Pharmacological blockade of B2-kinin receptor reduces renal protective effect of angiotensin-converting enzyme inhibition in db/db mice model

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1Laboratoire de Physiologie, Faculté de Médecine Rangueil, Toulouse; 2Institut National de la Santé et de la Recherche Médicale, Unité 858, Toulouse; and 3Université Toulouse III Paul-Sabatier, Institut de Médecine Moléculaire de Rangueil, Équipe 5, IFR31, Toulouse, France

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Buléon M, Allard J, Jaafer A, Pradaude F, Dickson Z, Ranera M-T, Pecher C, Girolami J-P, Tack I. Pharmacological blockade of B2-kinin receptor reduces renal protective effect of angiotensin-converting enzyme inhibition in db/db mice model. Am J Physiol Renal Physiol 294: F1249–F1256, 2008. First published March 26, 2008; doi:10.1152/ajprenal.00501.2007.—Diabetic nephropathy (DN) can be delayed by the use of angiotensin-converting enzyme inhibitors (ACEi). The mechanisms of ACEi renal protection are not univocal. To investigate the impact of bradykinin B2 receptor (B2R) activation during ACE inhibition, type II diabetic mice (C57BLKS db/db) received for 20 wk: 1) ACEi (ramipril) alone, 2) ACEi + HOE-140 (a specific B2R antagonist), 3) HOE-140 alone, or 4) no treatment. The development of DN, defined by an increase in albuminuria and glomerulosclerosis, was largely prevented by ACEi treatment (albuminuria: 980 ± 130 vs. 2,160 ± 330 mg/g creatinine; mesangial area: 22.5 ± 0.5 vs. 27.6 ± 0.3%). The protective effect of ramipril was markedly attenuated by B2R blockade (albuminuria: 2,790 ± 680 mg/g creatinine; mesangial area: 30.4 ± 1.1%), whereas HOE-140 alone significantly increased albuminuria. Despite such benefits, glomerular filtration rate remained unchanged, probably because of the combination of the hypertensive effect of diabetes in this model and the renal hemodynamic action of ramipril. Finally, the renal protective effect of ACEi was associated with a marked decrease in glomerular overexpression of insulin-like growth factor-1 (IGF-1) and transforming growth factor-β pathways, but also in advanced glycation end product receptors and lipid peroxidation assessed by 4-hydroxy-2-nonenal (4-HNE) adducts. Concomitant blockade of B2R partly restored glomerular overexpression of IGF-1 receptor β and 4-HNE complexes. These results support the critical role of B2R activation in the mediation of ACEi renal protection against DN and provide the rationale to examine the benefit of B2R activation by itself as a new therapeutic approach for DN.

Diabetic nephropathy (DN) is a major complication associated with the progression of both type 1 and type 2 diabetes. Optimization of glycemic control helps to reduce its onset. However, despite such efforts, DN is present in more than 40% of patients in both types of diabetes after 25 years of evolution (20). In type 2 diabetes, the future appears even worse, since the prevalence of the disease is still growing and the faint hope of reaching euglycemia is far less than in type 1 diabetes. For these reasons the research of new therapeutic strategies to protect against the development of DN is essential. Until now, the blockade of the renin angiotensin system, mainly with angiotensin-converting enzyme inhibitors (ACEi) but also with antagonists of the AT1 receptor for angiotensin II, was the only efficient treatment able to slow down the progression of DN (12, 25). It is usually considered that both families of drugs act through either inhibition of angiotensin II generation or blockade of its receptor (30, 31). Indeed, angiotensin II is a potent vasoconstrictor that promotes the synthesis of the highly fibrotic cytokine transforming growth factor-β (TGF-β) and stimulates the production of reactive oxygen species (8), leading to a globally profibrotic effect. However, some works suggest that this might not be their only mechanism of action. Indeed, in addition to the blockade of angiotensin II synthesis, ACEi also inhibit degradation of bradykinin (BK) by the ACE. As a result, bradykinin bioavailability increases, enabling the activation of its receptors. BK acts via two distinct G protein-coupled receptors named B1-kinin (B1R) and B2-kinin receptors (B2R). (11). Activation of the B2R induces powerful physiological actions that, on the whole, oppose those of angiotensin II. This raises the question of a potential direct renal protective effect of BK during ACEi treatment (11, 14). Most of the recent data obtained with genetically modified mice sustain such a hypothesis. Diabetic nephropathy is markedly enhanced in mice lacking the B2R (23) and in mice with genetically increased angiotensin I-converting enzyme expression (22), where B2R activation by endogenous kinin is abolished, suggesting that this receptor is involved in the renal protective effect of BK during DN. As further support of this hypothesis, our group has shown that in vivo, B2R activation reduces renal fibrosis following unilateral ureteral obstruction in mice, an effect associated with increased matrix degradation and increased synthesis of plasminogen activators (34). We also recently observed that in a model of streptozotocin (STZ)-induced diabetes in rats, the blockade of B2R blunted the beneficial effect of ACEi treatment on albuminuria (2). In contrast, a recent publication has provided contradictory information suggesting that B2R knockout in mice protects against the development of diabetic nephropathy (40). Thus it appears critical 1) to establish the contribution of B2R activation in the renal protective action of ACEi treatment during diabetic nephropathy and 2) to clarify the pathophysiological mechanisms affected.

The aim of the present study was to investigate, using the db/db mouse model of type 2 diabetes, the consequences of the chronic blockade of B2R during ACEi treatment of diabetic...
nephropathy. To achieve this goal, diabetic mice received treatment with ramipril, a molecule that has shown its efficacy in this circumstance (2, 29), either alone or in association with HOE-140, a specific and poorly reversible B2R antagonist (43). The consequences of this treatment on the development of DN (i.e., albuminuria, renal failure, and glomerulosclerosis) and on some of the main pathogenic mechanisms of diabetic glomerulopathy were studied after 20 wk of treatment. We found that the pharmacological blockade of the B2R markedly reduces the renal protective action of ACEi in this model of diabetic nephropathy. Furthermore, some of the crossover signaling pathways between B2R and ACEi renal protective effects were identified.

METHODS

Animal model. Obese diabetic C57BLKS db/db mice and heterozygote C57BLKS db/m mice were purchased from the Jackson Laboratories and kept in a temperature-controlled room on a 12:12-h light-dark cycle. To avoid a sex-related discrepancy in the results, only female mice were used. Animals were allowed free access to standard diet and tap water. Experiments were performed using zygote C57BLKS db/db mice purchased from Jackson Laboratories and kept in a temperature-controlled room on a 12:12-h light-dark cycle. To avoid a sex-related discrepancy in the results, only female mice were used. Animals were allowed free access to standard diet and tap water. Experiments were performed using 7-wk-old mice randomly assigned to four groups: either 1) untreated, or treated for 20 wk with 2) ACEi (ramipril, Aventis Pharma Germany; 1 mg·kg⁻¹·day⁻¹ in drinking water), 3) ACEi and B2R selective antagonist HOE-140 (Icatibant HOE-140, Aventis Pharma Germany; 250 μg·kg⁻¹·48 h⁻¹ subcutaneously), or 4) HOE-140 alone (250 μg·kg⁻¹·48 h⁻¹ subcutaneously). This dose was able to prevent the hypotensive effect of a single 100-μl intravenous bolus of 2 × 10⁻⁵ M BK (see RESULTS). Based on pilot experiments, this protocol of administration avoided the implantation of minipumps in these diabetic and obese mice, which are sensitive to infections and healing complications. In each group, age-matched heterozygote C57BLKS db/m mice were used as nondiabetic controls. Every other week, the mice were weighed and blood samples were collected from the tail in 12-h fasted mice to measure glucose concentration using Glucose RTU (BioMérieux, France). The mice were placed in metabolic cages to collect 24-h urine, and urinary albumin excretion was determined with a specific ELISA (Bethyl). Renal function, histology, and glomerular protein extraction were performed 20 wk later. Serum fructosamine, an index of glucose exposure, was dosed by a colorimetric method based on the reduction of nitrotetrazolium blue by ketoamines. All procedures involving experimental animals were approved by the French Accreditation of Laboratory Animal Care and performed in accordance with the guiding principles for animal research.

Renal function studies. For surgical procedures, mice were anesthetized with an intraperitoneal injection of 30 mg/kg of Etomidate Lipuro (Braun Medical). After tracheotomy, the left jugular vein was cannulated to perfuse inulin, and the left femoral artery was cannulated to monitor arterial blood pressure and to obtain blood samples. Urine was collected through an intravesical catheter. After surgery, mice were allowed to recover for 30 min. Renal function was evaluated for a 60-min clearance period. Glomerular filtration rate (GFR) was assessed by inulin clearance and expressed per gram of kidney weight. At the end of the study, a catheter was introduced into the abdominal aorta. The left kidney was excised and weighed. The right kidney was washed with 10 ml of PBS, fixed by an infusion of 10 ml of 10% formalin (pH 7.40), removed, and stored in formalin.

Glomerular histology and morphology. Formalin-fixed right kidneys were embedded in methyl methacrylate. Sections of 3-μm thickness were stained with periodic acid Schiff (PAS). Pictures were captured using a digital camera Nikon D1 (Nikon, Japan) connected to a light microscope. For each animal, pictures from 50 randomly chosen glomeruli were taken at magnification ×400 and analyzed using Photoshop software (Adobe System, San Jose, CA) and a public domain NIH Image program (http://rsb.info.nih.gov/nih-image/).

Briefly, the total cortical area was examined. A total of 50 glomerular images were randomly recorded by moving the slide from the outer to the inner cortex to obtain noncrossing sample fields. Images were processed using Photoshop software. Glomerular tufts (including all the cellular and interstitial components of the glomerulus, including podocytes and capillaries) were encircled, and the enclosed area was copied to create a new picture (5). The number of pixels (independent of their individual density) of this picture gave the surface area density of the tuft. According to DeHoff’s equation for the measurement of spheroids of differing size, the harmonic mean of glomerular areas (Svm) was used to calculate the mean glomerular volume (GlmVm) for each animal, using the formula GlmVm = 4/3(Svm)/3/2. From the glomerular picture, the entire amount of PAS-positive material, except for the peripheral basement membranes, was selected automatically using the properties of color recognition of the software and was manually completed by the inclusion of nuclei. The number of pixels in this area was considered to represent the mesangial area (i.e., mesangial cells and extracellular matrix areas) and was expressed as a fraction of the tuft surface area (5).

Glomerular isolation by magnetic sorting. Colloidal iron oxide suspension was prepared as described by Cook and Pickering (9) for rabbits and modified in our laboratory. Briefly, mice from the different experimental groups described above were anesthetized by intraperitoneal injection of 150 mg/kg Inactin. Ten milliliters of colloidal iron oxide suspension were injected through the abdominal aorta following a 10-ml PBS rinse. Kidneys were removed, and renal cortex was sliced and pressed through a 125-μm² graded sieve. The glomeruli were then magnetized and washed three times in PBS to obtain a 93% purity suspension. Proteins were extracted using a lysis buffer [10% glycerol, 20 mM Tris, 140 mM NaCl, 10 mM sodium pyrophosphate, 10 mM sodium fluoride, 2 mM sodium orthovanadate, 3 mM EDTA, 10 μg/ml aprotinin, 1.5 μM benzamidine, 50 μM PMSF, 10 μg/ml leupeptin, 1% phosphatase inhibitor cocktail 2 (Sigma), and 1% Triton X-100] added to the last sediment of glomeruli. All procedures were performed at 4°C. The suspension of glomeruli was sonicated for 1 min and centrifuged (15,000 rpm for 45 min at 4°C). The supernatant was stored at ~80°C until Western blot analysis was performed. Protein concentration was determined using a colorimetric method (Bio-Rad DC protein assay).

Western blot analysis. Proteins (20–25 μg) were separated by electrophoresis in polyacrylamide gels (NuPage 4–12% Bis-Tris precast gels; Invitrogen) and electrophoretically transferred to nitrocellulose membranes (Hybond-ECL; Amersham). After 1-h incubation at room temperature in Tris-buffered saline, 5% milk, or 1% milk plus 1% BSA and 0.05% Tween-20, the blots were exposed to antibodies recognizing either insulin-like growth factor-1 receptor (IGF-1Rβ), insulin receptor substrate-1 (IRS-1), ERK1/2, phospho-ERK1/2, AGE receptor (RAGE), TGF-β type II receptor (TGF-βRII), B2R, and 4-hydroxy-2-nonenal (4-HNE) for 1 night at 4°C. The primary antibodies were revealed using the corresponding rabbit or donkey peroxidase-conjugated secondary antibodies for 1 h at room temperature. Peroxidase activity was detected using a chemiluminescence substrate (Super Signal West Pico chemiluminescence substrate; Pierce) and Kodak Biomax Light film. Primary and secondary antibodies were all purchased from Santa Cruz Biotechnology, except for anti-RAGE (Chemicon International), anti-B2R (BD Transduction Laboratory), and anti-β-actin (Sigma).

Statistical analysis. Since the number of animals did not always allow us to assume a Gaussian distribution, comparisons among experimental groups were performed using the nonparametric Kruskal-Wallis test. When this test indicated a significant difference, a post hoc test (Dunn’s multiple comparison test) was performed using GraphPad Prism 4.0 (GraphPad Software). P < 0.05 was considered statistically significant.
RESULTS

Efficiency of B2R blockade in vivo. The first step was to determine the time course of HOE-140 administration that allowed in vivo blockade of B2 receptors. The efficiency of this treatment with the B2R antagonist was studied by blood pressure responsiveness to an intravenous bolus of BK (2 × 10⁻⁵ M, 100 μl). In db/db mice treated with HOE-140 alone at the dose of 250 μg·kg⁻¹·48 h⁻¹ for 1 wk, the hypotensive response to BK was almost completely blunted (Fig. 1). The maximum decrease of mean arterial blood pressure (MABP) following the bolus of BK was 36.0 ± 13.4 mmHg (n = 6) for control db/db mice and 13.3 ± 7.0 mmHg for db/db mice treated with HOE-140 (n = 5, P < 0.05). In HOE-treated mice, BK induced a transient hypertensive effect that may result from the consequences of prolonged B2R blockade of vasoconstrictor tone.

General characteristics. The characteristics of the five groups of mice at the end of the experimental period are presented in Table 1. The body and kidneys of db/db mice were significantly heavier (P < 0.05) than those of db/m mice. All the db/db mice showed substantial hyperglycemia (P < 0.001) and a significant increase in the fructosamine level (P < 0.05) compared with db/m mice. Treatment with ACEi had no effect on the increases in body and kidney weight or on blood glucose and fructosamine levels at the end of the experimental period. MABP in db/db mice was significantly (P < 0.05) decreased compared with nondiabetic db/m mice, MABP was slightly but significantly (P < 0.05) lower in ACEi-treated mice than in untreated diabetic mice. This effect of ACEi was completely reversed in the presence of HOE-140.

Urinary albumin excretion. As shown in Fig. 2A, urinary albumin excretion at the end of the study was significantly higher in db/db mice than in db/m mice. ACEI treatment prevented this increase, and coadministration of HOE-140 blunted the benefit of ACEI on urinary albumin excretion. Unexpectedly, db/db mice that received HOE-140 alone exhibited a significant increase in urinary albumin excretion compared with untreated db/db mice.

Glomerular filtration. In diabetic db/db untreated mice, GFR was significantly (P < 0.05) lower than in the nondiabetic db/m mice (Fig. 2B). GFR was not significantly different among the three groups of db/db mice despite a tendency to be slightly higher in ACEI + HOE-140-treated mice.

Glomerular histology and morphology. As illustrated in Fig. 3, all db/db mice presented a significant increase in glomerular volume (P < 0.001) compared with the nondiabetic db/m mice. Treatment with ACEI, the B2R antagonist alone, or both drugs failed to induce any significant changes in glomerular volume. Glomerulosclerosis was assessed by the determination of mesangial volume. In db/db control mice, mesangial volume was significantly higher (P < 0.05) than in the nondiabetic db/m mice. Interestingly, treatment with ACEI significantly prevented (P < 0.05) this increase in mesangial volume, leading to a volume similar to that of the nondiabetic mice. Concomitant treatment with HOE-140 abolished (P < 0.01) the effect of ACEI treatment, whereas HOE-140 alone had no significant effect on mesangial expansion.

Glomerular protein expression. The B2R was spontaneously expressed in the glomeruli of both db/m and db/db mice (Fig. 4A). Although the statistical difference was not significant, B2R tended to increase in diabetic mice and remained closer to that of the db/m group in the glomeruli of animals treated with ACEI alone or with HOE-140 (Fig. 4A). Glomerular protein expression of IGF-1R, IRS-1, RAGE, and TGF-βRII were increased in diabetic db/db mice compared with nondiabetic db/m mice (Fig. 4, B, C, E, and F). Treatment with ACEI reduced overexpression of all these signaling proteins, particularly for TGF-βRII. The changes associated with ACEI treatment on IGF-1R expression were attenuated by coadministration of HOE-140. Although diabetes had no significant impact on total ERK1/2 glomerular expression, activated forms of these MAP kinases, assessed by the expression of their tyrosine phosphorylated forms, were strongly increased in diabetes (Fig. 4D). The band corresponding in particular to phospho-ERK1 was reduced when db/db mice were treated with ACEI alone or in combination with HOE-140. Figure 4G shows glomerular expression of 4-HNE adducts, an index of protein peroxidation. Formation of 4-HNE occurs endogenously during lipid peroxidation of polyunsaturated fatty acids that can act as a “toxic second mediator” exhibiting a wide range of biological activities. Compared with the pattern observed in db/m mice, 4-HNE-protein conjugates were significantly increased in db/db C mice, showing major bands at 250, 100, 75, 70, and 45 kDa. In the diabetic ACEI-treated group, the 4-HNE-protein profile was noticeably modified, especially the 100- and 70-kDa bands. These bands were suppressed, exhibiting a pattern very close to that of nondiabetic db/m mice, except for a more pronounced accumulation of 4-HNE on the same proteins. Interestingly, this restoration of a near-normal glomerular pattern of 4-HNE-protein conjugates was partly prevented when HOE-140 was coadministered with ACEI, thus going back to a profile close to that of diabetic mice untreated or treated with HOE-140 alone (not shown).

Fig. 1. Effect of B2-kinin receptor (B2R) blockade by HOE-140 on the acute hypotensive effect of bradykinin (BK). Db/db mice were treated with a subcutaneous injection of HOE-140 (250 μg·kg⁻¹·48 h⁻¹), mean arterial blood pressure was measured 48 h after the last injection with HOE-40. Control db/db mice (n = 6) and db/db mice treated by HOE-140 (n = 5) received an intravenous bolus of 100 μl of saline followed by 2 boluses of BK (2 × 10⁻⁵ M, 100 μl), and mean arterial blood pressure was measured intrafemorally.
DISCUSSION

Until now, the most efficient approach delaying the progression of DN relied on the blockade of the renin angiotensin system, particularly with ACE inhibitors. This pharmacological strategy is multifaceted, since it includes control of blood pressure, decrease in proteinuria, inhibition of fibrosing cytokines, vasopeptidase inhibition, and oxidative stress modulation. Which of these events occurs first and is the most important remains an unanswered question. It also creates a space for optimization of the therapeutic approach of blocking or even reversing diabetic nephropathy. The dual action of ACEi, namely, angiotensin II synthesis inhibition and BK degradation prevention, already leads to unanswered questions about the mechanism(s) of their renal protective effect. As recently reviewed (11, 14), BK by itself exerts some renal protective effects that involve activation of the type 2 receptor (B2R). Two of the most convincing arguments are that 1) B2R knockout in mice is associated with the worsening of renal lesions in various models of nephropathy, including DN (23, 33), and 2) direct B2R activation using kinin infusion prevents renal inflammation and glomerulosclerosis via inhibition of oxidative stress in Dahl salt-sensitive rat (7). In a recent study (2), we observed that the blockade of the B2R in a model of STZ-induced diabetes in rats blunted the beneficial effects of ACEi treatment on urinary albumin excretion. However, another recent publication (40) provides a contradictory conclusion regarding the protective action of B2R activation in diabetes, thus reopening the debate on this critical point. In this study, B2R−/− knockout mice were protected against the increase in urinary albumin excretion and glomerular lesions resulting from STZ-induced diabetes. This discrepancy could be explained by the fact that, compared with B2R+/+ animals, B2R−/− mice also exhibit spontaneous upregulation of the B1R (15) that was even reinforced by diabetes. This is the reason why we chose the pharmacological blockade of the B2R rather than its genetic knockout model. Furthermore, we focused on the renal effects of direct inhibition of the B2R in db/db mice, a model of spontaneous type 2 diabetes that exhibits delayed glomerulosclerosis far closer to the human disease than the rapidly evolving nephropathy observed in the acutely catabolic STZ-induced type 1 diabetes. Finally, in the report by Tan et al. (40), the lack of the B2R during diabetes was rather protective. Such a result is in contradiction with the report by Smithies’s group and many others (7, 22, 23, 27) and with the present study, in which blockade of the B2R induced some deleterious effects such as increased albuminuria. However, when the B2R was recruited by ACEi treatment, it then led to a marked protective effect against glomerulosclerosis. This suggests that there is a tonic and protective activation of the B2R in DN that is significantly enhanced by ACEi-treatment. Tan et al. were not able to study this effect, since their mice did not express the B2R. The concomitant involvement of the B1R cannot be ruled out even if its role in DN remains uncertain. Expression of the B1R has been reported in various tissues of diabetic models but has not yet been reported in db/db mice. A recent study (1) investigated the expression of the B1R in ob/ob obese diabetic mice, a model close to the db/db model. Although the expression of the B1R in the kidney was not shown, the overall expression of the B1R in other tissues was much weaker than that of the B2R.

Table 1. Characteristics of experimental groups of mice

<table>
<thead>
<tr>
<th></th>
<th>db/m C</th>
<th>db/db C</th>
<th>db/db ACEi</th>
<th>db/db ACEi+HOE</th>
<th>db/db HOE</th>
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<tbody>
<tr>
<td>Body weight, g</td>
<td>29.1±1.5</td>
<td>39.0±2.9a</td>
<td>37.7±3.8a</td>
<td>41.9±2.1b</td>
<td>50.8±3.6b</td>
</tr>
<tr>
<td>Kidney weight, mg</td>
<td>305±21</td>
<td>401±26a</td>
<td>389±8b</td>
<td>412±16b</td>
<td>416±20b</td>
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<tr>
<td>Blood glucose, g/l</td>
<td>2.05±0.11</td>
<td>9.64±0.83c</td>
<td>8.55±0.71c</td>
<td>8.10±0.44c</td>
<td>7.69±0.62c</td>
</tr>
<tr>
<td>Fructosamine, μmol/l</td>
<td>211±8</td>
<td>280±16a</td>
<td>306±24a</td>
<td>279±15b</td>
<td>282±12b</td>
</tr>
<tr>
<td>Blood pressure, mmHg</td>
<td>89.9±3.3</td>
<td>78.0±2.0b</td>
<td>64.8±2.9b,cd</td>
<td>78.8±3.4asc</td>
<td>74.7±2.6b</td>
</tr>
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</table>

Values are means±SE. db/m C, nondiabetic control db/m mice; db/db C, diabetic control mice; db/db ACEi, diabetic db/db mice treated with angiotensin-converting enzyme inhibitors; db/db ACEi+HOE, diabetic db/db mice treated with ACEi and B2R antagonist HOE-140; db/db HOE, diabetic db/db mice treated with HOE-140 alone. *P < 0.05; **P < 0.01; †P < 0.001 vs. db/m C. *P < 0.05 vs. db/db C. *P < 0.05 vs. db/db ACEi. When results were not significant for any comparison, no symbol was added.

Fig. 2. Urinary albumin excretion (mg albumin/g creatinine; A) and glomerular filtration rate (GFR; μl/min·g−1·kidney−1; B) measured in nondiabetic control db/m mice (db/m; n = 12), diabetic control mice (db/db C; n = 8), diabetic db/db mice treated with angiotensin-converting enzyme inhibitors (db/db ACEi; n = 9), diabetic db/db mice treated with HOE-140 alone (db/db HOE; n = 8), and diabetic db/db mice treated with HOE-140 alone (db/db HOE; n = 8). Values are means±SE. *P < 0.05; **P < 0.01 (pairwise comparison of the groups).
which is consistent with some of our preliminary results (Buleón M, personnel communication; not shown). However, because B2R blockade demonstrated very significant effects compared with those of ACEi, we focused in this study on the role of the B2R only.

The reduction of glomerulosclerosis by ACEi has been well demonstrated by several independent groups (4, 37). However, until now, most of the conclusions suggested that ACEi acts via suppression of angiotensin II generation, tending to disprove any noticeable role for BK. Using a model of STZ-induced diabetes in rats, Allen et al. (3) showed that HOE-140 treatment had no effect on albuminuria or glomerulosclerosis in ACEi-treated animals. In contrast, we found that direct B2R blockade severely reduced the protective effect of ACEi on morphological renal changes, which strongly supports the critical involvement of the BK pathway. One difference could well be reduced intrarenal ACE activity associated with high ACE2 expression in \( \text{db/db} \) mice (45). Another possible difference is that B2R glomerular expression tends to increase in \( \text{db/db} \) mice (Fig. 4), leading to an increased sensitivity to BK. ACEi exert important systemic and renal hemodynamic effects. The decrease in systemic blood pressure (Table 1), which is believed to partly mediate the renal protective effect of ACEi (10), is completely prevented by concomitant HOE-140 treatment in our model. A critical difference between the \( \text{db/db} \) model and human type 2 diabetes is that the former develops a decrease in blood pressure, whereas the latter is commonly associated with hypertension. The low blood pressure observed in \( \text{db/db} \) mice could be explained by the low ACE activity and increased ACE2 expression (45). Such a pattern results in low angiotensin II availability, possibly associated with angiotensin 1–7 generation and thereby with B2R activation (35, 41).

Although this increased sensitivity of \( \text{db/db} \) mice to BK has not been investigated per se, this point is consistent with 1) the lower MABP of \( \text{db/db} \) mice, 2) the correction of the ACEi hypotensive effect by HOE, and 3) the effect of HOE alone, especially on microalbuminuria. This difference could explain the prominent impact of BK during ACEi treatment in our model, whereas the role of angiotensin II in its human counterpart is probably more prominent.

Another difference between humans and \( \text{db/db} \) mice is the apparent lack of improvement of the GFR in anesthetized animals under the influence of ACEi. It is likely that the hypersensitivity of \( \text{db/db} \) mice to BK accounts for such a result, comparable in a way to the temporary worsening of chronic renal failure in some patients after the introduction of ACEi (19).

Our study provides more information regarding the mechanisms of the renoprotective effect of B2R activation during ACEi treatment. In addition to its beneficial effect on the diabetic kidney structure, certain critical signaling pathways involved in the pathophysiology of DN are also affected. On the basis of previous results (2, 6, 26, 27, 36), B2R activation could contribute to the reduction of growth factor/cytokine glomerular pathways recruitment and a reduction of oxidative stress indexes. It is beyond the scope of this report to review the involvement of these numerous factors in the pathogenesis of DN. On the basis of a previous study (2), we chose to focus on IGF-1, TGF-\( \beta \), and RAGE pathways, whose contributions to DN appear to be modulated by B2R activation. The role of the renal IGF-1 pathway during the early phase of DN has been suggested (16, 21, 39). More recently, TGF-\( \beta \) has emerged as a major deleterious cytokine that largely contributes to the progression of DN, since long-term prevention of mesangial

![Fig. 3. Pathological changes in the kidneys of the experimental groups. A: representative photomicrographs (magnification ×400) of periodic acid Schiff (PAS)-stained kidney sections. The glomeruli of \( \text{db/db} \) mice treated with HOE are not shown, since they were similar to those of control \( \text{db/db} \) mice. B: quantitative analysis of the histomorphological parameters mean glomerular volume (\( B1 \)) and relative mesangial volume (\( B2 \)) measured in \( \text{dbm C} (n = 6), \text{dbdb C} (n = 6), \text{dbdb ACEi} (n = 6), \text{dbdb ACEi/HOE} (n = 60), \text{and dbdb HOE} (n = 6) \). Values are means ± SE. **P < 0.01; ***P < 0.001 (pairwise comparison of the groups).](http://ajprenal.physiology.org/)
matrix expansion and renal insufficiency can be achieved by the administration of a monoclonal anti-TGF-β antibody in \textit{db/db} diabetic mice (46). Not surprisingly, protein glomerular expression of IGF-1R, IRS-1, and TGF-βRII as well as ERK1/2 activation were significantly increased in untreated diabetic mice. ACEi treatment partly prevented the increase in TGF-βRII, IGF-1R, and the activation of ERK1/2 MAP kinases. The decrease in IRS-1 overexpression could result not only from a decreased recruitment of IGF-1 pathway but also from the improvement of insulin sensitivity. In this respect, it is well documented that ACEi improve insulin resistance (11, 17, 25, 30, 31, 36, 37). As expected, ACEi-treated mice showed a reduced expression of both IGF-1Rβ and IRS-1. Furthermore, cotreatment with HOE-140 blunted the beneficial effect of ACEi treatment regarding IGF-1 receptor expression.

Oxidative stress is a major contributor to the development of DN. Among the mechanisms that induce an increase in cellular oxidative stress, the involvement of AGE/RAGE pathway plays a pivotal role in diabetes, since it is highly stimulated (32). RAGE-overexpressing mice are partly protected against DN (44), but conversely, the administration of anti-RAGE antibodies was able to prevent upregulation of the TGF-β pathway and to attenuate DN (13). It has been shown in vitro that ACEi stimulate the expression of soluble RAGE and thereby prevent AGE accumulation in experimental diabetes (17, 18). In our work, ACEi treatment largely prevented the upregulation of RAGE glomerular expression, an effect that appears to be independent of B2 receptor activation. However, AGE/RAGE is not the only pathway involved in increase oxidative stress in diabetes. Since one of the final effects of oxidation can be biochemical modification of proteins, we chose to focus on the glomerular accumulation of HNE-protein complexes that reflect lipid peroxidation. HNE-protein complexes are relatively stable molecules that can pass among subcellular compartments (42) and have the capacity to interact with many cell proteins and thereby impair their functions. It is now widely recognized that 4-HNE adducts are major cytotoxic products playing a role in the progression of atherosclerosis (24), ischemic acute renal failure (28), and human diabetic nephropathy (38). Therefore, controlling 4-HNE adduct accumulation could contribute to renal protection in diabetes. Our results indicate that in the \textit{db/db} model as well, 4-HNE adducts were increased at the glomerular level. Most of these changes were prevented by ACEi treatment. This benefit was mostly...
dependent on B2R activation, since the 4-HNE profile almost returned to that of diabetic untreated mice when HOE-140 was coadministered with ACEi. This strongly suggests that BK contributes to protecting against cellular oxidative stress in diabetes, an observation that fits with previous studies by ourselves and others (2, 6, 23). Further investigation into the mechanisms of BK-mediated reduction of oxidative stress in diabetes is needed.

In conclusion, ACEi (i.e., ramipril) are able to attenuate the development of diabetic nephropathy in this model of spontaneous type 2 diabetes in mice and are associated with a beneficial impact on several critical glomerular signaling pathways such as those involving IGF-1, TGF-β, and RAGE but also oxidative stress. This effect is partly mediated by B2R activation. Through in vivo B2R blockade, the present study finally provide a critical but not exclusive contradiction to the common belief that ACEi renal protective effect is mostly mediated by their ability to decrease angiotensin II production. This now provides the rationale to examine whether B2R activation by itself could represent a new and complementary therapeutic approach for diabetic nephropathy.

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