Expression and Function of Receptors for Advanced Glycation End Products in Bovine Corneal Endothelial Cells

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Purpose. The corneal endothelium is a target of the aging process. This study was undertaken to reveal the relationship between corneal endothelial cell (CEC) death and the accumulation of advanced glycation end products (AGEs), by investigating the possible mechanism of accumulation of AGE in CECs and its effects on CEC death.

Methods. First, the in vivo expression of the receptor was investigated for AGE (RAGE) and galectin-3, both receptors for AGE, at both the mRNA and protein levels. Second, AGEs were added to the culture media of the cultured CECs, and the uptake of AGEs, the generation of reactive oxygen and the number of apoptotic cells also increased.

Results. Immunohistochemistry and RT-PCR demonstrated that both RAGE and galectin-3 were expressed in bovine CECs. After administration of AGE-modified bovine serum albumin to the culture medium, uptake of AGE was observed in the cytoplasm of the cultured bovine CECs. In addition, with increasing concentration of AGEs, the generation of reactive oxygen and the number of apoptotic cells also increased.

Conclusions. These results show that the accumulation of AGEs in CECs induced apoptosis, in part, by increasing cellular oxidative stress. The accumulation of AGEs in the CECs of elderly patients may be involved in the loss of CECs during the aging process. (Invest Ophthalmol Vis Sci. 2003;44:521–528)

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The corneal endothelium is a target of the aging process.1 With increasing age, the density of the corneal endothelial cells (CECs) is known to decrease. In fact, Bourne et al.2 estimate that CEC density decreases by 0.6% per year. Because of changes in CEC density, polymegathism and pleomorphism typically arise.1,2 In diabetic patients, the degree of polymegathism and pleomorphism is significantly increased in CECs, even though the density of the CECs is unchanged.3

In addition, the normal function of CECs is altered during aging. For example, phosphatic metabolism, such as the synthesis of adenosine triphosphate (ATP)4 and prostaglandin E2,5 decreases in CECs with age. Also, increased permeability of the corneal endothelium is observed with increased age; thus, the ability of CECs to function as a barrier diminishes.1 Therefore, data associated with the aging of the corneal endothelium are accumulating; however, the mechanism or mechanisms involved are still unknown.

Advanced glycation end products (AGEs) have been proposed as common denominators for the pathogenesis of age-related diseases,6 such as age-related macular degeneration,7,8 atherosclerosis,9 Alzheimer’s disease,10,11 and diabetic complications, such as diabetic retinopathy,12–14 nephropathy,15 and neuropathy.16 AGEs are produced by the nonenzymatic reduction, oxidation, and condensation of reducing sugars and the amino group or N-terminal group of proteins, collectively known as glycoxidation.17,18 AGEs are known to modify proteins, such as bovine serum albumin (BSA) and collagen at lysine and/or arginine residues.19 These AGE-modified proteins accumulate in tissue and cartilage with increasing age, and this accumulation is accelerated in patients with diabetes.20 AGE modification of proteins deteriorates or eliminates their function.21,22 In addition, AGEs are known to impair cellular function by increasing cellular oxidative stress on binding to their specific cell surface receptors, such as receptor for AGE (RAGE) and galectin-3.23,24 The damage to proteins by modification of AGEs and the deleterious effect on cells are associated with the aging process and the pathogenesis of diabetic complications.8

In a previous report, we showed that formation of AGEs in the basement membrane of corneal epithelial cells plays an important role in diabetic keratopathy, a delay in the corneal epithelial wound healing process.21 In addition, we compared accumulation of AGEs in CECs obtained from patients aged more than 50 years in whom diabetes was or was not present. However, the effect of the accumulation of AGEs and the mechanism of action on CECs remain unclear.

In the present study, we identified a possible mechanism of CEC loss, as seen in the aging process, and its association with the accumulation of AGEs. We determined the presence of AGEs in CECs and the effect they have on CECs in vitro. In addition, we investigated the expression RAGE and galectin-3 in vivo and in vitro.

Materials and Methods

Preparation of Recombinant Human Galectin-3

Recombinant human galectin-3 was prepared as described previously.25,26 Briefly, DNA encoding for galectin-3 was inserted into the pET vector (Novagen, Madison, WI) at the EcoRI site, followed by

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transformation of *Escherichia coli*. Galectin-3, a 32-kDa protein, was purified from *E. coli* lysate with a galactose-conjugated Sepharose 4B column (Amersham Biosciences, Buckinghamshire, UK). Partial amino acid sequencing if the protein is N-terminal region revealed that it is a fusion protein of 12 of the amino acids from the pET vector sequence and human galectin-3 (data not shown).

Preparation of Polyclonal Anti–galectin-3 Antibody
To raise the polyclonal antibody against human galectin-3, 1.0 mg of galectin-3 in 50% Freund’s complete adjuvant was injected intradermally into a rabbit at 20 sites, followed by five booster injections with 0.5 mg of galectin-3 in 50% (vol/vol) Freund’s incomplete adjuvant. Serum was collected 10 days after the final immunization, followed by purification as IgG by protein-G-conjugated affinity chromatography.

The specificity of the antibody was confirmed by immunoblot assay. The human galectin-3 antibody exhibited cross-reactivity with bovine galectin-3 (data not shown).

Preparation of Polyclonal Anti-RAGE
To generate an antibody specific for RAGE, a fragment of human RAGE peptide at the carboxyl terminal (E*1*EPEAEGSTGGP*1*6) was conjugated with keyhole-limpet hemocyanin. The conjugated peptide (0.5 mg) in 50% (vol/vol) Freund’s complete adjuvant was injected intradermally into 20 cutaneous sites in a rabbit, followed by three booster injections with 0.2 mg of the final immunization. Serum was collected 10 days after the final immunization, followed by purification as IgG by protein-G-conjugated affinity chromatography. The sequence of the carboxyl terminal of bovine RAGE is E*1*EPEAEGSTGGP*1*6 with more than 92% of homology to that of human RAGE. The antibody cross-reacts to bovine RAGE (data not shown).

Immunohistochemistry
Fresh bovine corneas were purchased from an abattoir. The corneas were fixed with 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 15 minutes. After three washes for 10 minutes each, the corneas were embedded in optimal cutting temperature (OCT) compound (Miles Laboratories, Naperville, IL). Frozen sections, 6 μm in thickness, were cut (Kryostat 1720; Leitz, Wetzlar, Germany). After washes with PBS three times for 5 minutes each, the sections were treated with 3% hydrogen peroxide in PBS for 15 minutes to inactivate the endogenous peroxidase activity. After thorough washing, the sections were incubated with 10% normal rabbit serum for 20 minutes at room temperature to avoid nonspecific binding of the primary antibodies. The sections were then incubated overnight at 4°C with 3 μg/mL of the anti-RAGE and anti-galectin-3 polyclonal antibodies in PBS containing 1% BSA. Immunoreactivity was detected by the streptavidin-biotin method. The procedure was performed in triplicate.

Expression and Cloning Bovine RAGE and Galectin-3
Total RNA was isolated from fresh bovine CECs with extraction reagent (Isogen, Nippon Gene, Toyama, Japan). Reverse transcription of 10 μg total RNA was performed (Superscript II reverse transcriptase; Gibco-BRL, Grand Island, NY). A primer pair of galectin-3 was designed based on the sequence of the complete human galectin-3 cDNA in the gene bank. The sense primer was designed at the proline-glycine-alanine-tyrosine (PGAY) repeat motif, and the antisense primer at the carbohydrate recognition and binding site of galectin-3. The sense primer had a sequence of 5'-GAAGCGTGGTTAAGTGGAGGC-3', which corresponded to nucleotides 171 to 189 of the human galectin-3 gene, and an antisense primer of 5'-GGATGCGCTGTTAAGTGGAGGC-3'.

5' GAAGCGTGGTTAAGTGGAGGC-3'...
was analyzed using nitro blue tetrazolium (NBT) as previously described. The tubes were centrifuged at 500 g, and a second extraction using 200 μL of pyridine was repeated. After centrifugation, the colored extracts were combined and read in a spectrophotometer (Spectra Max190; Molecular Devices, Sunnyvale, CA) at 515 nm. In each experiment, the content of reduced NBT was quantitatively measured, as previously described. Brieibly, the cultured cells were centrifuged at 1000g at 4°C for 15 minutes. After aspiration of the supernatant, 200 μL of pyridine (Sigma) was added to the purple granule button and kept in boiling water for 10 minutes. The tubes were centrifuged at 500g, and a second extraction using 200 μL of pyridine was repeated. After centrifugation, the colored extracts were combined and read in a spectrophotometer (Spectra Max190; Molecular Devices, Sunnyvale, CA) at 515 nm. In each experiment, the content of reduced NBT in approximately 10⁶ cultured bovine CECs was analyzed.

Detection of Apoptosis

To determine whether AGE induces apoptosis in cultured CECs, the number of apoptotic cells were counted after terminal deoxynucleo-

Molecular Devices, Sunnyvale, CA) at 515 nm. In each experiment, the content of reduced NBT in approximately 10⁶ cultured bovine CECs was analyzed.

The effect of the AGE-BSA on the formation of reactive oxygen species was analyzed using nitro blue tetrazolium (NBT) as previously described. 31 CECs (4 × 10⁵) were cultured for 48 hours in a 12-well plate and used in the experiment. After starvation in culture medium containing 1% FBS overnight, 0 to 10,000 μg/mL of AGE-BSA or CML-BSA was added to the culture medium. After 2 days of incubation, NBT was added to the culture medium, to a nal concentration of 1 mM and incubated for 60 minutes at 37°C. The concentration of reduced NBT was quantitatively measured, as previously described. 32 Brieﬂy, the cultured cells were centrifuged at 1000g at 4°C for 15 minutes. After aspiration of the supernatant, 200 μL of pyridine (Sigma) was added to the purple granule button and kept in boiling water for 10 minutes. The tubes were centrifuged at 500g, and a second extraction using 200 μL of pyridine was repeated. After centrifugation, the colored extracts were combined and read in a spectrophotometer (Spectra Max190; Molecular Devices, Sunnyvale, CA) at 515 nm. In each experiment, the content of reduced NBT in approximately 10⁶ cultured bovine CECs was analyzed.

Measurement of Reactive Oxygen Species using NBT

As shown in Figure 2A, PCR with cDNA from bovine CECs and primers for galectin-3 produced two fragments (330 and 240 bp) that were shorter than predicted (370 bp). These shorter fragments were probably produced because the sense primer for galectin-3 was designed for the repeating PGAY sequence in human galectin-3. Each PCR fragment was cloned into the TA cloning vector and sequenced. Each PCR fragment showed the same 3'-end nucleotide sequence with different 5'-end sequences. The sequence of the longest PCR product corresponded to 226 to 542 nucleotides of human galectin-3. The longest PCR fragment was aligned to human galectin-3 with the highest identity of 77.0% and 76.0% at nucleotide acid and protein level, respectively (Fig. 3). In the region corresponding to the carbohydrate-recognition and

tidyl transferase-mediated nick end labeling (TUNEL) staining with an in situ apoptosis detection kit (ApopTag; Intergen, Purchase, NY). The CECs were cultured on round glass coverslips and placed at the bottom of a 24-well culture dish. Cells (2 × 10⁵) were cultured in each well for 48 hours and used for the experiment. After overnight starvation in culture medium containing 1% FBS, the nonadherent cells were washed out by gentle pipetting. Then, 0 to 10,000 μg/mL AGEBSA or CML-BSA was added to the culture medium and maintained for 2 days. In accordance with the manufacturer’s protocol for detecting apoptosis, the number of apoptotic cells was determined by light microscope. At ×100, 10 visual fields were randomly selected in each well, and the total number of cells and apoptotic cells were counted.

Statistics

The differences were calculated with a one-way fractional ANOVA test or two-way factorial ANOVA. Significance was set at P < 0.05.

RESULTS

Immunoreactivity for both galectin-3 and RAGE was recognized in CECs, but not in corneal stroma (Fig. 1). As shown in Figure 2A, PCR with cDNA from bovine CECs and primers for galectin-3 produced two fragments (330 and 240 bp), while the sense primer for galectin-3 was designed for the repeating PGAY sequence in human galectin-3. Each PCR fragment was cloned into the TA cloning vector and sequenced. Each PCR fragment showed the same 3'-end nucleotide sequence with different 5'-end sequences. The sequence of the longest PCR product corresponded to 226 to 542 nucleotides of human galectin-3. The longest PCR fragment was aligned to human galectin-3 with the highest identity of 77.0% and 76.0% at nucleotide acid and protein level, respectively (Fig. 3). In the region corresponding to the carbohydrate-recognition and
binding sites, the identity was more than 90% at both nucleotide acid and protein level. Expression of RAGE mRNA was noted in bovine CECs (Fig. 2B), and sequences of the PCR products corresponded to those from human RAGE (data not shown).

The localization of CML in cultured bovine CECs is shown in Figure 4. CML was not detected in CECs treated with BSA (Fig. 4A). Three days after incubation with 2 mg/mL of AGE-BSA, the immunoreactivity to CML was detected in the cytoplasm of CECs (Fig. 4B). In contrast, the immunoreactivity to CML was very weak in CECs incubated with 2 mg/mL CML-BSA (Fig. 4C).

Figure 5 shows the concentration of reactive oxygen in the cultured bovine CECs. The concentration of reduced NBT increased linearly with the addition of AGE-BSA or CML-BSA in culture medium. A significant increase in the amount of reduced NBT was detected in the concentrations of 100 to 10,000 μg/mL AGE-BSA and 250 to 10,000 μg/mL CML-BSA compared with the control (no AGE-BSA or CML-BSA). Compared with the two groups of AGE-BSA and CML-BSA, the

**Figure 3.** Galectin-3 gene sequence. (A) Alignment of human and mouse galectin-3 DNA sequences corresponding to 230 to 589 of human sequence with the bovine one, which we have disclosed on the bottom. *Shaded areas:* Identical DNA sequences; *dashes:* gaps in the sequence needed to maintain alignment. (B) Alignment of human and mouse galectin-3 amino acid sequences corresponding to 60 to 178 of human sequence with the bovine one in the bottom row. The bovine galectin-3 sequences were aligned to human ones with the highest identity of 77.0% and 76.0% at nucleotide acid and amino acid level, respectively.
amount of reduced NBT in AGE-BSA was significantly increased compared with that in CML-BSA (two-way factorial ANOVA, P < 0.05).

Figure 6A shows the rate of apoptotic CECs exposed to various concentrations of AGE-BSA or CML-BSA in the culture medium. The rate of the TUNEL-positive apoptotic cells increased with AGE-BSA and CML-BSA at concentrations of 250 to 10,000 µg/mL in the culture medium, compared with the CECs treated with BSA (Fig. 6A). AGE-BSA induced significantly more apoptosis than CML-BSA (two-way factorial ANOVA, P < 0.05). Figure 6B shows an example of TUNEL-positive apoptotic cells exposed to 1000 µg/mL AGE-BSA in the culture medium for 2 days. The apoptotic cells had condensed nuclei, fragmentation of chromatin, and decreased cell volume.

DISCUSSION
In the current study, the AGE receptors, RAGE and galectin-3, were expressed in the corneal endothelium in vivo. Those receptors served to incorporate AGEs into the cytoplasm, which led to the formation of reactive oxygen species and apoptosis. The concentration at which AGEs induces formation of reactive oxygen species and apoptosis varies, depending on the condition of the experiment, but included a range of 14.5 to 2000 µg/mL. In our experiment, a significant increase in the formation of reactive oxygen species and apoptosis was observed at 100 and 250 µg/mL of AGE-BSA or higher. Those AGE concentrations are much higher than that present in the aqueous humor. However, the concentration of AGEs present in the CECs in vivo may be much higher than that present in the aqueous humor, because AGEs gradually accumulate in CECs, which do not turn over during a person’s life. One of the purposes of the present study is to reveal the mechanism of the accumulation of AGE in CECs. The results of the study suggest that AGEs present in CECs may originate, at least in part, from AGE receptor uptake of AGEs present in the aqueous humor. However, we cannot deny the possibility that part of the AGE accumulation in corneal endothelium is from modification of intracellular proteins.

Several AGE receptors have been reported to date, such as galectin-3, RAGE, 80K-H, OST-48, CD36, and membrane scavenger receptors. The function of the AGE receptors is not fully understood. One proposed role of AGE receptors is to incorporate AGEs into the cytoplasm, which led to the formation of reactive oxygen species and apoptosis. The concentration at which AGEs induces formation of reactive oxygen species and apoptosis varies, depending on the condition of the experiment, but included a range of 14.5 to 2000 µg/mL. In our experiment, a significant increase in the formation of reactive oxygen species and apoptosis was observed at 100 and 250 µg/mL of AGE-BSA or higher. Those AGE concentrations are much higher than that present in the aqueous humor. However, the concentration of AGEs present in the CECs in vivo may be much higher than that present in the aqueous humor, because AGEs gradually accumulate in CECs, which do not turn over during a person’s life. One of the purposes of the present study is to reveal the mechanism of the accumulation of AGE in CECs. The results of the study suggest that AGEs present in CECs may originate, at least in part, from AGE receptor uptake of AGEs present in the aqueous humor. However, we cannot deny the possibility that part of the AGE accumulation in corneal endothelium is from modification of intracellular proteins.

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containing 1000 condensed nuclei, fragmentation of chromatin, and decreased cell stress cytokines,45,46 and the induction of apoptosis.33,47

into AGE peptides, which is easily excreted in the urine.42 This endocytosis, the AGE-proteins in serum are partially digested by AGE receptors, which only 9 were CML adducts.29 Thus, AGE-BSA contains CML and non-CML adducts in the same preparation of BSA. The CML content of CML-BSA used in the present study was 9.25 mol/mol of BSA, indicating that the amounts of CML adducts of AGE-BSA and CML-BSA were similar.29 The binding affinity of AGE-BSA and CML-BSA differs between RAGE and galectin-3.36,43 RAGE has a high affinity to both AGE-BSA and CML-BSA, whereas galectin-3 has a high affinity to some of the non-CML adducts of AGE-BSA.36,43 Therefore, the biological effect of CML-BSA is mediated by RAGE.

When bovine CECs were cultured in medium containing AGE-BSA for 3 days, CML was detected in the cytoplasm of these cells. In contrast, the immunoreactivity to CML in the aqueous humor is slightly higher in diabetic patients than in normal control subjects; however, Hashimoto et al.51 have reported that there is no significant difference in the concentration of pentosidine, one of the end products of AGEs in CECs of diabetic patients.50 These changes are thought to be involved in the pathogenesis of diabetic complications and the aging process.

The accumulation of AGEs in CECs involves apoptosis, it opens the possibility that the density of CECs would be less than that in nondiabetic patients. However, the density of CECs does not differ significantly between diabetic and nondiabetic patients, although there is an increase in the degree of pleomorphism in CECs of diabetic patients.20 These phenomena may be explained by considering the concentration of AGEs in the aqueous humor. Endo et al.55 have reported that the concentration of AGEs in the aqueous humor is slightly higher in diabetic patients than in normal control subjects; however, Hashimoto et al.51 have reported that there is no significant difference in the concentration of pentosidine, one of the end products of AGEs in CECs of diabetic patients. These changes are thought to be involved in the pathogenesis of diabetic complications and the aging process.
of the AGEs. This means that concentration of AGEs in CECs may depend on the age and not so much on the state of diabetes. For this reason, the decrease in corneal endothelial density is dependent on age and not on the diabetic state.

The purpose of the present study was to reveal the mechanism of CEC death during aging. Our previous study demonstrated that cultured human CECs become senescent more quickly in vitro when the cells are obtained from older donors.52 This result indicates that CECs become senescent in vivo as the person gets older. In general, cellular senescence has been attributed to both the shortening of telomeres and/or cellular damage. However, human CECs maintain their telomere length because they do not proliferate in vivo.53 Thus, senescence of human CECs in vivo is thought to be due to cellular damage. The current results suggest that accumulation of AGEs may be one cause of cellular damage of human CECs in vivo. Therefore, our results indicate that accumulation of AGEs plays an important role in the aging of CECs.

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References


