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 species, and the induction of apoptosis were investigated.

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, polymegethism and pleomorphism typically arise.1,2 In diabetic patients, the degree of polymegethism 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 ε-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.25

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 32kDa 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 intra-dermally 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 (E149EPAGESTGGP154) was conjugated with keyhole-limpet hemocyanin. The conjugated peptide (0.5 mg) in 50% (vol/vol) Freund’s complete adjuvant was injected intra-dermally 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 E149EPAGESTGGP154 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 5 μg/mL of the anti-RAGE and anti-galectin-3 polyclonal antibodies in PBS containing 1% BSA. Immunoreactivity was detected by the streptavidin-biotin-peroxidase method (Histofine SAB-PO[R] kit; Nichirei, Tokyo, Japan), according to the manufacturer’s protocol. The final reaction product was visualized with 3,3′-diaminobenzidine tetrahydrochloride (DAB). Experiments were 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 carboxylic recognition and binding site of galectin-3. The sense primer had a sequence of 5′-CTATCTGGGAGCTTACCC-3′, which corresponded to nucleotides 171 to 189 of the human galectin-3 gene, and an antisense primer of 5′-GAAGCTGGTCTGGTAAATGGGAGGC-3′, which corresponded to nucleotides 519 to 542.

A primer pair for bovine RAGE was designed in accordance with a previous report. The sense primer had the sequence of 5′-GGAGATGCGTATGCTCCATCATGTCG-3′, which corresponded to nucleotides 56 to 77, and the antisense primer of 5′-CCTTGGCATCGAGTAAGCAG-3′, which corresponds to nucleotides 494 to 515.

Using the above primers, cDNA was amplified by PCR according to the after: 30 cycles of 60 seconds at 94°C, 60 seconds at 58°C, and 60 seconds at 72°C. PCR products were then subcloned into TA vectors (Invitrogen, San Diego, CA). Positive clones were confirmed by sequence analysis, with fluorescent dideoxynucleotides and an automated sequencer (model 310; Applied Biosystems, Foster City, CA).

### Cell Culture

Primary cultured bovine CECs were used. Eyes from 3-year-old cattle were obtained from an abattoir, and the corneal buttons were prepared within 3 hours after enucleation. CECs with Descemet’s membrane were dissected under a microscope and separated in the presence of trypsin-EDTA (GibcoBRL). Cells were cultured in 60-mm culture dishes (Falcon, Lincoln Park, NJ) in Eagle’s minimum essential medium (EMEM; Gibco) with 15% fetal bovine serum (FBS) and 20 mg/L gentamicin (Gibco) in humidified atmosphere with 5% CO₂ at 37°C. Second-phase cells were used in this study.

### AGE- and CML-BSA Preparation

AGE-bovine serum albumin (BSA; low-endotoxin BSA; Sigma, St. Louis, MO) was prepared by incubating 20% BSA for 30 days with 250 mM glucose-6-phosphate at 37°C in phosphate-buffered saline (PBS; pH 7.4) under sterile conditions. Nα-(carboxymethyl)Lysine (CML)-BSA was prepared according to a published method. Briefly, 2 mg/mL BSA was incubated with 0.75 M glyoxylic acid (Sigma) and 0.3 M NaCNB₃ (Sigma) in PBS at 37°C for 24 hours. After the end of incubation, the solution was lyophilized and reconstituted with distilled water (DW). Finally, the condensed solutions were dialyzed against PBS, sterile filtered through 0.22-μm nylon filters (Pall Corp., Ann Arbor, MI).

### Immunohistochemical Localization of AGE in Cultured CECs

Primary cultured bovine CECs were seeded onto sterilized, round glass coverslips of 12-mm diameter and allowed to reach 70% confluence. Then, 2 mg/mL BSA or AGE-BSA was added to the culture medium and incubated for 3 days. The localization of AGE was examined immunohistochemically.

An anti-AGE monoclonal antibody (6D12) was prepared as previously described. Briefly, mice were immunized with AGE-modified albumin, and the splenic lymphocytes from the immunized mouse were fused to myeloma cells. The culture supernatant of hybrid cells was screened by its reactivity to AGES. The selected cell lines were injected into BALB/c mice for production of ascites. The antibody was purified by protein G-Sepharose diethylaminoethyl (DEAE)-cellulose chromatography. Our recent study revealed that this antibody recognizes CML protein adducts as an epitope. The localization of AGE in the cultured CECs was visualized using the streptavidin-biotin method. Briefly, cultured CECs on round glass coverslips were washed three times with 0.01 M PBS (pH 7.4) and fixed with 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 15 minutes. After three washes in PBS for 5 minutes each, the samples were treated with 3% hydrogen peroxide in PBS for 15 minutes to inactivate the endogenous peroxidase activity. After a thorough wash, the samples were incubated with 10% normal rabbit serum for 20 minutes at room temperature to avoid nonspecific binding of the primary antibodies. The samples were incubated overnight at 4°C with 3 μg/mL of the anti-CML monoclonal antibody (6D12) in PBS containing 1% BSA. Immunoreactivity was detected by the streptavidin-biotin-peroxidase method (Histofine SAB-PO kit; Nichirei), according to the manufacturer’s protocol. The final reaction product was visualized.
The tubes were centrifuged at 500 g and the purple granule button and kept in boiling water for 10 minutes. The supernatant was then washed out by gentle pipetting. Then, 0 to 10,000 μg/ml AGE-BSA 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 microscopy. 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) 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
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
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 \( \mu \text{g/mL} \) 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 \( \mu \text{g/mL} \) 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 induce formation of reactive oxygen species and apoptosis varies, depending on the condition of the experiment, but included a range of 14.5 to 2000 \( \mu \text{g/mL} \). In our experiment, a significant increase in the formation of reactive oxygen species and apoptosis was observed at 100 and 250 \( \mu \text{g/mL} \) 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 macrophage scavenger receptors. The function of the AGE receptors is not fully understood. One proposed role of AGE...
receptors is the endocytosis of AGE-modified proteins. On endocytosis, the AGE-proteins in serum are partially digested into AGE peptides, which is easily excreted in the urine. This means that AGE receptors serve as scavengers to inhibit the accumulation of AGES in the body. Another possible role of AGE receptors is the activation of intracellular signaling pathways. The interaction of AGES and AGE receptors induces oxidative stress, a reduction in the antioxidant defense mechanism, activation of NF-κB, the increased expression of stress cytokines, and the induction of apoptosis.

These changes are thought to be involved in the pathogenesis of diabetic complications and the aging process. AGES induce oxidative stress and vice versa. In other words, an increase in oxidative stress leads to the accumulation of AGES. Increased oxidative stress accelerates the intracellular oxidation of sugars and proteins, which help to form AGES and AGE-modified proteins. In addition, the presence of AGES stimulates the expression of AGE receptors, including RAGE. Taken together, these findings show that accumulation of AGES in CECs may accelerate the intracellular generation of AGES and the uptake of AGES from the aqueous humor due to increased oxidative stress.

In the present study, we compared the biological effect of AGE-BSA and CML-BSA on cultured bovine CECs. AGE is a generic term used to classify various adducts of proteins and reducing sugars. In the preparation method of AGE-BSA used in the present study, 40 of 59 lysine residues were modified, of which only 9 were CML adducts. 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. The binding affinity of AGE-BSA and CML-BSA differs between RAGE and galectin-3. 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. 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 was very weak when the CECs were cultured in medium containing CML-BSA. These results suggest that the interaction of galectin-3 and non-CML components of AGE-BSA is necessary for endocytosis. However, this does not mean that galectin-3 is the only receptor involved in the process of AGE endocytosis. Yamamoto et al. have reported that RAGE is involved in the endocytosis of AGES. In addition, other receptors for AGES (80K-H, OST-48, CD36, and macrophage scavenger receptor) detected, although weakly, in CECs treated with CML-BSA indicates that there are mechanisms of AGE endocytosis that are unrelated to galectin-3.

The biological effect of AGE- and CML-BSA was slightly different in NBT and TUNEL assays. Both AGE- and CML-BSA induced apoptosis and the formation of reactive oxygen in cultured CECs dose dependently. However, AGE-BSA was more effective than CML-BSA at inducing the formation of reactive oxygen and apoptosis at concentrations of 250 to 10,000 μg/mL and 1000 to 10,000 μg/mL, respectively. The difference in the biological effect between AGE- and CML-BSA seems unrelated to the number of CML adducts in the BSA molecule, because the number of CML adducts in AGE-BSA was not less than that of CML-BSA. These results indicate that not only CML adducts but also non-CML adducts of AGE-BSA were important in inducing reactive oxygen formation and apoptosis.

If 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. These phenomena may be explained by considering the concentration of AGES in the aqueous humor. Endo et al. 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. have reported that there is no significant difference in the concentration of pentosidine, one
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. 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. 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


