Development and prevention of advanced diabetic nephropathy in RAGE-overexpressing mice

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Vascular complications arising from multiple environmental and genetic factors are responsible for many of the disabilities and short life expectancy associated with diabetes mellitus. Here we provide the first direct in vivo evidence that interactions between advanced glycation end products (AGEs; nonenzymatically glycosylated protein derivatives formed during prolonged hyperglycemic exposure) and their receptor, RAGE, lead to diabetic vascular derangement. We created transgenic mice that overexpress human RAGE in vascular cells and crossbred them with another transgenic line that develops insulin-dependent diabetes shortly after birth. The resultant double transgenic mice exhibited increased hemoglobin A1C and serum AGE levels, as did the diabetic controls. The double transgenic mice demonstrated enlargement of the kidney, glomerular hypertrophy, increased albuminuria, mesangial expansion, advanced glomerulosclerosis, and increased serum creatinine compared with diabetic littermates lacking the RAGE transgene. To our knowledge, the development of this double transgenic mouse provides the first animal model that exhibits the renal changes seen in humans. Furthermore, the phenotypes of advanced diabetic nephropathy were prevented by administering an AGE inhibitor, (±)-2-isopropylidenehydrazono-4-oxo-thiazolidin-5-ylacetanilide (OPB-9195), thus establishing the AGE-RAGE system as a promising target for overcoming this aspect of diabetic pathogenesis.

double transgenic animals developed renal insufficiency and advanced glomerulosclerosis that resembled human diabetic nephropathy. This in vivo approach has thus established the functional importance of the AGE-RAGE system in the development of diabetic nephropathy, and the RAGE-overexpressing IDDM mice are regarded as the first single animal model in which the process of diabetes-induced kidney changes leading to ESRD can be followed. The AGE-RAGE system would seem to be a promising target for the prophylaxis and therapy of diabetic complications, and a study with (±)-2-isopropylidenehydrazono-4-oxo-thiazolidin-5-y lacetanilide (OPB-9195) (17) included in this paper suggests that the inhibition of AGE formation could be an effective remedy.

Methods

Construction of transgenic mice and induction of diabetes. A mouse flk-1 promoter previously reported to be active in vascular ECs in vitro was used (18). The 0.9-kbp fragments of the mouse flk-1 promoter and the 3.4-kbp fragments of the entire exonic and intronic region of the human RAGE gene (provided by T. Ikemura and K. Sugaya, National Institute of Genetics, Mishima, Japan) were ligated in the correct orientation by a modified polymerase chain reaction method (19). Primers used in the PCR reactions were 5′-GAGGTACCAATGATGAGGATCGG-3′ and 5′-CTGCTGTTCGCTGCATCTGACTCGCGCTGTT-3′ (nucleotides –623 to –597, +280 to +299) for mouse flk-1 (18), and 5′-ATGGCCGCGGAACAGCAGTT-3′ and 5′-GAGGCGCCGCACTTTCTCCACCTGAGTATA-3′ (nucleotides 6665–6685, 10027–10049) for human RAGE gene (20), containing KpnI and NotI sites (underlined sequences), respectively. The resultant 4.3-kbp hybrid gene was microinjected into fertilized eggs as described (16). Six out of 24 newborn offspring carried the transgene, as detected by PCR analysis of DNA from tail tissue using primers for flk-1 promoter (5′-AGGATCCGCTACACCAACGGAAATGTCCTGAGG-3′ and 5′-CTGCTGTTCGCTGCATCTGACTCGCGCTGTT-3′) (20). RAGETg was crossbred with another transgenic mouse carrying human cDNA for inducible nitric oxide synthase (iNOS) under the control of the insulin promoter (iNOS-Tg) (16). There was no expression of iNOS protein in the mutant 102 RAGETg mice (16). The resultant four groups of male littermates were used for analysis after PCR verification of the transgenes. Each group was fed either normal or 0.28% OB-9195 mixed mouse chow (provided by Fujii Memorial Research Institute, Otsuka Pharmaceutical, Ohtsu, Japan) from 1 to 6 months after birth. The levels of blood glucose and hemoglobin A1c (HbA1c) were measured from tail vein blood using Dexter Z sensor and DCA2000 analyser (Bayer Medical, Tokyo, Japan) (21), respectively.

The procedures were approved by the Institutional Animal Care and Use Committee guidelines at Tohoku University and at Kanazawa University Graduate School of Medical Science.
RT-PCR. Total RNA was isolated from various tissues, and from isolated renal glomeruli, of transgenic or control mice using the guanidinium thiocyanate method, and reverse-transcribed (22). The isolation of glomeruli from mouse kidneys was performed as described (23). Primer sequences for human RAGE mRNA detection were 5′-AAGCCCTGTTGCCTAATGAG-3′ and 5′-CACCAATTTGACCTCCTCCA-3′ (nucleotides 508–528 and 728–747 in GenBank AB036432); those for mouse RAGE mRNA detection were 5′-CTTGGGTGCTCTTACG-3′ and 5′-GATCCTGGTGCTCTTACGGTCC-3′ (nucleotides 31–52 and 1209–1230 in GenBank L33412); those for mouse GAPDH mRNA detection were the same as described (24). The amounts of total RNA templates (100 ng) and the numbers for amplification cycles (35 cycles for human RAGE and 30 cycles for mouse RAGE and GAPDH) were chosen in quantitative ranges. An aliquot of each RT-PCR product was electrophoresed on 2% agarose gel containing ethidium bromide.

Isolation of ECs and monocytes, and Western blot analysis. ECs from mouse renal cortex were cultivated for 2 days in a gelatin-coated plate after isolation by specific selection with rat anti-mouse CD31/PECAM-1 mAb–coated (MEC7.46; HyCult Biotechnology b.v.) magnetic beads (Dynabeads M-450 sheep anti-rat IgG; Dynal, Oslo, Norway) as described (25). Monocytes were isolated from peripheral blood by Ficoll-Paque (Pharmacia Biotech AB, Uppsala, Sweden) centrifugation followed by magnetic cell sorter (MACS; Miltenyi Biotec, Bergisch Gladbach, Germany) using CD11b/Mac-1 Ab–coated MicroBeads (Miltenyi Biotec). We created RAGETg by introducing into fertilized ova of C57BL/6J × CBA/J F1 mice a transgene carrying human RAGE genomic DNA under the control of the murine flk-1 promoter, which

**Figure 2**

Renal changes in the early stage. (a) Kidney weight/body weight ratio. Inset: Sagittal section of the kidney at 4 months of age. Bar, 5 mm. (b) Albuminuria. Filled circles, DM+RAGETg+; open circles, DM+RAGETg−; filled squares, DM+RAGETg+; open squares, DM+RAGETg−. Data are mean ± SEM. *P < 0.02, †P < 0.05 compared with DM+RAGETg−. Statistical analysis was performed by t test.
acts in ECs (18) (Figure 1a). PCR analysis revealed that five out of six potentially transgenic mice exhibited transgene transmission into their germlines. Two independent lines, 102 and 103, carrying high copy numbers, were used for subsequent experiments. RT-PCR analysis with human RAGE-specific primers revealed active transcription of the transgene in the lung, skin granulation tissue (the focus of angiogenesis), kidney, heart, aorta, and eyes of each line, but not in controls (Figure 1b). Immunofluorescent examination of kidney sections demonstrated that glomeruli of RAGETg were positively stained for human RAGE in an EC pattern, but not in controls (Figure 1c). Immunoblotting of cell extracts from renal cortical ECs demonstrated the overexpression of RAGE proteins in RAGETg (Figure 1d). Expression of the RAGE protein was also detected in monocytes from peripheral blood of RAGETg (Figure 1d).

**Induction of diabetes.** There are several means to induce diabetes in experimental animals (35, 36). Chemical or surgical maneuvers for diabetes induction might, however, cause some diversity among individual animals in terms of the extent of severity and the onset of diabetes. Accordingly, we employed a genetic approach by which a diabetic state and advanced glycation as well would be most stably induced. That is, RAGETg was crossbred with iNOSTg that consistently develops IDDM as early as 1 week after birth due to the iNOS-mediated selective destruction of insulin-producing pancreatic β cells (16). RAGETg was back-crossed to the nontransgenic parental strain CD-1 of iNOSTg for 4 or 5 generations to unify the genetic background. Then, the heterozygotes of male iNOSTg and female RAGETg were mated, thereby yielding four groups of littermates at five or six generations with CD-1 background, which carried both, either, or neither of the transgenes. They were tentatively designated DM‘RAGETg’, DM‘RAGETg’, DM RAGETg’, and DM RAGETg, since the mice carrying the iNOS transgene exclusively developed hyperglycemia regardless of the presence or absence of the RAGE transgene. Blood analysis revealed sustained hyperglycemia and high HbA1c levels in the former two groups but not in the latter two (Table 1). There were no significant differences in these indices between DM‘RAGETg’ and DM‘RAGETg’ (Table 1). Body weight was also invariant between the two groups at all time points tested during the 6-month observation period (data not shown). To determine the levels of circulating AGEs, serum was differentially measured by competitive ELISA for CML (derivative of AGEs mainly formed by peroxidation) and for non-CML AGEs (28). Serum non-CML AGE levels rapidly increased with time in both DM‘RAGETg’ and DM‘RAGETg’ mice, but without significant differences between them at each time point (Table 1). There was a tendency of higher serum CML levels in the diabetic groups than in the nondiabetic groups, but without significant differences (Table 1). These findings were comparable to observations in human diabetic and nondiabetic subjects (28). With the 103 line, similar results were obtained by blood glucose, HbA1c, and serum AGE assays (data not shown).

**Phenotypic changes of the kidney.** The kidney weight/body weight ratios from DM‘RAGETg’ showed a marked increase when compared with age-matched DM‘RAGETg’ mice (Figure 2a). The urinary albumin/creatinine ratio became significantly higher in DM‘RAGETg’ than in the other groups at 4 months (Figure 2b). The microscopic lesions noted in the diabetic groups consisted of glomerular cell proliferation, glomerular hypertrophy, mesangial expansion, and glomerulosclerosis. DM‘RAGETg’ showed accelerated increases in glomerular cell proliferation and glomerulus...
lar volume in comparison with DM+RAGETg– mice (Figure 3). Diffuse glomerulosclerosis progressed as the mice aged in both groups. However, there was a conspicuous difference in the severity of mesangial expansion and glomerulosclerosis at 4 months between DM+RAGETg+ and DM+RAGETg–, as evidenced by increased accumulation of PAS-positive materials in the mesangial area of the former (Figure 4, a–d). Quantitative examinations of at least 50 glomeruli per mouse revealed significant increases in mesangium area, mesangium fraction (relative mesangium area calculated as mesangium area/glomerular area ratio) (Figure 5), and sclerosis index in DM+RAGETg+ compared with DM+RAGETg– mice at 4 months of age (Figure 6a). Immunostaining showed that significant amounts of not only non-CML AGEs but also CML accumulated in the mesangial area in the diabetic mice, but not in nondiabetic mice (Figure 7, a–d). At 6 months of age, the serum creatinine level of DM+RAGETg+ increased to 1.24 ± 0.07 mg/dl, being the highest among the groups (Figure 6a). Further, typical nodular lesions and hyaline arteriosclerosis were noted at 8 months of age in DM+RAGETg+ (Figure 4e). Since hypertension has been known to be another risk factor for progressive glomerular disease (37), the blood pressure was monitored. Though DM+RAGETg+ showed a slightly higher value at 6 months of age, there was no statistically significant difference in systolic blood pressure among the four groups (DM+RAGETg+, 135 ± 8 mmHg; DM+RAGETg–, 108 ± 10 mmHg; DM–RAGETg+, 109 ± 9 mmHg; DM–RAGETg–, 108 ± 10 mmHg). Experiments with the line 103 series revealed a similar tendency in all of the above indices.

**Table 1**

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (mo)</th>
<th>Mice (n)</th>
<th>Blood glucose (mg/dl)</th>
<th>HbA1c (%)</th>
<th>CML (U/ml)</th>
<th>Non-CML AGES (U/ml)</th>
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<tbody>
<tr>
<td>DM+RAGETg+</td>
<td>2</td>
<td>4</td>
<td>509 ± 61</td>
<td>8.0 ± 0.6</td>
<td>4.1 ± 0.4</td>
<td>10.3 ± 0.4</td>
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<td>4</td>
<td>3</td>
<td>609 ± 94</td>
<td>9.5 ± 0.1</td>
<td>3.7 ± 0.6</td>
<td>11.9 ± 1.0</td>
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<tr>
<td></td>
<td>6</td>
<td>7</td>
<td>547 ± 13</td>
<td>8.3 ± 0.6</td>
<td>7.7 ± 0.1</td>
<td>24.2 ± 1.3</td>
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<td>OPB</td>
<td>6</td>
<td>8</td>
<td>693 ± 26</td>
<td>9.4 ± 0.5</td>
<td>5.4 ± 0.4a</td>
<td>14.2 ± 0.8c</td>
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<tr>
<td>DM+RAGETg–</td>
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<td>6</td>
<td>482 ± 22</td>
<td>8.2 ± 0.4</td>
<td>3.4 ± 0.5</td>
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<tr>
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<td>5</td>
<td>447 ± 45</td>
<td>9.1 ± 0.5</td>
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<td>14.4 ± 2.5</td>
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<tr>
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<td>6</td>
<td>9</td>
<td>503 ± 19</td>
<td>7.5 ± 0.8</td>
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<td>586 ± 74</td>
<td>8.9 ± 0.9</td>
<td>4.3 ± 1.0b</td>
<td>10.2 ± 2.6c</td>
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<tr>
<td>DM–RAGETg+</td>
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<td>6</td>
<td>177 ± 5</td>
<td>3.2 ± 0.2</td>
<td>2.9 ± 0.6</td>
<td>2.5 ± 1.0</td>
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<tr>
<td></td>
<td>4</td>
<td>6</td>
<td>157 ± 3</td>
<td>3.8 ± 0.3</td>
<td>3.3 ± 0.6</td>
<td>6.4 ± 1.6</td>
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<tr>
<td></td>
<td>6</td>
<td>11</td>
<td>134 ± 4</td>
<td>&lt;2.5</td>
<td>7.6 ± 0.3</td>
<td>20.2 ± 1.7</td>
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<tr>
<td>OPB</td>
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<td>145 ± 16</td>
<td>&lt;2.5</td>
<td>6.3 ± 1.0</td>
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<tr>
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<td>188 ± 8</td>
<td>3.3 ± 0.1</td>
<td>2.6 ± 1.0</td>
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<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>157 ± 4</td>
<td>3.4 ± 0.3</td>
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<tr>
<td></td>
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<td>125 ± 5</td>
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<tr>
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<td>169 ± 9</td>
<td>&lt;2.5</td>
<td>5.0 ± 0.7</td>
<td>8.7 ± 1.1</td>
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</table>

Data are expressed as the mean ± SEM. OPB, oral OPB-9195 administration for 5 months. *P < 0.002 and **P < 0.05 compared with CML values of DM+RAGETg+ and DM+RAGETg– at 6 months of age without OPB-9195 treatment, respectively. &P < 0.002 and #P < 0.05 compared with non-CML AGE values of DM+RAGETg+ and DM+RAGETg– at 6 months of age without OPB-9195 treatment, respectively. Statistical analysis was performed by t test. A high non-CML AGE level was noted in DM RAGETg+ at 6 months; the reason for this may be partly explained by hemolysis.

**Figure 5**

Mesangial expansion. Mesangium area (left) and mesangium fraction (right). Numbers on columns indicate months of age. Data are mean ± SEM. *P < 0.05. Statistical analysis was performed by t test.
cantly suppressed the increases in the kidney weight/body weight ratio (Figure 6b) and the sclerosis index and serum creatinine (Figure 6a) of DM+RAGETg+ at 6 months of age. A similar tendency was observed in experiments with the line 103 series (data not shown).

Discussion
In its early phase, diabetic nephropathy is characterized by increased albuminuria, glomerular hypertrophy, and nephromegaly (37). Mesangial expansion, glomerulosclerosis, and increased serum creatinine then follow in the late phase (37). In this study, the diabetic mouse itself, which we used to mate with the RAGETg, showed glomerular hypertrophy until 4 months of age and progressive mesangial expansion and glomerulosclerosis afterward. Furthermore, overexpression of human RAGE gene in ECs, which normally were only faintly stained for RAGE protein in renal arteries, arterioles, and glomerular capillaries (39–41), was found to result in a significant acceleration of all of the early- and late-phase indices of diabetic nephropathy. Because the extent of this acceleration was roughly proportional to the degree of RAGE transgene expression, and because circulating levels of AGEs and their deposition in renal glomeruli were essentially invariant between the IDDM animals carrying or not carrying the RAGE transgene, it was considered to be the level of RAGE expression that had rate-limited the progression of diabetic nephropathy. The higher expression of RAGE induced the earlier and higher expression of endogenous mouse RAGE in renal glomeruli under diabetic conditions (Figure 7e). The upregulation of the endogenous RAGE would then superdrive the development of the renal lesions in DM+RAGETg+. In addition, oral administration of a thi-
azolidine compound, OPB-9195, significantly suppressed the development of the renal insufficienty, nephromegaly, and glomerulosclerosis in DM’RAGETg+ without affecting the levels of blood glucose or HbA1c. OPB-9195 is known to inactivate carbyl intermediates of nonenzymatic glycation with an activity about one order of magnitude more potent than that of aminoguanidine (17). The prevention of diabetic nephropathy by OPB-9195 in the transgenic mice was associated with a decrease in AGEs, though this could reflect other hither unknown properties of the drug. These results indicate that endothelial RAGE and its engagement by AGEs contribute to the full expression of diabetic nephropathy, and that the AGE-RAGE system could become a target for intervention in this disease.

Then, how does the AGE-RAGE interaction lead to such kidney changes? It is reported that AGE-RAGE interactions upregulate the production of various cytokines and growth factors such as TNF-α (42), PDGF (22), and VEGF (12) via oxidant stress formation. TNF-α and VEGF are known to increase vascular permeability and to diminish barrier properties (43). This may underlie the increased albuminuria. AGE-RAGE interactions also have been shown to stimulate endocytosis and transcytosis of AGEs in ECs (44), thus probably causing the abluminal accumulation of AGEs, to which mural cells like mesangial cells would then be exposed. AGE-induced oxidant stress might also accelerate CML production in situ in the glomeruli (45). The exposure to AGEs has been shown to be followed by the transcriptional induction of the mesangial cell synthesis of type IV collagen, a major component of the expanded ECM in diabetic nephropathy (46, 47). This induction was also proved to be mediated by RAGE (15). In addition, positive staining for type I and IV collagen was noted in the glomeruli of the present nephropathy model (data not shown). Moreover, EC expression of VCAM-1 is also known to be induced by AGE engagement of RAGE (48), enhancing mononuclear cell adhesion to the capillary wall, which would allow macrophage invasion into the mesangial area. This may provide an additional source of cytokines such as TGF-β that can contribute to the development of glomerulosclerosis. The flk-1 promoter employed to construct RAGETg in this work is known to also work in the monocyte-macrophage lineage (49). The RAGE overexpression in monocytes (Figure 1d) is considered to be consistent with this notion and may augment the interaction with AGE on invaded macrophages, thereby contributing to accelerating the progression of nephropathy in the present model. RAGE engagement by endogenous ligands, namely amphoterin (50) and EN-RAGE (S100/calgranulins; ref. 51), is reportedly involved in the network formation of cerebral neurons and in proinflammatory reactions, respectively. The S100/calgranulins are known to be released from activated inflammatory cells, including mononuclear phagocytes as well as polymorphonuclear leukocytes and lymphocytes (52). The immuno-fluorescence analysis of the kidney sections revealed that renal glomeruli were stained for S100/calgranulins in diabetic (DM’RAGETg+ and DM’RAGETg–) but not in nondiabetic (DM-RAGETg+ and DM-RAGETg–) groups, the heaviest stain being marked in DM’RAGETg+ (data not shown). This suggests that the diabetic kidney contains two RAGE ligands, both nonenzymatically glycated adducts and S100/calgranulin proteins, and that S100/calgranulins accumulating in the kidney lesions could further activate ECs and monocytes/macrophages via their engagement of RAGE. AGEs are senescent proteins that accumulate during prolonged diabetic exposure, and can also engage cell surface RAGE, this resulting in the deterioration of vascular functions (12, 15, 53). Diabetic complications appear to exploit molecular devices primarily evolved for development and survival.

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