization for decorin was performed, which showed expression of decorin mRNA in podocyte distribution in both mgR/+ and mgR/mgR mice (Fig. 6D).

DISCUSSION

Our findings indicate that in mgR/+ or mgR/mgR mice, the sequelae of glomerular hypertension or hyperperfusion are attenuated, resulting in an amelioration of renal damage. Following induction of glomerular hypertension with DOCA (5), most mgR/mgR mice died probably from aortic dissections, as internal bleeding was commonly detected after opening of the body cavity. Pereira et al. (15) described occasional death of vascular etiology including aortic dissections in mice underexpressing fibrillin-1, arguing for a decreased elasticity of the vasculature. It thus seems conceivable that an additional hypertensive mechanical strain will frequently result in disruption of the structural integrity of vessels exposed to high blood pressure in these mice. mgR/+ mice did not die of aortic dissections after treatment with DOCA. Despite comparable blood pressure levels in wild-type and mgR/+ mice after induction of hypertension, albuminuria and glomerulosclerosis in mgR/+ mice were significantly lower than the values reached by their wild-type littersmates.

These findings are in accordance with the results from another model of glomerular mechanical strain, the STZ model of type 1 diabetes. STZ-treated animals suffer from early glomerular hyperfiltration (25), resulting in hypercellularity and only mild expansion of the glomerular matrix (6). This additional model was applied to avoid vascular injury caused by hypertension in mice with a homozygous mutation of the fibrillin-1 gene. Additionally, the STZ model was induced in female mice, because many male mgR/mgR mice survived only a few weeks even without induction of DOCA hypertension. Most of the STZ-treated female mgR/mgR mice survived

Table 1. Physiological parameters of DOCA-salt treated mice

<table>
<thead>
<tr>
<th></th>
<th>Body Weight, g</th>
<th>Urine Volume, ml/24 h</th>
<th>Food Intake, mg/24 h</th>
<th>Relative Kidney Weight, mg/g body wt.</th>
<th>Creatinine Clearance, ml/h/100 g body wt.</th>
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<tbody>
<tr>
<td>WT NaCl</td>
<td>28.4±0.9</td>
<td>2.2±0.3</td>
<td>2.1±0.3</td>
<td>7.9±0.4</td>
<td>90.8±6.5</td>
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<tr>
<td>WT DOCA</td>
<td>29.7±0.9</td>
<td>9.4±1.8</td>
<td>2.4±0.3</td>
<td>11.4±0.4</td>
<td>81.4±10.3</td>
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<tr>
<td>mgR/+ NaCl</td>
<td>29.2±0.5</td>
<td>4.2±1.2</td>
<td>1.7±0.3</td>
<td>8.0±0.3</td>
<td>105.3±25.7</td>
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<tr>
<td>mgR/+ DOCA</td>
<td>28.6±0.9</td>
<td>13.9±2.1</td>
<td>2.8±0.5</td>
<td>11.2±0.5</td>
<td>93.4±28.4</td>
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</tbody>
</table>

Values are means ± SE. NaCl, NaCl-treated controls; DOCA, DOCA-salt-treated mice; WT, wild-type mice; mgR/+, mice with a heterozygous mutation in the fibrillin-1 gene.

Table 2. Physiological parameters of STZ-treated mice

<table>
<thead>
<tr>
<th></th>
<th>Body Weight, g</th>
<th>Urine Volume, ml/24 h</th>
<th>Food Intake, mg/24 h</th>
<th>Relative Kidney Weight, mg/g body wt.</th>
<th>Urine Creatinine, µg/24 h</th>
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<tbody>
<tr>
<td>WT co</td>
<td>23.7±0.4</td>
<td>1.4±0.5</td>
<td>2.3±0.4</td>
<td>10.0±0.45</td>
<td>427.7±38.9</td>
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<td>WT STZ</td>
<td>21.5±0.4</td>
<td>4.9±1.3</td>
<td>3.4±0.3</td>
<td>11.53±0.4</td>
<td>531.8±45.3</td>
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<tr>
<td>mgR/+ co</td>
<td>22.4±0.4</td>
<td>1.0±0.2</td>
<td>2.7±0.1</td>
<td>9.25±0.35</td>
<td>421.0±29.1</td>
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<tr>
<td>mgR/+ STZ</td>
<td>21.4±0.5</td>
<td>5.2±1.6</td>
<td>3.2±0.3</td>
<td>11.95±0.55</td>
<td>492.9±65.0</td>
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<tr>
<td>mgR/mgR co</td>
<td>24.3±0.6</td>
<td>1.4±0.4</td>
<td>2.8±0.3</td>
<td>9.77±0.23</td>
<td>351.9±15.6</td>
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<tr>
<td>mgR/mgR STZ</td>
<td>22.8±0.3</td>
<td>3.8±1.5</td>
<td>3.2±0.3</td>
<td>11.68±0.62</td>
<td>404.7±41.4</td>
</tr>
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</table>

Values are means ± SE. co, solvent controls; STZ, streptozotocin-treated mice; mgR/mgR, mice with a homozygous mutation in the fibrillin-1 gene.
the 5 wk of observation. Although in mgR/+ or mgR/mgR mice blood glucose levels even tended to be higher after STZ treatment than in wild-type mice, the increase in albuminuria was attenuated compared with wild-type. Moreover, the increase in glomerular size observed in diabetic wild-type mice

Fig. 5. Systolic blood pressure (A), blood glucose (B), glomerular size (C), and albuminuria (D) in solvent controls (co) or STZ WT mice and mice with a heterozygous (mgR+/+) or homozygous (mgR/mgR) mutation in the fibrillin-1 gene. *P < 0.05 STZ-treated mice vs. co.

Fig. 6. Detection of decorin in glomeruli of STZ-treated mice. A–C: immunohistochemical detection of decorin protein in mice with a homozygous (A) and heterozygous (B) mutation in the fibrillin-1 gene and in WT mice (C). D: in situ hybridization detecting podocyte localization of decorin mRNA. E: sense control of in situ hybridization. Note the absence of reactivity in podocytes. Black arrows point to exemplary podocytes with positive staining for decorin. White arrows point to glomeruli of WT mice without decorin staining. Bar = 50 μm.
compared with controls was blunted in diabetic mgR+/+ mice, arguing for a protective role for fibrillin-1 in the maintenance of glomerular structure during diabetic nephropathy. However, a significant induction of glomerular matrix deposition in diabetic mice was not observed. This finding may be due to the short duration of diabetes, or to the fact that we used female mice, which are less susceptible to develop glomerulosclerosis than are male mice (2). As a consequence, differences in glomerular matrix expansion among the three genotypes investigated could not be detected.

Why are mice with a mutation of the fibrillin-1 gene apparently protected from an increase in albuminuria following hypertension or diabetes? If the deposition of fibrillin-1 itself would contribute to glomerular damage, a reduced expression of fibrillin-1 might well be protective. mgR/mgR mice express fivefold less fibrillin-1 compared with wild-type litters, which is in accordance with previously published data (8, 15). mgR/+ mice do not display a significant underexpression of fibrillin-1 per se, but induction of cortical fibrillin-1 expression seems to be attenuated in mgR/+ mice after glomerular injury (DOCA glomerular hypertension or STZ diabetic nephropathy) compared with wild-type mice after glomerular injury. Alternatively, a compensatory upregulation of other matrix molecule(s) in mice with a mutation in the fibrillin-1 gene could exert protective effects after DOCA or STZ treatment.

Decorin is a small dermatan-sulfate proteoglycan that can form complexes with fibrillin-1 (29). In decorin-deficient mice, an overexpression of fibrillin-1 was observed, which most likely contributed to the preservation of kidney morphology after pressure-induced renal injury (21). Moreover, decorin seems to have antifibrotic properties, as it has been successfully used as a therapeutic agent to reduce glomerulosclerosis in experimental glomerulonephritis (3). Conversely, the absence of decorin leads to enhanced tubulointerstitial fibrosis following obstruction of the kidney (20).

An increase in decorin expression in the mouse kidney cortex has been observed after the onset of STZ diabetes (13). To determine the source of cortical decorin expression, several renal cell types were studied regarding their ability to express decorin. In cultivated mesangial and proximal tubular epithelial cells, decorin is constitutively expressed and upregulated by high glucose, whereas glomerular epithelial and endothelial cells do not express decorin (13). In normal kidneys of adult rats, parietal epithelial cells and interstitial cells express decorin (19). Expression of decorin in mesangial cells in vivo was only detected in trace amounts (19). This is in accordance with our findings regarding decorin expression in the glomeruli of mice. In wild-type mice, no detectable glomerular decorin protein staining was observed. In contrast, glomeruli of mgR/+ and mgR/mgR mice showed decorin mRNA and protein expression in podocytes after STZ treatment. According to earlier reports, fibrillin-1 is not expressed in podocytes; therefore, the expression of decorin in podocytes from fibrillin-1-underexpressing mice seems not to represent a compensatory mechanism in which decorin as an inducer of fibrillin-1 becomes upregulated (21). However, it is conceivable that reduced amounts of fibrillin-1 in the mesangial matrix may lead to changes in matrix assembly and composition, resulting in the release of growth factors and cytokines normally sequestered within the extracellular matrix. Thus transforming growth factor-β1, IL-6, or IL-10, factors that have been shown to regulate the expression of decorin (14, 27), once released from the mesangial matrix could pass through the glomerular basement membrane and induce decorin in podocytes.

Although the mechanisms of the antiproteinuric effects of decorin are still unknown, it is tempting to speculate that decorin, which has been shown to protect endothelial and tubular epithelial cells from apoptosis by binding to IGF-IR and inducing Akt/PKB (20, 23, 24), might have similar effects on podocytes. This in turn might lead to reduced podocyturia (31) and could explain how decorin facilitates the reduction of albuminuria described here and which has also been observed after administration of decorin (3) and by decorin gene transfer (12) in a model of mesangioproliferative glomerulonephritis.

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