Advanced Glycation End Product 3 (AGE3) Suppresses the Mineralization of Mouse Stromal ST2 Cells and Human Mesenchymal Stem Cells by Increasing TGF-β Expression and Secretion

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In diabetic patients, advanced glycation end products (AGEs) cause bone fragility because of deterioration of bone quality. We previously showed that AGEs suppressed the mineralization of mouse stromal ST2 cells. Transforming growth factor (TGF)-β is abundant in bone, and enhancement of its signal causes bone quality deterioration. However, whether TGF-β signaling is involved in the AGE-induced suppression of mineralization during the osteoblast lineage remains unknown. We therefore examined the roles of TGF-β in the AGE-induced suppression of mineralization of ST2 cells and human mesenchymal stem cells (hMSCs). AGE3 significantly ($P<0.001$) inhibited mineralization in both cell types, whereas transfection with siRNA for the receptor for AGEs (RAGE) significantly ($P<0.05$) recovered this process in ST2 cells. AGE3 increased ($P<0.001$) the expression of TGF-β mRNA and protein, which was partially antagonized by transfection with RAGE siRNA. Treatment with a TGF-β type I receptor kinase inhibitor, SD208, recovered AGE3-induced decreases in osterix ($P<0.001$) and osteocalcin ($P<0.05$) and antagonized the AGE3-induced increase in Runx2 mRNA expression in ST2 cells ($P<0.001$). Moreover, SD208 completely and dose-dependently rescued AGE3-induced suppression of mineralization in both cell types. In contrast, SD208 intensified AGE3-induced suppression of cell proliferation as well as AGE3-induced apoptosis in proliferating ST2 cells. These findings indicate that, after cells become confluent, AGE3 partially inhibits the differentiation and mineralization of osteoblastic cells by binding to RAGE and increasing TGF-β expression and secretion. They also suggest that TGF-β adversely affects bone quality not only in primary osteoporosis but also in diabetes-related bone disorder.

Both diabetes mellitus (DM) and osteoporotic fractures are important healthcare problems, because they affect quality of life (QOL) and increase morbidity and mortality (1). Several community-based studies and some national databases indicate that the incidence of type 2 DM (T2DM) has increased over the past three decades (2). In Japan, as many as 13 million patients are thought to have osteoporosis, and this number is increasing (3–5). Previous studies have shown that, compared with nondiabetic subjects, patients with T2DM have a 1.4- to 4.7-fold increased risk of fracture, although they have normal or slightly increased bone mineral density (BMD) (6–8). These findings suggest that fracture risk in T2DM is not reflected by BMD but is related to bone fragility independent of BMD. Several studies have suggested that the pathogenesis of diabetic osteoporosis is related to decreased osteoblastic bone formation rather than increased osteoclastic bone resorption (9, 10).

Hyperglycemia in DM accelerates the formation of advanced glycation end products (AGEs), which result from a chain of chemical reactions in plasma or tissue that follow nonenzymatic Browning reactions between reducing sugars and free reactive amino groups of proteins (11, 12). The cellular interactions of AGEs are mediated by the re-

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Abbreviations:

ceptor for AGE (RAGE), which is a multiligand receptor belonging to the immunoglobulin superfamily and exerts biologic effects through binding to its ligands, including AGEs. Pentosidine is an AGE, and an increase in pentosidine cross-links in bone matrix is reported to impair bone mechanical properties in the absence of decreased BMD (13). Other studies have also shown a positive association between serum or urinary pentosidine levels and fracture risk in T2DM patients (14, 15). Therefore, AGEs may act as causative factors for poor bone quality. In contrast, low serum levels of endogenous soluble RAGE, which has extensive neutralizing effects against various AGEs, are a risk factor for the vertebral fractures prevalent in T2DM patients (16). In an in vitro study, we found that AGE2 and AGE3 suppressed the mineralization of mouse stromal ST2 cells (17, 18) by inhibiting the expression of osteoblastogenetic mRNAs such as those for osteocalcin (OCN) and osterix (OSX) (19, 20). Moreover, these AGEs significantly suppressed cell growth and increased apoptotic cell death (19). However, the biologic substances that mediate these detrimental effects of AGEs on the osteoblast lineage remain unknown.

Transforming growth factor (TGF)-β is a multifunctional polypeptide that regulates a variety of cellular functions, including cell proliferation, differentiation, migration, and apoptosis under physiologic and pathologic conditions (21). TGF-β is sequestered at high levels in bone matrix and is a critical regulator of osteogenesis (22). TGF-β activates intracellular Smad3, which, in turn, binds Runx2 at the *runx2* and *OCN* promoters to repress the transcription of genes required for osteoblast differentiation (23, 24). Previous animal studies have shown that reducing TGF-β signaling leads to increases in functional parameters of bone quality such as bone stiffness, as evaluated by the three-point bending test (25–27). Moreover, another animal study has shown that inhibition of TGF-β type 1 receptor kinase has anabolic and anticatabolic effects on bone by increasing both BMD and bone stiffness (28). These findings suggest that TGF-β signaling has detrimental effects on bone quality.

There is a documented association between AGE–TGF-β signaling and diabetic complications. In humans and in animal models, TGF-β mRNA and protein levels are significantly increased in the glomeruli and tubulointerstitium in diabetes (29–31), and administration of neutralizing anti-TGF-β antibodies to STZ-induced diabetic mice prevents glomerular hypertrophy (32). Moreover, AGEs stimulate TGF-β expression by mesangial cells (33, 34). In addition, TGF-β levels are significantly higher in patients with diabetic neuropathy than in those without it (35). In an experiment using human peripheral nerve microvascular endothelial cells, AGEs induced basement membrane hypertrophy and disrupted the blood–nerve barrier by the action of autocrine TGF-β released by pericytes (36). In the retina, TGF-β is important in controlling the formation of new vessels, and TGF-β1 is upregulated in proliferative diabetic retinopathy (37). Matsumoto et al (38) reported a relationship between glycoxidation and cytokine levels in the vitreous of eyes with diabetic retinopathy, and they suggested that elevated levels of pentosidine and TGF-β may play an important role in the development of diabetic retinopathy. Together, these findings suggest that AGEs can cause diabetic complications in the kidneys, nerves, and retina by increasing TGF-β levels. However, whether AGEs adversely affect osteoblastic mineralization and differentiation during diabetic bone disorder by enhancing TGF-β signals—as is seen in other complications of diabetes—is unknown.

Here, we addressed this issue by evaluating the role of TGF-β in the AGE3-induced suppression of osteoblastic differentiation and mineralization of ST2 cells and human mesenchymal stem cells (hMSCs). We found that AGE3 inhibited the differentiation and mineralization of these cells in part by binding to RAGE and increasing TGF-β expression and secretion.

Materials and Methods

Materials

Cell culture medium and supplements were purchased from GIBCO-BRL (Rockville, MD). Human recombinant BMP-2 was kindly provided by Astellas Pharmaceutical (Tokyo, Japan). All other chemicals were of the highest grade available commercially.

Cell culture

Mouse ST2 cells were purchased from the RIKEN Cell Bank (Tsukuba, Japan). They were cultured under 5% CO_2 at 37°C in α-minimum essential medium (α-MEM; containing 5.5 mmol/L glucose) supplemented with 10% fetal bovine serum (FBS) and 1% penicillin–streptomycin (GIBCO-BRL); the culture medium was changed twice weekly. To induce osteoblastic differentiation, ST2 cells were cultured in α-MEM supplemented with 10% FBS, 1% penicillin–streptomycin, 5 mM β-glycerophosphate, 100 μg/mL ascorbic acid, and 100 ng/mL BMP-2 after reaching confluence. hMSCs were purchased from Lonza (Walkersville, MD) and cultured in MSC basal medium (Lonza). To induce osteoblastic differentiation, hMSCs were cultured in MSC basal medium supplemented with 1% penicillin–streptomycin, β-glycerophosphate, 100 μg/mL ascorbic acid, and dexamethasone (Lonza) after reaching confluence.

Preparation of AGEs

AGE–BSA was prepared as described previously (20). AGE3 was prepared by incubating 50 mg/mL BSA (Sigma, St. Louis, MO) with 0.1 M glycolaldehyde (Sigma) at 37°C for 7 days under sterile conditions in 0.2 M sodium phosphate buffer (pH

7.4) containing 5 mM diethylenetriamine–pentaacetic acid. As a negative control, nonglycated BSA was incubated under the same conditions, except for the absence of glycolaldehyde. After the incubation period, low-molecular–weight reactants and aldehydes were removed by using a PD-10 column (GE Healthcare Bio-Sciences AB, Uppsala, Sweden) and dialyzing against phosphate-buffered saline (PBS).

Mineralization assay

The mineralization of ST2 cells and hMSCs was assessed in 6-well or 12-well plates by using von Kossa staining and Alizarin Red staining. Cells were stained with $AgNO_3$ and fixed with 2.5% NaS_2O_3 according to the von Kossa method to detect phosphate deposits in bone nodules (20, 39). At the same time, duplicate plates were fixed with ice-cold 70% ethanol and stained with Alizarin Red to detect calcification. For quantification, cells stained with Alizarin Red were destained with ethylpyridinium chloride, the extracted stain was transferred to a 96-well plate, and the absorbance at a wavelength of 550 nm was measured with a microplate reader, as previously described (20, 39).

Quantification of secreted TGF-β1

The concentration of TGF-β1 in whole-cell lysates or culture medium was determined by using commercially available diagnostic kits (R&D Systems, Minneapolis, MN). In brief, samples were activated with 1 N HCl for 10 minutes at room temperature, followed by neutralization with 1.2 N NaOH in HEPES. Samples were added to the wells of microtiter plates, which were coated with a monoclonal anti-TGF-β1 antibody. After incubation of the sample for 2 hours at room temperature, a horseradish-peroxidase–conjugated polyclonal antibody against TGF-β1 was added and the plates were incubated for another 2 hours. The assay was developed with peroxidase substrate for 30 minutes at room temperature in the dark. Absorbance was measured at 450 nm, and a reference wavelength of 540 nm was used. Standard curves for TGF-β1 were prepared by using serial dilutions of exogenous TGF-β1.

Real-time PCR quantification of gene expression

SYBR Green chemistry was used to quantify the amounts of mRNAs for TGF-β and a housekeeping gene, 36B4, according to an optimized protocol (20, 39, 40). Total RNA was isolated by using Trizol reagent (Invitrogen, San Diego, CA) and further cleaned by two successive phenol–chloroform extractions. First-strand cDNA was synthesized by using an oligo-dT primer and a SuperScript-III cDNA synthesis kit (Invitrogen). Sense and antisense oligonucleotide primers were designed according to published cDNA sequences by using Primer Express (version 2.0.0, Applied Biosystems, Carlsbad, CA). The cDNA was amplified by using an ABI PRISM 7000 sequence detection system (Applied Biosystems Inc.). The cDNA-specific SYBR Green Mix was incorporated into the PCR buffer provided in the QuantiTect SYBR PCR kit to allow for quantitative detection of the PCR product in a 25-μL reaction volume. The temperature profile of the reaction was 60°C for 2 minutes, followed by 95°C for 15 minutes and 40 cycles of denaturation at 94°C for 15 seconds and annealing and extension at 60°C for 1 minute. Primer sequences were as follows: TGF-β, 5′-TGAACCAAGGAGACGGAATACAGG-3′ and 5′-GCCATGAGGAGCAGGAAGGG-3′; OCN, 5′-TGCTTGTGAC-GAGCTATCAG-3′ and 5′-GAGGACAGGGAGGATCAAGT-3′; OSX, 5′-CCCTTCTCAAGCACCAATGG-3′ and 5′-AGGGTGGGTAGTCATTTGCATAG-3′; Runx2, 5′-AAGTGCGGTGCAAACTTTCT-3′ and 5′-TCTCGGTGGCTGGTAGTG A-3′; and 36B4, 5′-AAGCGCGTCCTGGCATTGTCT-3′ and 5′-CCGCAGGGGCAGCAGTGGT-3′ .

RNA interference (RNAi) for RAGE

RNAi was used to downregulate the expression of RAGE in ST2 cells. RAGE small interfering RNA (siRNA) and negative-control siRNA duplexes were designed and synthesized by Ambion (Austin, TX). For gene knockdown experiments, ST2 cells were seeded in 6-well plates and cultured at 37°C for 48 hours in α-MEM containing 10% FBS and antibiotics, followed by 24 hours incubation in medium without antibiotics. Cells then were transfected with siRNAs (50 nM) by using Lipofectamine (Invitrogen, San Diego, CA) according to the manufacturer's instructions. After another 48 hours of culture, cells were transferred to another plate containing fresh α-MEM supplemented with 10% FBS and antibiotics.

Evaluation of cell proliferation

ST2 cells ware seeded on 96-well plates at a density of 3000 cells/well and were incubated overnight in α-MEM containing 10% FBS and antibiotics. The next day, the cells were treated with either BSA (negative control) or AGE3. At the end of the experimental protocol, ST2 cells were labeled with bromodeoxyuridine (BrdU) for 2 hours at 37°C. The ST2 cells then were fixed and denatured for 30 minutes at room temperature, followed by exposure to a peroxidase-conjugated anti-BrdU antibody (Roche Diagnotics, Indianapolis, IN) for 90 minutes at room temperature. The ST2 cells then were washed three times with PBS and incubated with a peroxidase substrate solution (Roche Diagnotics, Indianapolis, IN) at room temperature until the development of a noticeable color. The color change was quantified by using the absorption spectrometer to determine the amount of cell proliferation. An absorbance wavelength of 370 nm and reference wavelength of 492 nm were used.

Assessment of apoptotic cell death

ST2 cells ware seeded on 96-well plates at a density of 3000 cells/well and incubated overnight at 37°C in α-MEM with 10% FBS and antibiotics. The next day, the cells were treated with either BSA (negative control) or AGE3. The cells then were lysed, and the DNA fragments in the supernatant were quantified in an ELISA (Cell Death Detection ELISA Plus, Roche Molecular Biochemicals, Indianapolis, IN) on day 3 after treatment.

Apoptosis was evaluated in differentiated ST2 cells and hMSCs. Cells were treated with either BSA or AGE3, as described earlier, on day 11 after reaching confluence. On day 14, the cells were lysed, and DNA fragments in the supernatant were analyzed by using an ELISA (Roche Molecular Biochemicals).

Statistical analysis

Results are expressed as means ± SEM. Differences between groups were evaluated by using one-way analysis of variance (ANOVA), followed by Fisher's protected least significant difference test. For all statistical tests, a value of $P < .05$ was considered to indicate a statistically significant difference.

Results

Effect of AGE3 on mineralization of ST2 cells and hMSCs

Treatment of ST2 cells with 200 μg/mL AGE3 for 14 and 21 days or of hMSCs with 200 μg/mL AGE3 for 14 days inhibited mineralization according to both von Kossa and Alizarin Red staining (Figures 1A and C). Alizarin red quantification analysis of ST2 cells and hMSCs showed that AGE3 significantly ($P < .001$) inhibited mineralization by 71% on experimental day 21 and 83% on day 14, respectively, relative to control values (Figure 1B and D) .

Effect of RAGE siRNA on AGE-suppressed mineralization in ST2 cells

AGEs are known ligands of RAGE, and we previously showed that AGE3 significantly increased RAGE mRNA expression in ST2 cells on days 2 and 3 after treatment (19, 20). We therefore investigated whether transfection with RAGE siRNA recovered the mineralization suppressed by AGE3 in ST2 cells. RAGE siRNA transfection partially but significantly ($P < .05$) decreased the amount of RAGE mRNA (Figure 2A), and the mineralization of the transfected cells recovered by 17% ($P < .01$), as determined by Alizarin Red staining and quantification (Figure 2B). This result suggests that AGE3 suppresses the mineralization of ST2 cells in part by binding to RAGE.

Effects of AGE3 on expression of TGF-β mRNA and protein in ST2 cells and hMSCs

Next, we examined the effects of AGE3 on the expression of TGF-β mRNA and protein in ST2 cells and hMSCs. According to real-time PCR assays, AGE3 significantly ($P < .001$ all comparisons) increased the expression of TGF-β mRNA in ST2 cells on days 3, 5, and 7 after treatment (Figure 3A). AGE3 also significantly increased TGF-β protein levels of ST2 supernatants on days 5 and 7 ($P < .01$) and whole-cell lysates on days 1 through 7 ($P < .001$), as measured with ELISAs (Figure 3B). In hMSCs, AGE3 significantly ($P < .001$) increased the levels of TGF-β protein in whole-cell lysates on days 1 through 7 (Figure 3B). Transfection of RAGE siRNA into ST2 cells decreased ($P < .05$) the AGE3-induced increase in TGF-β protein secretion by 24%, as determined by ELISA (Figure 4).

Effects of a TGF-β type I receptor kinase inhibitor on expression of OSX and OCN mRNAs in ST2 cells and on AGE-suppressed mineralization in ST2 cells and hMSCs

We previously showed that OSX and OCN mRNA levels in ST2 cells were suppressed by AGE3 (19). Here, we used real-time PCR assays to examine the effects of a TGF-β type I receptor kinase inhibitor, SD208, on these processes. Treatment with SD208 (2.5 μM) significantly ($P < .05$) recovered the expression of OSX and OCN mRNAs in ST2 cells on day 14 (Figure 5A and B, respec-

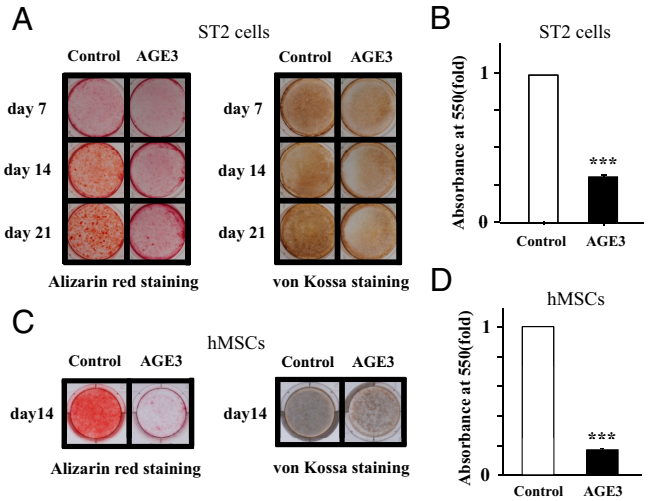

Figure 1. Effects of AGE3 on mineralization of ST2 cells and hMSCs. Bovine serum albumin (BSA; control; 200 μg/mL) or AGE3 (200 μg/mL) was added after the cells reached confluence. A, Alizarin Red and von Kossa staining of cultured ST2 cells on days 7, 14, and 21 after treatment with BSA or AGE3. B, Quantification of Alizarin Red staining of the ST2 cells in each treatment group. C, Alizarin Red and von Kossa staining of cultured hMSCs on day 14 after treatment with BSA or AGE3. D, Quantification of Alizarin Red staining of hMSCs in each treatment group. $***P < .001$ compared with control. The results shown are representative of 3 independent experiments and are expressed as means ± SEM of fold increase relative to control (BSA) values (n = 6).

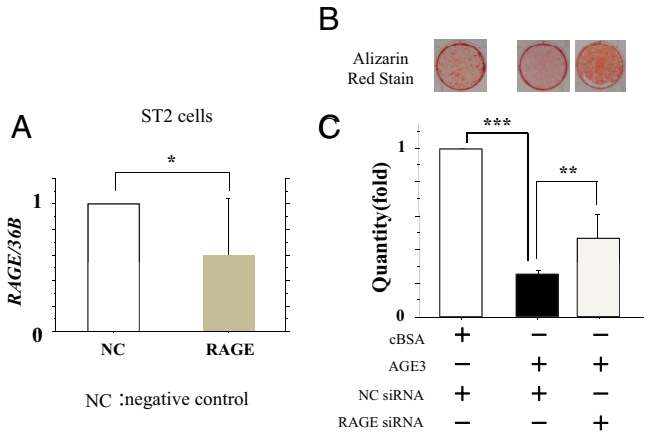

Figure 2. Efficiency of knockdown of RAGE and effects of RAGE siRNA transfection in mineralization of ST2 cells suppressed by AGE3. (A) Effect of siRNA on RAGE mRNA expression in ST2 cells. ST cells were transfected with siRNAs (50 nM) by using Lipofectamine. Total RNA was collected on day 3 and RAGE mRNA was measured by real-time PCR. B, Alizarin red staining was performed on day 7 after Negative control or RAGE siRNA transfection. Control BSA and AGE3 were added after the cells reached confluence. Plate view of Alizarin red staining in cultured ST2 cells with 200 μg/mL of either control BSA or AGE3 for 14 days. C, Quantification of Alizarin red staining of the cells with each treatment. $*P < .05$, $**P < .01$ and $***P < .001$ compared to control.

tively). In contrast, treatment with SD208 significantly ($P < .001$) antagonized the AGE3-induced increase in Runx2 mRNA expression in ST2 cells on day 14 (Figure 5C). Moreover, Alizarin Red staining showed that treatment with SD208 (1 to 2.5 μM) significantly ($P < .001$) and dose-dependently recovered the AGE3-induced suppression of mineralization in ST2 cells and hMSCs (Figure 6A and B).

Effects of AGE3 and SD208 on proliferation and apoptosis of proliferating ST2 cells and on apoptosis of differentiating ST2 cells and hMSCs

We previously reported that AGE3 decreased cell growth and increased apoptosis in subconfluent ST2 cells (19). We therefore examined the effects of SD208 on the number and apoptosis of AGE3-treated ST2 cells to clarify the role of TGF-β signaling in proliferation of ST2 cells. Treatment with SD208 (2.5 μM) significantly ($P < .001$ both comparisons) intensified the AGE3-induced suppression of ST2 cell growth (Figure 7A), as well as their AGE3-induced apoptosis (Figure 7B). We also examined the effects of AGE3 or SD208 on the apoptosis of ST2 and hMSCs in the mature stages. The results showed that these agents did not affect the apoptosis of either cell type after they had reached confluence and began differentiation (that is, on days 11 through 14; data not shown).

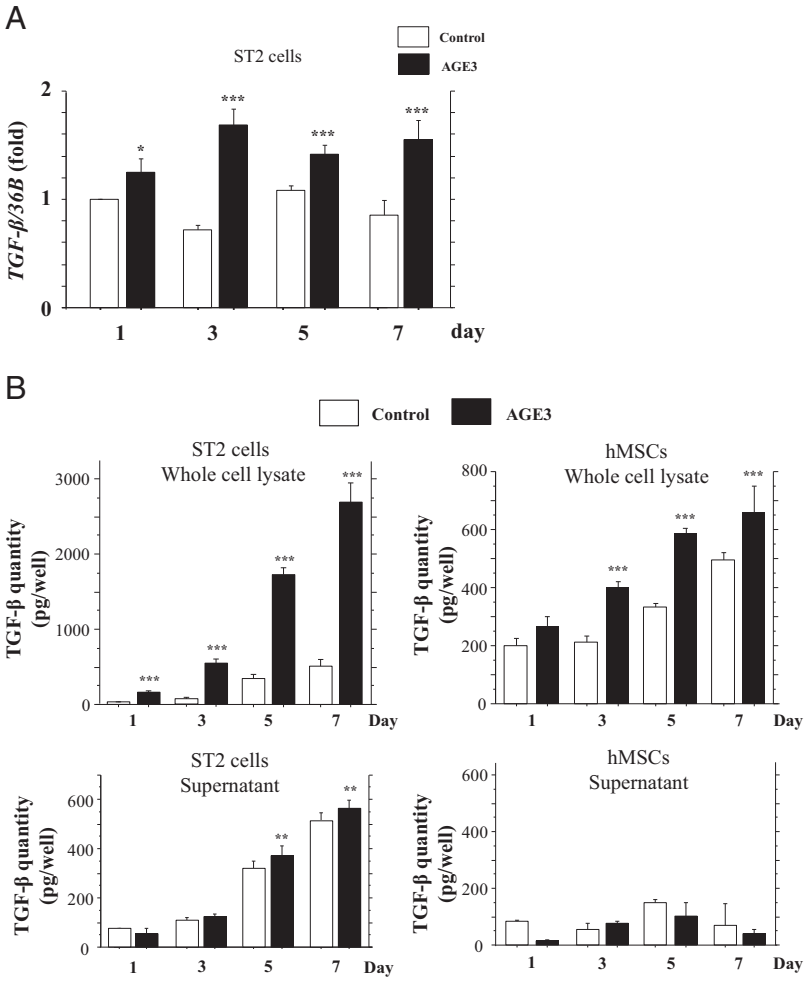

Figure 3. Effects of AGE3 on TGF-β mRNA (A) and protein expressions (B) in ST2 cells and hMSCs. (A) Effects of AGE3 on TGF-β mRNA expressions in ST2 cells. Two hundred μg/mL of either control BSA or AGE3 were added after the cells reached confluence. Total RNA was collected on days 1, 3, 5 and 7, and TGF-β mRNA was measured by real-time PCR. Results are expressed as the mean ± SEM fold increase over control values (N = 10). *$P < .05$ and ***$P < .001$ compared to control on the same day. B, Effects of AGE3 on TGF-β protein expressions in ST2 cells and hMSCs. Two hundred μg/mL of either control BSA or AGE3 were added after the cells reached confluence. Supernatants or whole cell lysates were collected on days 1, 3, 5 and 7. Quantification of TGF-β protein on days 1, 3, 5 and 7 was performed by ELISA. Results are expressed as the mean ± SEM (n = 6). **$P < .01$ and ***$P < .001$ compared to control on the same day.

Discussion

Here, we found that AGE3 suppresses mineralization of mouse stromal ST2 cells as well as hMSCs by increasing TGF-β expression and secretion (Figures 3, 5, 6). Treatment with a TGF-β type I receptor kinase inhibitor, SD208, recovered the AGE3-induced decreases in OSX and OCN and antagonized the AGE3-induced increase in Runx2 mRNA expression in ST2 cells (Figure 5). Moreover, SD208 completely and dose-dependently recovered the AGE3-induced suppression of mineralization in both cell types (Figure 6). These findings suggest that AGE3–TGF-β signaling has negative effects on, and impairs osteoblastic differentiation in, both cell types at the maturation stage. Accumulating evidence indicates that the TGF-β signal suppresses osteoblast differentiation in vitro (23, 24, 41, 42). Alliston et al (23) showed that the TGF-β–Smad3 signal repressed the expression of Runx2 and OCN mRNAs at 48 hours and 6 days, respectively, and decreased mineralization at 10 days in osteoblastic cells treated with TGF-β. Kang et al (24) showed that a controlled balance of histone acetylation and deacetylation at the OSE2 sequence of the OCN promoter regulates osteoblastic differentiation and that TGF-β induces and stabilizes HDAC4 and

HDAC5, which modulate the repression of Runx2-mediated transcription of the OCN gene. Their results indicated that the interaction of TGF-β/Smad3 signaling with HDACs represses Runx2 and OCN function in differentiating osteoblasts (22). Maeda et al (41) showed that the TGF-β type I receptor kinase inhibitor, SB431542, greatly enhanced the osteoblastic differentiation of mouse C2C12 cells. Takeuchi et al (42) reported that treatment with SB431542 inhibited endogenous TGF-β and increased the formation of mineralized nodules. These authors demonstrated that inhibition of TGF-β released stromal cells from differentiation arrest due to multiple myeloma and facilitated the formation of terminally differentiated osteoblasts (40). Our findings that SD208-induced inhibition of TGF-β signaling increased the mineralization of ST2 cells and hMSCs agree with these previous results and suggest that AGEs augment these inhibitory effects of TGF-β on osteoblastic differentiation.

We found that the AGE3–TGF-β signal increased Runx2 mRNA expression in ST2 cells on day 14 after

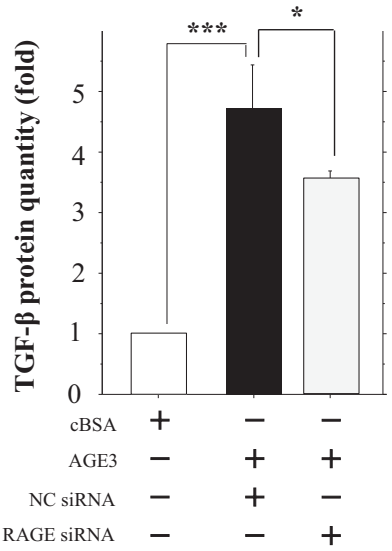

Figure 4. Effects of RAGE siRNA transfection on TGF-β protein expressions increased by AGE3 in ST2 cells. Two hundred μg/mL of either control BSA or AGE3 were added after the cells reached confluence. Total RNA was collected on day 7 after RAGE siRNA transfection. Real-time PCR was performed as described in Materials and Methods. $*P < .05$ and $***P < .001$ compared to negative control siRNA.

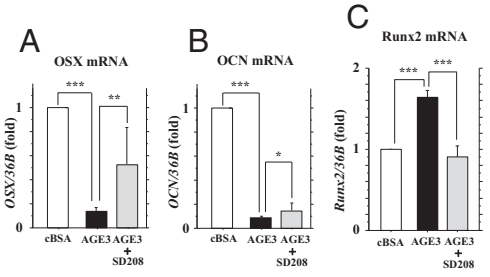

Figure 5. Effects of a TGF-β type I receptor kinase inhibitor on OSX(A), OCN(B) and Runx2(C) mRNA expressions affected by AGE3 in ST2 cells. Two hundred μg/mL of either control BSA or AGE3 with or without SD208 (2.5 mM), a TGF-β receptor kinase inhibitor, were added after the cells reached confluence. Total RNA was collected on day 14, and OSX, OCN and Runx2 mRNA expressions were measured by real-time PCR. Results are expressed as the mean ± SEM fold increase over control values (n = 6). $*P < .05$, $**P < .01$, and $***P < .001$ compared to levels of mRNA expressions treated with AGE3 alone.

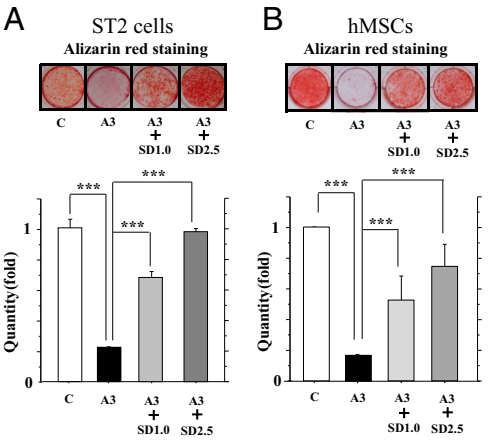

Figure 6. Effect of a TGF-β receptor type I kinase inhibitor in mineralization of ST2 cells (A) and hMSCs (B) suppressed by AGE3. Two hundred μg/mL of either control BSA or AGE3 were added after the cells reached confluence. SD208 (1.0 or 2.5 mM) was added with AGE3 on the same time. Plate view of Alizarin red staining in cultured ST2 cells and hMSCs for 14 days. Quantification of Alizarin red staining of the cells was performed with each treatment. Results are expressed as the mean ± SEM fold increase over control values (n = 6). $***P < .001$ compared to Alizarin red quantity treated with AGE3 alone.

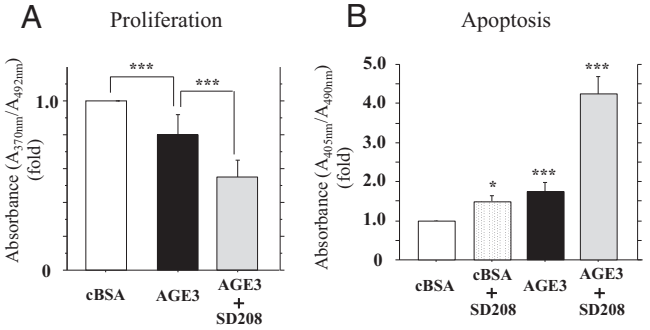

Figure 7. Effects of a TGF-β receptor type I kinase inhibitor on the cell proliferation (A) and apoptosis (B) of ST2 cells. (A) Effects of AGE3 with or without SD208 on the cell proliferation of ST2 cells. The cells were seeded on 96-well plates at a density of 3000 cells/well, and were incubated overnight. On the next day, the cells were treated with 200 μg/mL of either control BSA or AGE3 in the presence or absence of 2.5 mM SD208 for 3 days. Cell proliferation was evaluated by BrdU on day 3. $***P < .001$ compared to AGE3 alone. B, Effects of AGE3 with or without SD208 on the apoptotic cell death of ST2 cells. The cells were seeded on 96-well plates at a density of 3000 cells/well and were incubated overnight. On the next day, the cells were treated with 200 μg/mL of either control BSA or AGE3 in the presence or absence of 2.5 mM SD208 for 3 days. The apoptotic cell death was analyzed in an ELISA for DNA fragments by an absorbance at 405 nm. $*P < .05$ and $***P < .001$ compared to control BSA.

treatment with AGE3. Our preliminary experiments showed that AGE3 treatment did not affect Runx2 mRNA expression in the cells on day 7, indicating that Runx2 mRNA expression increased during the late stage of cell differentiation. Runx2 is known to have contradictory effects during the early, compared with late, stages of osteoblastic differentiation. During early differentiation, Runx2 directs multipotent mesenchymal cells to the osteoblast lineage and inhibits them from differentiating along the adipocyte and chondrocyte lineages. In contrast, after multipotent mesenchymal cells differentiate to preosteoblasts, Runx2 directs them toward becoming immature osteoblasts but inhibits their further maturation and transition into osteocytes, keeping osteoblasts in an immature stage (43). Therefore, the suppression of OCN and OSX expression and the AGE3-associated enhancement of Runx2 expression at the late osteoblastic differentiation stage likely would act in concert to inhibit the differentiation of preosteoblasts to mineralizing mature osteoblasts and seems to be in accord with the AGE3-induced suppression of mineralization of ST2 cells and hMSCs.

In our study and previous ones, our AGE3 preparation inhibited the mineralization of osteoblastic MC3T3-E1 and ST2 cells as well as hMSCs (19, 20). These effects were not toxic, because we previously showed that AGE3 prepared by the same method enhanced the calcification of rat vascular smooth muscle cells, in contrast to its effect on these osteoblastic cells (44). These findings suggest that the biologic activities of our AGE3 preparation are similar to those of endogenous AGEs in patients with DM, namely bone fragility and vascular calcification.

We found that siRNA-induced inhibition of RAGE recovered AGE3-induced suppression of mineralization (Figure 2) and antagonized AGE3-induced increases in TGF-β protein in ST2 cells (Figure 4). These results demonstrate that, by binding to RAGE, AGE3 at least contributed to the increased expression of TGF-β protein and suppressed mineralization of ST2 cells. AGEs have multiple receptors, including RAGE, CD36, lectin-like oxidized low-density lipoprotein (LDL) receptor 1, macrophage scavenger receptors, and AGER1, 2, and 3 (45–50). The presence of multiple AGE receptors may explain why RAGE siRNA had only a partial effect on the cells in our study. We performed another experiments using a neutralizing antibody against human RAGE (R & D systems, Minneapolis, MN), which has approximately 10% cross-reactivity with recombinant mouse RAGE, and found that the antibody failed to recover mineralization suppressed by AGE3 in ST2 cells or hMSCs at the concentration range from 5 to 15 μg/ml (data not shown). It might be because these antibody concentrations were not high enough to block the RAGE activities in the cells.

TGF-β exerts contradictory effects on bone cells depending on their maturation stage. In proliferating osteoblasts, TGF-β stimulates osteoblastic proliferation and the formation of periosteal woven bone when it is injected directly onto the periostea of the parietal bones of rats (51, 52). Treatment of human osteoblast cells with TGF-β downregulates the expression of the Wnt antagonist sFRP-1 and prolongs the life of these cells (53). Other researchers have shown that TGF-β decreases TNF-α-induced apoptosis in murine osteoblasts (54). In addition, TGF-β prevents the osteoblastic apoptosis induced by skeletal unloading via PI3K–Akt signaling (55). In contrast, several studies in mature osteoblasts have shown that the TGF-β signal suppresses osteoblastic differentiation in vitro, as mentioned earlier (23, 24, 41, 42, 56). Another study has shown that TGF-β added to confluent cultures inhibits the formation of bone nodules by reducing their number and total area (57). In our study, when ST2 cells were proliferating and subconfluent, SD208-induced inhibition of TGF-β signaling intensified AGE3-induced suppression of cell growth and AGE3-induced cell apoptosis (Figure 7). These results suggest that the TGF-β signal antagonizes the detrimental effects of AGE3 by increasing cell number and reducing apoptosis in proliferating ST2 cells. These findings contrast with those we obtained by using confluent cells, in which the TGF-β signal augmented the detrimental effects of AGE3 on osteoblast differentiation. Therefore, our results also indicate that TGF-β has biphasic and contradictory effects in ST2 cells, depending on their maturation stage. These findings suggest that we should consider the extent of cell maturation when we target TGF-β signals to treat diabetic osteoporosis. Animal studies using diabetic and nondiabetic wild-type and RAGE knockout mice are needed to demonstrate the role of TGF-β in diabetic bone loss and to ascertain the relevance of our findings in the clinical context.

A recent meta-analysis (7) showed that, compared with non-DM controls, T2DM patients had higher spine and hip BMD than did non-DM controls (z-scores = 0.41 and 0.27, respectively) but T1DM patients had lower spine and hip BMD (z-scores = −0.22 and −0.37, respectively). This discrepancy is partly because T2DM patients typically are obese and insulin resistant, whereas T1DM patients lack these features. Several studies have shown that body weight is positively correlated with BMD, probably because of mechanical stress, and that loss of body weight lowers BMD values (58–60). The increased levels of circulating insulin due to insulin resistance may exert anabolic actions on bone (61), and high BMD is a very consistent finding across a wide range of hyperinsulinemic states (62, 63). However, clinical studies (64, 65) have

shown that serum OCN levels are lower in T2DM patients than in non-DM subjects and that serum OCN increases after glycemic control is achieved in diabetic patients. These findings indicate that T2DM patients still have diminished bone formation despite slightly increased BMD. Because here we examined the effects of AGEs on osteoblastic differentiation in the absence of mechanical stress or high insulin levels, our study design likely reflects the conditions of typical T1DM and of T2DM without obesity or insulin resistance.

Our study had several limitations. We did not examine whether AGE receptors other than RAGE or other components of TGF-β and the RAGE signaling pathway were involved in the inhibition of osteoblastic differentiation of ST2 cells and hMSCs. In addition, we did not examine the signals that mediated AGE3-induced suppression of osteoblast proliferation and stimulation of apoptosis, nor the crosstalk between AGE signals and TGF-β signals.

In conclusion, we found that AGE3 inhibited the differentiation and mineralization of osteoblastic ST2 cells and hMSCs by binding to RAGE and increasing TGF-β expression and secretion after the cells reached confluence. These findings suggest that TGF-β causes a deterioration in bone quality, not only during primary osteoporosis but also during diabetes-related bone disorder, and that TGF-β adversely affects not only kidney, retina, and nerves, but also the bone, as part of diabetic complications.

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