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Pentosidine Deposition Affects Biomechanical Properties of Achilles Tendon in Diabetic Rats

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Abstract

Pentosidine, a biomarker for advanced glycation end products (AGEs), accumulates in vessels, kidney, skin, and bone and induces serious pathological conditions in diabetic patients. However, the relationship between AGE deposition and biomechanical weakness in tendons has not been elucidated. We hypothesized that diabetic status might induce excessive pentosidine deposition in tendon tissue and that accumulated pentosidine might modify the biomechanical properties of the diabetic tendon. In this study, we assessed the effect of pentosidine on cellular viability, senescence, and gene expression of type I/III collagens in NIH3T3 fibroblasts. Pentosidine deposition and the biomechanical properties of diabetic Achilles tendon were investigated using a diabetic rat model. Pentosidine induced cellular senescence of NIH3T3 fibroblasts in a dose-dependent manner without affecting cellular viability. Moreover, pentosidine decreased gene expression of type I/III collagens in NIH3T3 fibroblasts. Diabetic rats showed a higher level of pentosidine deposition in their Achilles tendons compared with that in normal rats. In addition, the toughness and ultimate stress of the Achilles tendon were lower in diabetic rats. Our results suggest that pentosidine may induce cellular senescence and inhibit collagen synthesis in tendon fibroblasts. Moreover the accumulated pentosidine may alter the biomechanical properties of the Achilles tendon in the diabetic rats. Hence the suppressed collagen synthesis may cause the deterioration of the tendon mechanical properties. These phenomena might be one of the reasons of the tendon deterioration in the diabetic patients.

Keywords Advanced glycationendproducts; Pentosidine; Biomechanical property; Tendon; Diabetes mellitus; Senescence; Fibroblast

Introduction

In diabetic patients, advanced glycation end products (AGEs) accumulate in the vessels, kidney, skin, bones, and other tissues [1-6] and results in diabetic vascular complications such as retinopathy [5,6], nephropathy [2], and neuropathy [7]. Moreover, osteoporosis is caused by the deposition of AGEs in bone tissue [3,4,8]. However, the effect of AGE deposition on tendon tissue has not been fully investigated.

Several authors have studied the effect of AGEs on cultured cells [9-13]. AGEs are cytotoxic to human gingival fibroblasts depending on their concentration and incubation time [9]. AGEs increase inflammatory mediators such as monocyte chemotactic protein 1, interleukin 6, and vascular cell adhesion molecule 1in vascular adventitial fibroblasts [10]. AGEs increase tumor necrosis factor-αand induce cell apoptosis by activating the nuclear factor-κ B pathway in human embryonic kidney and human mesangial cells [11]. In addition, AGEs induce fibroblast apoptosis through the activation of reactive oxygen species, mitogen-activating protein kinase, and forkhead box protein O1 transcription factor [12]. These studies indicate that AGEs induce inflammation and apoptosis by deteriorating the viability of fibroblasts.

AGEs alter the biomechanical properties of tendon tissue. Rabbit glycated Achilles tendons show decreased maximum load and increased Young's modulus in vitro [13,14]. Animal models of hyperglycemic conditions and obesity have been used for *in vivo* studies. The tail tendon fibrils in diabetic rats display pentosidine deposition that is 2.5 times greater than that in normal rats [15]. Conversely, Young's modulus is decreased in the patella tendons of streptozotocin (STZ)-induced diabetic rats [16]. Cross-linked AGEs increase the stiffness of myocardial and vascular tissues [17,18]. In addition, AGEs increase the stiffness of the skin and aorta and decrease the elasticity of these tissues in hyperglycemic rats [19]. These findings suggest that AGEs deteriorate the mechanical properties of tendons. However, the relationship between biomechanical properties and the level of AGE deposition in tendon tissue remains unknown.

Pentosidine is a well-characterized AGE found in increased levels in diabetes. We hypothesized that (1) diabetic rats have a greater amount of pentosidine in tendon tissue than that of the normal rats, and (2) the amount of pentosidine deposited modifies the biomechanical properties of the tendon tissue. In the present study, we assessed the effect of pentosidine on cultured fibroblasts and investigated the relationship between biomechanical tissue properties and the amount of pentosidine in rat Achilles tendons.

Methods

In vitro study

Quantitative real-time polymerase chain reaction (PCR) analysis

NIH3T3 cells were seeded in a 12-well plate and cultured in the manner described above. After 1 week of culture, total RNA was extracted using a QuickGene SP kit (Fujifilm, Tokyo, Japan). RNA samples (1 μg) were reversetranscribed to complementary DNA. SYBR-Green (Agilent Technologies, Tokyo, Japan) PCR was performed using these complementary DNAs as templates. Mean cycle threshold (Ct) values were used to calculate gene expression with normalization to hypoxanthinephosphoribosyltransferaseas an internal control. The primer sequences were as follows: forward, 5′-GTGGTTCGTGACCGTGACC-3′,and reverse, 5′-GAGTGGCACATCTTGAGGTC-3′ for the α1 chain of type I collagen (Col1a1); forward, 5′-CTGGAAAGAGTGGTGACAG-3′,and reverse, 5′-TCCTCGATGTCCTTTGATGC-3′, for the α1 chain of type III collagen (Col3a1) [20]. After 3 minutes of initial denaturation at 95°C, PCR was performed with 45 cycles of 10 seconds of denaturation at 95°C and 30 seconds of annealing and extension at 55°C. Quantification was achieved using the comparative Ct method according to the manufacturer protocol. Expression was quantified using the delta-delta Ct method.

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In vivo study

Animals and plasma glucose measurements

Four male Otsuka Long-Evans Tokushima fatty (OLETF) rats and 2 male Long-Evans Tokushima Otsuka (LETO) rats aged 20 weeks were supplied by Shimizu Laboratory Supplies Co. Ltd. (Kyoto, Japan). The OLETF rat is an animal model of human non-insulin-dependent diabetes mellitus established from an outbred Long-Evans strain [21]. Nearly 100% of male OLETF rats develop a diabetic syndrome at 25 weeks of age. LETO rats served as normal controls. Body weight and blood sugar levels were measured at the time of sacrifice. Plasma glucose levels were measured in a central vein using a blood glucose meter (ONETOUCH UltraVue, LIFESCAN Inc., Tokyo, Japan). The bilateral Achilles tendons were collected-8 from OLETF rats and 4 from LETO rats-and stored at -20°C until analysis.

Biomechanical analysis

The biomechanical properties of the Achilles tendons were carried out using an Instron Testing Device, Model 5965 (Instron Japan Co. Ltd., Kanagawa, Japan). The specimens were thawed at room temperature and secured between 2 clamps (Figure 1). The circumference of each Achilles tendon (mm) was measured at the mid-part of the fixed tendon, and the cross-sectional area (mm^2) was calculated. The length of the tendon (mm) was measured as the distance between the clamps. Then the tendon was tugged to rupture at a rate of 1,000 mm/min. The data were digitized and imported into a computer. From the analysis of the stress-strain relationship, ultimate stress (N/mm^2), Young's modulus of elasticity (N/mm^2), toughness (N/mm^2), and strain to failure (%) were calculated for each specimen. The ruptured specimens were placed into saline and stored for histopathological assessment.

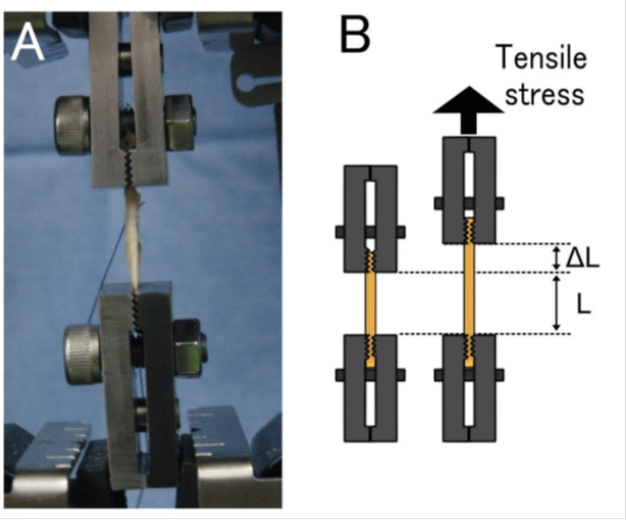

Figure 1. Experimental setup for biomechanical testing.(A) Achilles tendonswere clamped to the Instron testing device at both ends. (B) Tensile strain was calculated using the following equation: strain (%) = ΔL (mm) / L (mm) × 100.

Histopathological analysis

After 24 hours of fixation in formalin, the specimens were embedded in paraffin and sectioned. The sections were stained with hematoxylin and eosin, and the degree of tissue degeneration was assessed with light microscopy using the Bonar scale [22]. Specimens with a Bonar score of 3 or higher were characterized as having tissue degeneration and excluded from the study. The sections were also stained with an anti-pentosidine monoclonal antibody, KH012 (Trans Genic Inc., Kobe, Japan). After reacting with primary antibody, the sections were reacted with 3,3′-diaminobenzidine solution without counterstaining. All control sections were completely negative. The percentage of stained area was calculated using the following method.

The images of the stained sections were obtained in 3 high-power fields and imported into a computer. The total pentosidine-positive area (%) and the pentosidine-positive area of the nuclei (%) were quantified in each image using the image analysis software Image J (version 1.44p, National Institutes of Health, Bethesda, MD, USA), and the average area of 3 high-power fields was calculated. Then, the pentosidine-positive area of the extracellular matrix (ECM; %) was calculated by subtracting the pentosidine-positive area of the nuclei from the total pentosidine-positive area.

Statistical analyses

Statistical analyses were performed using commercial software (StatMate III, Atms Co., Ltd., Tokyo, Japan). The data from the water-soluble tetrazolium-1 assay, β-galactosidase assay, and real-time RT-PCR were analyzed using one-way analysis of variance between groups with and without various concentrations of pentosidine. The pentosidine-positive area and the biomechanical properties of OLETF rats were compared with those of LETO rats using Mann-Whitney's U-test. Pearson's correlation coefficients were also assessed to identify correlations between the pentosidine-positive area of the ECM and the biomechanical properties of the Achilles tendons. Statistical significance was defined as a P value less than 0.05.

Results

In vitro study

Pentosidine administration had no effect on the cell viability of NIH3T3 fibroblasts (Figure 2A). In the cell senescence assay, pentosidine increased the senescence-associated β-galactosidase activity of NIH3T3 fibroblasts in a dose-dependent manner (Figure 2B). Fluorescence observed in cells treated with 0.5 and 1.0 μmol/L of pentosidinewas significantly greater than that in control cells.

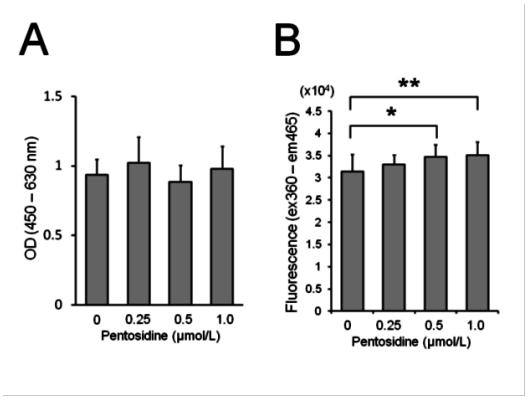

Figure 2. Effect of pentosidine on cell viability and cellular senescence in NIH3T3 fibroblasts.(A) Water-soluble tetrazolium-1 assay showed that cell viability was not influenced by an increase in pentosidine concentration. (B) Pentosidine increased the cell senescence of NIH3T3 fibroblasts in a dose-dependent manner. Significantly higher senescence-associated β-galactosidase activity was observed in the 0.5 and 1.0 μmol/L pentosidine groups compared with that in the control group. *p<0.05; **p<0.01.

Real-time PCR analysis showed that pentosidine reduced the expression of Col1a1 and Col3a1 in a dose-dependent manner (Figures 3A and B). Gene expression of Col1a1 and Col3a1 in cells treated with 0.5 and 1.0μmol/L of pentosidine were suppressed compared with that in cells cultured in the standard medium.

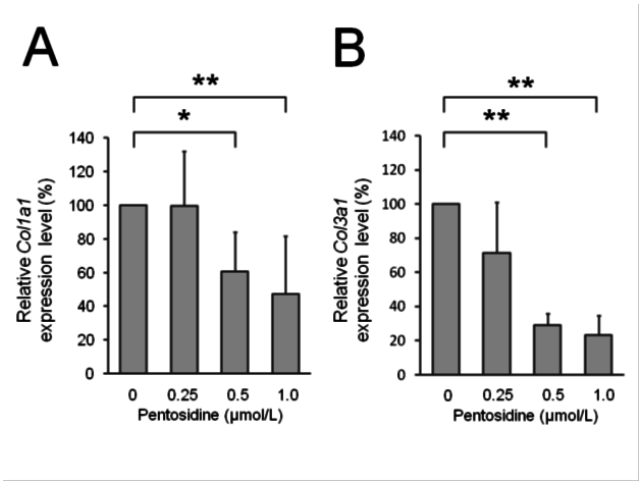

Figure 3. Effect of pentosidine on collagen I/III gene expression in NIH3T3 fibroblasts.Gene expression of the α1 chain of collagen I(Col1a1) (A) and collagen III (Col3a1) (B) was decreased by pentosidine treatment. In the 0.5 and 1.0 μmol/L pentosidine groups, pentosidine significantly suppressed the gene expression of Col1a1 and Col3a1 compared with that in the control group. *po.<0.05; **p<0.01.

In vivo study

Plasma glucose levels of OLETF rats were greater than 200 mg/dL; however, those of LETO rats were less than 100 mg/dL (p<0.001, Table 1). Body weight in OLETF rats was significantly increased compared with that in LETO rats (p<0.001,Table 1). The cross-sectional area of the Achilles tendons of OLETF rats did not differ from that in LETO rats (Table 1). In the biomechanical analysis, the ultimate stress of the Achilles tendons in OLETF rats was lower than that of LETO rats (Table 1). However, no statistically significant difference was observed between these groups (p=0.08). Young's elastic modulus and strain to failure in OLETF rats were similar to those in LETO rats (Table 1). Although statistical significance was not observed, toughness in OLETF rats was relatively lower than that in LETO rats (Table 1).

	OLETF rats (n=8)	LETO rats (n=4)	OLETF vs. LETO
Bodyweight (g)	533.7 (57.6)	471.9 (26.2)	p<0.001
Plasma glucoselevel(mg/dL)	549 (139)	75 (26)	p<0.001
Cross-sectionarea of tendon (mm^2)	3.5 (0.7)	3.7 (1.1)	N.S.
Ultimatestress (N/mm^2)	6.66 (2.52)	9.12 (3.22)	N.S.
Young'smodulus (N/mm^2)	50.7 (22.1)	51.6 (7.5)	N.S.

Toughness (N/mm^2)	121.8 (76.9)	169.4 (102.7)	N.S.
StraintoFailure (%)	22.7 (11.7)	28.7 (5.4)	N.S.
Data are presented as mean (SD). Significanceis set at p<0.05.			

Table 1. Biomechanical properties of Achilles tendons in OLETF and LETO rats

Histopathological analysis showed that the Bonar scores of all specimens included into this study were less than 3. Immunohistological analysis revealed that a greater amount of pentosidine deposition occurred in the Achilles tendons of OLETF rats compared with those in the tendons of LETO rats (Figure 4A and B). Significant differences between OLETF and LETO rats were observed in the area stained by the anti-pentosidine antibody (p<0.001; Figure 4C).

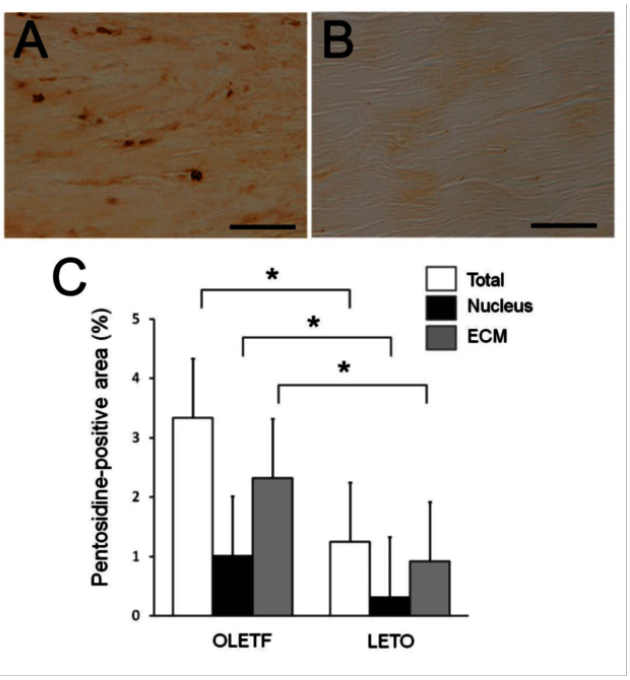

Figure 4. Histopathologic findings for Achilles tendons in diabetic and non-diabetic rats(A, B) Achilles tendons of Otsuka Long-Evans Tokushima fatty (OLETF) rats had a higher level of pentosidine deposition compared with that in Long-Evans Tokushima Otsuka(LETO) rats. Bars, 50μm. (C) The pentosidine-positive area in OLETF rat tendons was significantly increased compared with that of LETO rat tendons (p<0.001) *p<0.001.

The ultimate stress of the Achilles tendons was decreased as the pentosidine-positive area in the tendon ECM increased (r=-0.59, p<0.05; Figure 5A). The percentage of the pentosidine-positive area in the tendon ECM did not influence Young's elastic modulus (r=-0.30, p>0.05). No significant correlation was also observed between toughness and thepentosidine-positive area (r=-0.50, p>0.05).

Discussion

The results of this study showed that the Achilles tendons of OLETF rats, which are animal models of type II diabetes, had a greater level of pentosidine deposition compared with that in the Achilles tendons of LETO rats.

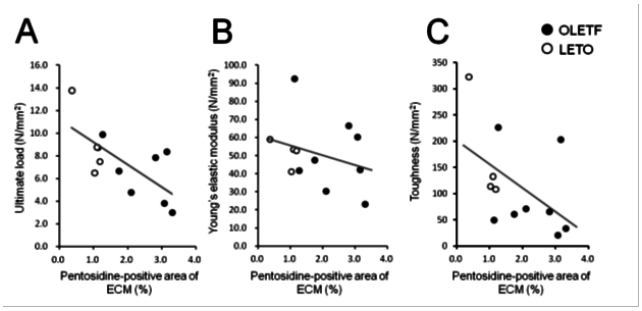

Figure 5. Relationship between pentosidine deposition and biomechanical properties of rat Achilles tendons.(A) Ultimate stress was negatively correlated with the percentage of the extracellular matrix (ECM)area stained by an anti-pentosidine antibody (r=-0.59, p<0.05). (B) Young's elastic modulus had no correlation with the percentage of pentosidine-positive ECM area. (C) No significant correlation was observed between toughness and the pentosidine-positive area.

Furthermore, the ultimate stress of the Achilles tendon decreased as pentosidine deposition in the tendon ECM increased. Our results suggest that the presence of diabetes mellitus may deteriorate tendon biomechanical properties by increasingpentosidine deposition.

Pentosidine in tendon tissue increaseswithaging and a hyperglycemic condition [19,23]. AGEs have cytotoxicity [9] and induce inflammation and apoptosis in fibroblasts [10,12]. In addition, AGEs deteriorate the mechanical properties of tendons [16]. The current study showed that pentosidine induced cell senescencein NIH3T3 fibroblasts in a dose-dependent manner without affecting cell viability. Moreover, the expression of Col1a1 and Col3a1 was decreased in fibroblasts treated with pentosidine,indicating that pentosidine may deteriorate cell activity and impede tendon tissue turnover and remodeling.

In this study, we used OLETF rats as models of type II diabetes mellitus. In type I diabetic rats, the hyperglycemic condition negatively affects the mechanical properties of the patella tendon [16]. Fox et al. [16] have shown that Young's modulus is significantly decreased in STZ-induced diabetic male Lewis rats compared with that in control rats. However, no significant differences in mean load-to-failure or stiffness were observed between the groups. In our study, the ultimate stress of the Achilles tendons decreased as the level of pentosidine deposition in the tendon ECM increased. These differences may be related to the type of diabetes mellitus. STZ induces a loss of body weight in rats, which decreases the cross-sectional area of the tendon tissue [16], in turn altering its mechanical properties. In OLETF rats, the ultimate stress of the Achilles tendon was lower than that in LETO rats even though body weight in OLETF rats was higher. Moreover, the STZ-induced diabetic rat is an acute-onset model of diabetes,whereastheOLETF rat model represents chronic diabetes

mellitus. These findings suggest that the glycation of the tendon tissue may alter the biomechanical properties of the tendons.

Pentosidine forms cross-links between lysine and arginine residues and is not expected to be deposited in the nuclei. However, our study showed that the nuclei were stained by the anti-pentosidine antibody. A previous study has shown that the distribution of pentosidine and other AGEs is stronger in the cells than in the ECM of arthritic cartilage [24]. The mechanical properties of tendon tissue might be related to ECM condition; therefore, we calculated the area of the ECM stained by an anti-pentosidine antibody excluding the nuclei. Our results showed that the pentosidine-positive area in the ECM was negatively correlated with the ultimate stress of rat Achilles tendon. Pentosidine, which deposits in collagen fibers, may modify the biomechanical properties of tendon tissue. In this study, we assessed the effect of pentosidine on fibroblasts in vitro and demonstrated that pentosidine deposits in the collagen fibrils and affects the biomechanical properties of the tendon collagen [15]. Moreover, pentosidine can affect the biology of satellite cells and stem cells around collagen bundles. The deposited pentosidine might induce cellular senescence of fibroblast precursors and inhibit collagen gene expression in fibroblasts,in turn causing a decline in collagen turnover and inducing the aging of tendon tissue.

The potential clinical relevance of this study is that greater pentosidine deposition on tendon tissue might be observed in patients with type II diabetes mellitus and that this deposition deteriorates the biomechanical properties of human tendon tissue. Preventing pentosidine deposition may be a potential therapeutic approach for tendinopathy and tendon rupture in diabetic patients.

This study has several limitations. First, we used 20-week-old OLETF and LETO rats. We intended to assess the biomechanical properties of the tendon tissue without degenerative change. OLETF ratsdisplaytype II diabetes at 20 weeks of age; however, the duration of hyperglycemic condition is short. The older rats should be investigated in future studies. Second, we measured the amount of pentosidine deposition in the Achilles tendons using immunohistological analysis. High-performance liquid chromatography may be required to assess the amount and quality of the deposited pentosidine. Third, we used the NIH3T3 cells in vitro study. NIH3T3 fibroblasts are derived from mouse embryo fibroblasts, and NIH3T3 cells would expect to be different from tendon fibroblasts. The in vitro experiments should be repeated with primary tendon fibroblast cells in the further study. Forth, we did not evaluate the β-galactosidaseactivityand the expression of collagengenes in the Achilles tendon and hence these data of the OLETF rats were not compared with those of the control rats. The further study is needed to clarify the effect of the senescence and gene expression of the tendon tissue on the biomechanical properties in the diabetes mellitus.

In conclusion, pentosidine induced cellular senescence of NIH3T3 fibroblastsin a dose-dependent manner without affecting cellularviability.Pentosidine also decreased the gene expression of Col1a1 and Col3a1 in NIH3T3 fibroblasts. In diabetic rats, the ultimate stress of the Achilles tendon decreased as the amount of pentosidine deposition increased. Our results suggest that pentosidine may induce cellular senescence of tendon fibroblasts and inhibit collagen synthesis in the diabetic tendon. Therefore, pentosidine might deteriorate the biomechanical properties of the tendons of diabetic patients.

Acknowledgements

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References

1. Schalkwijk CG, Miyata T (2012) Early- and advanced non-enzymatic glycation in diabetic vascular complications: the search for therapeutics. Amino Acids 42: 1193-1204.
2. Smit AJ, Gerrits EG (2010) Skin autofluorescence as a measure of advanced glycationendproduct deposition: a novel risk marker in chronic kidney disease. Curr Opin Nephrol Hypertens 19: 527-533.
3. Saito M, Fujii K, Soshi S, Tanaka T (2006) Reductions in degree of mineralization and enzymatic collagen cross-links and increases in glycation-induced pentosidine in the femoral neck cortex in cases of femoral neck fracture. Osteoporos Int 17: 986-995.
4. Saito M, Marumo K (2010) Collagen cross-links as a determinant of bone quality: a possible explanation for bone fragility in aging, osteoporosis, and diabetes mellitus. Osteoporos Int 21: 195-214.
5. Stitt AW, Frizzell N, Thorpe SR (2004) Advanced glycation and advanced lipoxidation: possible role in initiation and progression of diabetic retinopathy. Curr Pharm Des 10: 3349-3360.
6. Stitt AW, Curtis TM (2005) Advanced glycation and retinal pathology during diabetes. Pharmacol Rep 57 Suppl: 156-168.
7. Zochodne DW (2007) Diabetes mellitus and the peripheral nervous system: manifestations and mechanisms. Muscle Nerve 36: 144-166.
8. Wood RJ, O'Neill EC (2012) Resistance Training in Type II Diabetes Mellitus: Impact on Areas of Metabolic Dysfunction in Skeletal Muscle and Potential Impact on Bone. J NutrMetab 2012: 268197.
9. Yu S, Li H, Ma Y, Fu Y (2012) Matrix Metalloproteinase-1 of Gingival Fibroblasts Influenced by Advanced Glycation End Products and Their Association With Receptor of Advanced Glycation End Products and Nuclear Factor-?B in Gingival Connective Tissue. J Periodontol 83: 119-126.
10. Liu Y, Liang C, Liu X, Liao B, Pan X, et al. (2010) AGEs increased migration and inflammatory responses of adventitial fibroblasts via RAGE, MAPK and NF-kappaB pathways. Atherosclerosis 208: 34-42.
11. Liang YJ, Jian JH, Liu YC, Juang SJ, Shyu KG, et al. (2010) Advanced glycation end products-induced apoptosis attenuated by PPARdelta activation and epigallocatechingallate through NF-kappaB pathway in human embryonic kidney cells and human mesangial cells. Diabetes Metab Res Rev 26: 406-16.
12. Alikhani M, Maclellan CM, Raptis M, Vora S, Trackman PC, et al. (2007) Advanced glycation end products induce apoptosis in fibroblasts through activation of ROS, MAP kinases, and the FOXO1 transcription factor. Am J Physiol Cell Physiol 292: C850-856.
13. Molinari J, Ruszova E, Velebny V, Robert L (2008) Effect of advanced glycationendproducts on gene expression profiles of human dermal fibroblasts. Biogerontology 9: 177-182.
14. Reddy GK (2004) Cross-linking in collagen by nonenzymaticglycation increases the matrix stiffness in rabbit achilles tendon. Exp Diabesity Res 5: 143-153.
15. Odetti P, Aragno I, Rolandi R, Garibaldi S, Valentini S, et al. (2000) Scanning force microscopy reveals structural alterations in diabetic rat collagen fibrils: role of protein glycation. Diabetes Metab Res Rev 16: 74-81.
16. Fox AJ, Bedi A, Deng XH, Ying L, Harris PE, et al. (2011) Diabetes mellitus alters the mechanical properties of the native tendon in an experimental rat model. J Orthop Res 29: 880-885.

17. Kass DA, Shapiro EP, Kawaguchi M, Capriotti AR, Scuteri A, et al. (2001) Improved arterial compliance by a novel advanced glycation end-product crosslink breaker. Circulation 104: 1464-1470.
18. Wolffenbuttel BH, Boulanger CM, Crijns FR, Huijberts MS, Poitevin P, et al. (1998) Breakers of advanced glycation end products restore large artery properties in experimental diabetes. ProcNatlAcadSci U S A 95: 4630-4634.
19. Mikulíková K, Eckhardt A, Kunes J, Zicha J, Miksík I (2008) Advanced glycation end-product pentosidine accumulates in various tissues of rats with high fructose intake. Physiol Res 57: 89-94.
20. Tetsunaga T, Furumatsu T, Abe N, Nishida K, Naruse K, et al. (2009) Mechanical stretch stimulates integrin alphaVbeta3-mediated collagen expression in human anterior cruciate ligament cells. J Biomech 42: 2097-2103.
21. Kawano K, Hirashima T, Mori S, Saitoh Y, Kurosumi M, et al. (1992) Spontaneous long-term hyperglycemic rat with diabetic complications. Otsuka Long-Evans Tokushima Fatty (OLETF) strain. Diabetes 41: 1422-1428.
22. Cook JL, Feller JA, Bonar SF, Khan KM (2004) Abnormal tenocyte morphology is more prevalent than collagen disruption in asymptomatic athletes' patellar tendons. J Orthop Res 22: 334-338.
23. Naresh MD, Brodsky B (1992) X-ray diffraction studies on human tendon show age-related changes in collagen packing. Biochim Biophys Acta 1122: 161-166.
24. Hirose J, Yamabe S, Takada K, Okamoto N, Nagai R, et al. (2011) Immunohistochemical distribution of advanced glycation end products (AGEs) in human osteoarthritic cartilage. Acta Histochem 113: 613-618.