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**Type 2 diabetes and bone fragility in children and adults**

Faienza MF *et al*. T2D and bone

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**Abstract**

Type 2 diabetes (T2D) is a global epidemic disease. The prevalence of T2D in adolescents and young adults is increasing alarmingly. The mechanisms leading to T2D in young people are similar to those in older patients. However, the severity of onset, reduced insulin sensitivity and defective insulin secretion can be different in subjects who develop the disease at a younger age. T2D is associated with different complications, including bone fragility with consequent susceptibility to fractures. The purpose of this systematic review was to describe T2D bone fragility together with all the possible involved pathways. Numerous studies have reported that patients with T2D show preserved, or even increased, bone mineral density compared with controls. This apparent paradox can be explained by the altered bone quality with increased cortical bone porosity and compromised mechanical properties. Furthermore, reduced bone turnover has been described in T2D with reduced markers of bone formation and resorption. These findings prompted different researchers to highlight the mechanisms leading to bone fragility, and numerous critical altered pathways have been identified and studied. In detail, we focused our attention on the role of microvascular disease, advanced glycation end products, the senescence pathway, the Wnt/β-catenin pathway, the osteoprotegerin/receptor-activator of nuclear factor kappa B ligand, osteonectin and fibroblast growth factor 23. The understanding of type 2 myeloid bone fragility is an important issue as it could suggest possible interventions for the prevention of poor bone quality in T2D and/or how to target these pathways when bone disease is clearly evident.

**Key Words:** Type 2 diabetes; Bone remodeling; Cytokines; Bone fragility; Bone mineral density; Chronic kidney disease

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**Core Tip:** Type 2 diabetes (T2D) patients show increased susceptibility to bone fractures, despite their bone mineral density being normal or increased, leading to difficult identification for clinicians. The prevalence of T2D in adolescents and young adults is increasing alarmingly. Different researchers highlighted the mechanisms leading to bone fragility, and different critical altered pathways have been identified and studied. In this review, we described the different metabolic pathways responsible for bone fragility in patients with T2D. They can be useful for its management, although further studies are needed to deepen our understanding of the mechanisms underlying bone fragility in T2D.

**INTRODUCTION**

The prevalence of type 2 diabetes (T2D) mellitus in adolescents and young adults is increasing alarmingly. Data from the SEARCH study showed an annual increase of approximately 7% in the incidence of T2D among people aged 10-years-old to 19-years-old in the United States, with increases in all ethnic groups[1]. Increases in children, adolescents and young adults with T2D have been described across most regions of the world[2]. The highest T2D incidence rates in youth have been registered in Canadian First Nations, American Indian and Navajo nation, Australian Aboriginal and Torres Strait Islander and African American populations (31-94/100000 each year), while youths from non-Hispanic Caucasian populations (*i.e.,* United States and Europe) display the lowest incidence rates (0.1-0.8/100000 each year). Studies show the highest prevalence in youth from Mexico and Brazil, indigenous populations in Canada and the United States, together with Black populations in the Americas (160-3300/100000). Conversely, the lowest prevalence was registered in European populations (0.6-2.7/100000)[2].

A recent literature review examined country-specific prevalence and incidence data of youth-onset T2D published between 2008 and 2019[3]. The highest prevalence rates of youth-onset T2D were observed in China (520 cases/100000 people) and the United States (212 cases/100000) and the lowest in Denmark (0.6 cases/100000) and Ireland (1.2 cases/100000). However, the highest incidence rates were reported in Taiwan (63 cases/100000) and the United Kingdom (33.2 cases/100000), with the lowest in Fiji (0.43 cases/100000) and Austria (0.6 cases/100000). These differences in epidemiology data may be partially explained by variations in the diagnostic criteria used within studies, screening recommendations within national guidelines and race/ethnicity within countries.

The main predisposing risk factors for the development of T2D in pediatric age are represented by obesity, family history and sedentary lifestyle[4]. The mechanisms leading to T2D in young people are similar to those in older patients. However, the severity of onset, reduced insulin sensitivity and defective insulin secretion can be different in subjects who develop the disease at a younger age[5]. In particular, the phase of nutrient-induced insulin secretion might be impaired earlier in children and adolescents than in older subjects[6].

The comorbidities associated with T2D in young people include hypertension, cardiovascular disease, kidney impairment and retinopathy. Furthermore, psychosocial problems are often observed[7]. Altered bone quality has been reported in patients with T2D, possible mechanisms for the effect of T2D on bone mineral density (BMD) include the toxic effects of hyperglycemia, which may impair differentiation and proliferation of osteoblasts[8]. In addition, hyperglycemia can increase urine calcium excretion, which inhibits bone formation[8]. Thus, the objective of this review was to describe T2D bone fragility together with all the possible involved pathways.

**T2D AND BONE IMPAIRMENT**

Most studies have found that patients with T2D have preserved, or even increased, BMD compared with controls but display bone fragility with consequent increased susceptibility to fractures[9-11]. This apparent paradox is due to the altered bone quality in these patients. In detail, the spine trabecular bone score is decreased in patients with T2D, and it is a predictor of fracture risk independently of the BMD[12].

Furthermore, different studies have evaluated T2D effects on bone microarchitecture of the peripheral skeleton (radius and tibia) through high-resolution peripheral quantitative computed tomography. These studies have generally shown preserved, or even improved, trabecular bone microarchitecture in patients with T2D compared with controls[12-17]. Furthermore, some[14,15,17-19], but not all[16,20,21], studies report augmented cortical porosity in patients with T2D, and interestingly this parameter independently predicts fracture risk.

Another aspect of bone quality that might be impaired in patients with T2D is the mechanical characteristics that can be assessed through the measurement of the bone material strength index. However, discordant results have been reported on this issue. In detail, some authors found reduced bone material strength index in T2D in comparison with controls[20,22,23], whereas others reported no significant variation[16]. These different results could be associated to the different comorbidities characterizing T2D.

Several studies have noted reduced bone turnover in patients with T2D[20,24,25]. It has been reported that patients with T2D have reduced markers of bone formation [serum levels of procollagen type 1 amino-terminal propeptide and osteocalcin (OC)] as well as resorption (carboxy-terminal telopeptide of type 1 collagen)[20,24,26,27]. Moreover, Starup-Linde *et al*[28] demonstrated an inverse relationship between glycemic control (hemoglobin A1c) and OC levels and a similar trend for carboxy-terminal telopeptide of type 1 collagen and procollagen type 1 amino-terminal propeptide. N-terminal telopeptide of type 1 collagen and bone-specific alkaline phosphatase levels are not significantly different between patients with T2D and controls[29]. Very recently, it has been reported that thyroid homeostasis could affect bone turnover markers[30] and that follicle-stimulating hormone levels may contribute to the suppression of the same markers[31].

**MECHANISMS AND MOLECULAR PATHWAYS INVOLVED IN T2D BONE FRAGILITY**

An indication of mutual regulatory control of both bone and glycemic homeostasis recognizes the close interplay between these two systems. The common regulatory mechanisms involve microvascular disease, advanced glycation end products (AGEs), osteoprotegerin (OPG)/receptor-activator of nuclear factor kappa B ligand (RANKL), the Wnt/β-catenin pathway, osteonectin and fibroblast growth factor 23 (FGF23) (Table 1).

***Microvascular disease***

Microvascular disease is a common complication (retinopathy, nephropathy or neuropathy) of diabetes[32]. Angiopathy has been demonstrated in the iliac crest of diabetic patients[33]. Recently, decreased microvascular blood flow has been demonstrated to be linked with cortical porosity in patients with T2D, suggesting that microvascular disease negatively affects bone microarchitecture in T2D[16]. Consistently, cortical porosity of the distal radius and tibia is most pronounced in patients with T2D with microvascular disease[19]. In contrast, in 2022 it was found that the poorest femoral trabecular microarchitecture was associated with vascular complications in patients with T2D[34]. Patients with T2D with microvascular disease display a significantly lower trabecular bone score, after adjusting for confounders. Moreover, multivariable analysis demonstrated a significant correlation between low 25(OH) vitamin D levels and microvascular disease[35].

Several mechanisms have been proposed to explain how microvascular disease is associated with bone fragility in T2D. It is important to remember that skeletal blood flow provides growth factors, hormones, oxygen and nutrients affecting bone remodeling, suggesting that alteration in microvasculature leads to bone impairment. In the same manner as perivascular cells show stem-cell like properties and may differentiate in osteoblastic cells, blood vessels also release factors affecting the differentiation and activity of osteoblasts and osteoclasts[36]. Blood flow promotes angiogenesis and thus osteogenesis. Bone blood flow is reduced in T2D rats[37], and hypoxia increases the canal network in rat cortical bone[38], suggesting that insufficient oxygen and blood flow associated with microvascular disease alters bone microarchitecture. The recruitment of osteoprogenitors from blood vessels is fundamental for bone formation following osteoclast resorption[39]. Thus, microvascular disease could uncouple resorption and formation in cortical bone by impairing osteoprogenitor recruitment. However, further studies are needed to deepen our understanding of the mechanisms and in particular whether bone fragility is a comorbidity of T2D or a complication (this item is a matter of debate)[40].

***AGEs***

Hyperglycemia disturbs both bone cells and the extracellular matrix. The presence of glucose determines the production of intermediate products, which eventually generate the irreversible accumulation of AGE[41]. AGE accumulation leads to the synthesis of defective collagens as well as of reactive oxygen species, with consequent structural changes in the bone[42]. In detail, considering the organic bone matrix, these products lead to diminished bone strength[43,44]. Elevated AGE levels are associated with increased fracture risk[45].

The AGE-receptor for AGE (RAGE) binding generates reactive oxygen species production, macrophage and platelet activation, vascular inflammation and inflammatory cell migration[46]. All these events are involved in the onset and progression of typical macro- and microangiopathy associated with diabetes, thus leading to brittle bones with diminished strength and less capability to deform before fracturing[47].

RAGE is also expressed by immune cells and incites activation of the nuclear factor kappa-light-chain-enhancer of activated B cells, a central transcription factor of the immune and inflammatory response[46]. The AGE-RAGE interaction in immune cells leads to the increased expression of chemokines and adhesion molecules, secreting further RAGE ligands, supporting the inflammatory tissue response, regulating the activated macrophage reaction to enhance the destructive signals in the tissues and inhibiting the repair and remodeling responses[46]. AGEs may determine osteoclastogenesis and osteoblast alterations in the bone microenvironment due to the increase in inflammatory cytokines, leading to osteoporosis[48].

In detail, pentosidine, the most studied AGE, accumulates in the trabecular and cortical bone in patients with T2D and negatively affects their bone strength as well as probably leading to functional changes in osteoblasts and the bone mineralization process[49,50]. Consequently, trabecular and cortical bones show impaired biomechanical properties and decreased strength, together with altered osteoblast activity as well as adhesion to the collagen matrix and thus negatively affect bone homeostasis[45,50-52].

AGE bone content correlates with worse bone microarchitecture, including lower volumetric BMD, bone volume/total volume and increased trabecular separation/spacing[53]. High concentrations of AGEs blunt insulin-like growth factor I- mediated osteoblast stimulation and determines the resistance of osteoblasts to insulin-like growth factor I effects[54]. Consistently, insulin-like growth factor I serum levels have been found to be inversely correlated with the occurrence of vertebral fractures in T2D postmenopausal women[55].

***The role of cellular senescence in mediating skeletal fragility in T2D***

Different forms of stress can lead a cell to enter an irreversible permanent growth arrest known as senescence[56]. This is triggered by cyclin-dependent kinase inhibitors, remarkably p16Ink4a and p21Cip1, that antagonize the activity of cyclin-dependent kinases to stop cell proliferation[57,58]. Senescent cells display a transformed gene expression profile with an increase in senescent cell anti-apoptotic pathways as well as a senescence-associated secretory phenotype[59], typically consisting of proinflammatory cytokines, chemokines and matrix remodeling proteins[60,61]. A premature increase in senescent cells is evident in T2D, especially pancreatic β cells and bone[62,63]. In particular, osteocyte senescence has been demonstrated using an inducible obese mouse model of T2D. These mice display bone quality alterations quite similar to bones from humans with T2D, such as reduced biomechanical strength, defective cortical bone microarchitecture and low bone formation rates[63]. Furthermore, in this model, senescent osteocytes were identified for the high levels of p16Ink4a and p21Cip1, senescence-associated distension of satellites, increased telomere-associated foci (another cell marker of senescence) as well as typical increased expression of proinflammatory senescence-associated secretory phenotype and nuclear factor kappa-light-chain-enhancer of activated B cells[63].

Additionally, cellular senescence in T2D has been linked to the incidence of fracture in murine models and patients[64,65]. In detail, using a murine model of T2D reflecting both hyperinsulinemia caused by insulin resistance induced by a high-fat diet and insulinopenia induced by low dose streptozotocin, increased density of senescent cells has been demonstrated in the callus area in fracture healing[64]. Additionally, the same authors reported that cells of the osteoblastic lineage cultured with sera from patients with T2D displayed increased expression of the p53 responsive genes that are typical of a senescent microenvironment[64]. The decreased levels of serum senescent miR-31-5p in older diabetic women is linked to incidents of fragility fracture and can significantly predict fracture risk if combined with femoral neck and BMD measurements[65].

***The Wnt/β-catenin pathway***

The Wnt/β-catenin pathway activation promotes osteoblastogenesis and bone formation but inhibits osteoclastogenesis. Dickkopf-related protein 1 and sclerostin (encoded by *Sost*) antagonize the Wnt/β-catenin pathway by binding to low-density lipoprotein receptor-related protein 5 or 6, thus inhibiting osteoblastogenesis and promoting osteoclastogenesis[66].

Bone expression of sclerostin and Dickkopf-related protein 1 has been demonstrated to be high in T2D rat models[67,68]. Circulating sclerostin levels have also been found to be increased in patients with T2D[69] and correlated to the decrease in bone formation markers[70]. In contrast, in T2D postmenopausal women the high circulating levels of sclerostin are related to vertebral fractures[71]. Interestingly, T2D postmenopausal women with previous fractures display thinner cortical bone, together with a tendency towards larger volumetric bone density and elevated circulating levels of sclerostin compared with diabetic women without fractures and nondiabetic controls with fractures[72]. More recently, Piccoli *et al*[53] reported that *Sost* expression in RNA extracts from the femoral head of patients with T2D is significantly increased compared with the controls, although circulating sclerostin levels were found to be higher in T2D subjects but not statistically significant.

**OPG/RANKL**

OPG is a soluble tumor necrosis factor receptor superfamily member originally discovered in bone[73,74]. It is an anti-resorptive cytokine that works by binding and neutralizing the receptor activator for RANKL. RANKL is a molecule that induces osteoclast differentiation and activity[73,74]. The OPG/RANKL axis is also linked to the regulation of glucose homeostasis[75,76]. In detail, hyperglycemia downregulates RANKL expression, which inhibits the differentiation and activity of osteoclasts[73,76].

The duration of diabetes seems to negatively affect bone metabolism, but poor glycemic control (hemoglobin A1c ≥ 7.5%) has also been shown to be associated with an increased risk of fracture[77]. Decreased levels of RANKL have been reported in diabetic patients compared to healthy subjects[78]. This seems to be due to the increased number of immature osteoblasts and osteoclasts[79]. Other authors have reported that serum RANKL levels are reduced and OPG increased in diabetic patients with respect to nondiabetics and prediabetic subjects[80,81].

Furthermore, it has also been reported that high RANKL levels are related to a significantly increased risk of T2D development[82]. However, other authors did not measure significant differences in RANKL levels between patients with T2D and controls[29]. Human osteoblast cultures from cancellous bone biopsies of diabetic patients displayed a decreased RANKL/OPG ratio compared to the controls, suggesting that the bone turnover process is suppressed[83].

***Osteonectin***

Osteonectin is produced by osteoblasts and high osteonectin serum levels represent a marker of bone formation[84]. Osteonectin induces osteoblast differentiation, commitment and survival. *In vivo*, osteonectin-knock out and haploinsufficient mice show osteopenia with low bone turnover, a decreased number of osteoblasts as well as a reduced bone formation rate[85,86]. Additionally, Dole *et al*[87] reported that a single nucleotide polymorphism in the 3’ untranslated region of osteonectin determined variability in bone mass by modulating its expression. Patients with albuminuria had significantly higher levels of osteonectin compared with normoalbuminuric patients[88].

**T2D AND BONE-KIDNEY CROSS-TALK: THE ROLE OF BONE-DERIVED HORMONES**

Chronic kidney disease (CKD) represents a serious complication of T2D and impacts 25%-40% of the diabetic population[89], thus leading to end stage renal disease with the need for dialysis or kidney transplantation[90]. Although kidney replacement therapy improves long-term survival and quality of life in CKD patients, this survival highlights bone fragility as an emerging complication[91]. In a large cohort of patients with CKD followed between 1990 and 1999, Bal *et al*[92] demonstrated that the fracture risk was higher with a prolonged period of dialysis before transplantation, and both epidermal growth factor receptor decrease and albuminuria increase were considered important risk factors for fracture[93]. Bone fragility in CKD patients is dependent on several risk factors, and literature data demonstrate the impact of age, race (Caucasian) and sex, low body mass index < 23 kg/m2, glucocorticoid duration and immunosuppressive agents[94]. However, in addition to the described factors and dialysis vintage, diabetes and pancreas replacement therapy are also important risk factors for bone fragility[95,96].

In 2009, the Clinical Practice Guidelines for the Diagnosis, Evaluation, Prevention, and Treatment of CKD-Mineral and Bone Disorder (CKD-MBD) were originally published by Kidney Disease: Improving Global Outcomes[97]. This clinical syndrome defines a systemic disorder in CKD patients responsible for abnormalities in mineral metabolism, bone remodeling and vascular calcification. Despite the completion of several key clinical trials since the 2009 publication of the CKD-MBD guidelines, large gaps in the knowledge still remain[98]. Prospective studies are needed to determine the value of BMD and bone biomarkers as predictors of fractures[99] as well as the impact of different therapeutic approaches on bone fragility, especially in patients with both diabetes and kidney disease. Recent studies have demonstrated that CKD patients with T2D are at increased risk of bone diseases[100], which could involve FGF23.

***FGF23***

Ribeiro *et al*[101] described how the FGF23/klotho axis is a predictive factor for fractures in patients with T2D with early CKD and demonstrated that α-klotho and FGF23 independently influenced the occurrence of bone fractures. FGF23 is a bone-derived hormone secreted by osteocytes that regulates phosphate and vitamin D metabolism. It acts in the kidney through FGF receptors and klotho, thus preventing renal tubular reabsorption of phosphorus. FGF23 plays an important role in the development of bone and mineral disorders, and many studies over recent years, including patients with CKD and diabetes, have demonstrated that FGF23 levels increase in CKD patients and have an impact on bone disease, cardiovascular disease and all causes of mortality[102]. FGF23 can also induce secondary hyperparathyroidism by increasing the 24-hydroxylation of vitamin D, and these changes are associated with an increased risk of fracture in dialysis[103]. FGF23 levels are also further raised in CKD patients with diabetes who had had a previous fracture[101], thus underlying the association of a history of prior fracture with increased risk of hip fracture, as observed in all dialysis patients[104]. Moreover, FGF23 may also promote insulin secretion and insulin resistance[105], thus influencing the risk of adverse outcomes, especially under CKD conditions[106]. Thus FGF23 could represent a potential biomarker for CKD progression in diabetes[107] and be associated with multiple risk factors[108], including bone fragility.

FGF23 signaling on target tissues is mediated by FGF receptors and klotho, which functions as a coreceptor to increase the binding affinity of FGF23 for FGF receptors. Klotho can also circulate as a secreted protein and a physiologically active hormone. It has been demonstrated that insulin can stimulate the release of klotho by inducing the cleavage of the extracellular domain of klotho by ADAM10 and ADAM17 in the kidney[109]. Cleaved klotho can thus regulate both the phosphorus and calcium metabolism in the kidney and mineral homeostasis in the body through 1-alpha hydroxylase activity as well as parathyroid hormone and FGF23 secretion[110]. Klotho expression is significantly reduced by several kidney injuries such as glomerulonephritis, acute kidney injury, ischemia/reperfusion injury and delayed graft function[111,112], chronic allograft dysfunction[113,114] and renal cell carcinoma[115]. Low klotho levels are also associated with accelerated aging that can promote dysregulated mineral metabolism and osteoporosis. Thus, reduced klotho levels are considered early factors in the development of CKD-MBD[116,117]. Klotho levels are also compromised in patients with early CKD and diabetes[101], while lower levels of klotho seem to be an independent predictive factor for bone fracture[101].

***Sclerostin and OC***

The presence of diabetes may also increase sclerostin, an osteocyte-specific protein that inhibits bone formation, and higher serum sclerostin levels are associated with increased fracture rates[118]. Thus, sclerostin has been described as an important factor contributing to CKD-MBD[119]. In diabetic patients with CKD, sclerostin levels start to increase in the CKD-G3 stage, while patients in the CKD-G4/5 stages have dramatically increased levels of circulating sclerostin[120].

OC is another bone-derived hormone whose levels reflect the ability of osteoblasts to form bones[121]. OC is directly associated with glucose metabolism and experimental models show that OC can increase insulin production by pancreatic β cells and insulin sensitivity in peripheral tissues[122]. Moreover, insulin receptor signaling increases the production of OC in osteoblasts[123]. OC levels have been recently associated with the risk of incident diabetes and kidney complications, while increased levels have been described in CKD patients[124,125]. In early CKD patients with diabetes, OC levels independently influence the occurrence of bone fracture[101]. However, further studies are needed to confirm the specific role of OC in the context of diabetes and CKD.

Further research is also needed to assess the diagnostic and prognostic value of these bone turnover biomarkers in the field of CKD-MBD in the context of diabetes. However, the described hormones represent important factors for the development of bone diseases in the context of CKD and may be considered as targets for future clinical trials.

**CONCLUSION**

The studies reported in the present review describe altered bone quality and the possible mechanisms underlying its pathophysiology. Patients with T2D frequently display bone fragility, which is often an underdiagnosed condition in these subjects. The understanding of its pathophysiology is an important issue as it could suggest possible interventions for the prevention of poor bone quality in T2D. Additionally, the discovery of its pathophysiology could help to target these pathways when bone disease is clearly evident. Thus, the simultaneous use of anti-diabetic drugs and bone treating agents could help to ameliorate the quality of life of patients with T2D. This issue is of particular interest considering the life extension observed. Nevertheless, the possible interventions to improve bone quality in T2D require further investigation, which could determine different treatment approaches through personalized medicine.

**REFERENCES**

1 **Mayer-Davis EJ**, Lawrence JM, Dabelea D, Divers J, Isom S, Dolan L, Imperatore G, Linder B, Marcovina S, Pettitt DJ, Pihoker C, Saydah S, Wagenknecht L; SEARCH for Diabetes in Youth Study. Incidence Trends of Type 1 and Type 2 Diabetes among Youths, 2002-2012. *N Engl J Med* 2017; **376**: 1419-1429 [PMID: 28402773 DOI: 10.1056/NEJMoa1610187]

2 **Sayyed A**. International Diabetes Federation Diabetes Atlas – 10th Edition. [cited 40 April 2022]. Available from: https://www.metabolichealthdigest.com/international-diabetes-federation-diabetes-atlas-10th-edition/

3 **Lynch JL**, Barrientos-Pérez M, Hafez M, Jalaludin MY, Kovarenko M, Rao PV, Weghuber D. Country-Specific Prevalence and Incidence of Youth-Onset Type 2 Diabetes: A Narrative Literature Review. *Ann Nutr Metab* 2020; **76**: 289-296 [PMID: 32980841 DOI: 10.1159/000510499]

4 **Lascar N**, Brown J, Pattison H, Barnett AH, Bailey CJ, Bellary S. Type 2 diabetes in adolescents and young adults. *Lancet Diabetes Endocrinol* 2018; **6**: 69-80 [PMID: 28847479 DOI: 10.1016/S2213-8587(17)30186-9]

5 **Gungor N**, Bacha F, Saad R, Janosky J, Arslanian S. Youth type 2 diabetes: insulin resistance, beta-cell failure, or both? *Diabetes Care* 2005; **28**: 638-644 [PMID: 15735201 DOI: 10.2337/diacare.28.3.638]

6 **Druet C**, Tubiana-Rufi N, Chevenne D, Rigal O, Polak M, Levy-Marchal C. Characterization of insulin secretion and resistance in type 2 diabetes of adolescents. *J Clin Endocrinol Metab* 2006; **91**: 401-404 [PMID: 16291705 DOI: 10.1210/jc.2005-1672]

7 **Zuckerman Levin N**, Cohen M, Phillip M, Tenenbaum A, Koren I, Tenenbaum-Rakover Y, Admoni O, Hershkovitz E, Haim A, Mazor Aronovitch K, Zangen D, Strich D, Brener A, Yeshayahu Y, Schon Y, Rachmiel M, Ben-Ari T, Levy-Khademi F, Tibi R, Weiss R, Lebenthal Y, Pinhas-Hamiel O, Shehadeh N. Youth-onset type 2 diabetes in Israel: A national cohort. *Pediatr Diabetes* 2022; **23**: 649-659 [PMID: 35521999 DOI: 10.1111/pedi.13351]

8 **Thrailkill KM**, Lumpkin CK Jr, Bunn RC, Kemp SF, Fowlkes JL. Is insulin an anabolic agent in bone? Dissecting the diabetic bone for clues. *Am J Physiol Endocrinol Metab* 2005; **289**: E735-E745 [PMID: 16215165 DOI: 10.1152/ajpendo.00159.2005]

9 **Bonds DE**, Larson JC, Schwartz AV, Strotmeyer ES, Robbins J, Rodriguez BL, Johnson KC, Margolis KL. Risk of fracture in women with type 2 diabetes: the Women's Health Initiative Observational Study. *J Clin Endocrinol Metab* 2006; **91**: 3404-3410 [PMID: 16804043 DOI: 10.1210/jc.2006-0614]

10 **Ma L**, Oei L, Jiang L, Estrada K, Chen H, Wang Z, Yu Q, Zillikens MC, Gao X, Rivadeneira F. Association between bone mineral density and type 2 diabetes mellitus: a meta-analysis of observational studies. *Eur J Epidemiol* 2012; **27**: 319-332 [PMID: 22451239 DOI: 10.1007/s10654-012-9674-x]

11 **Leslie WD**, Aubry-Rozier B, Lamy O, Hans D; Manitoba Bone Density Program. TBS (trabecular bone score) and diabetes-related fracture risk. *J Clin Endocrinol Metab* 2013; **98**: 602-609 [PMID: 23341489 DOI: 10.1210/jc.2012-3118]

12 **Patsch JM**, Burghardt AJ, Yap SP, Baum T, Schwartz AV, Joseph GB, Link TM. Increased cortical porosity in type 2 diabetic postmenopausal women with fragility fractures. *J Bone Miner Res* 2013; **28**: 313-324 [PMID: 22991256 DOI: 10.1002/jbmr.1763]

13 **Heilmeier U**, Cheng K, Pasco C, Parrish R, Nirody J, Patsch JM, Zhang CA, Joseph GB, Burghardt AJ, Schwartz AV, Link TM, Kazakia G. Cortical bone laminar analysis reveals increased midcortical and periosteal porosity in type 2 diabetic postmenopausal women with history of fragility fractures compared to fracture-free diabetics. *Osteoporos Int* 2016; **27**: 2791-2802 [PMID: 27154435 DOI: 10.1007/s00198-016-3614-7]

14 **Burghardt AJ**, Issever AS, Schwartz AV, Davis KA, Masharani U, Majumdar S, Link TM. High-resolution peripheral quantitative computed tomographic imaging of cortical and trabecular bone microarchitecture in patients with type 2 diabetes mellitus. *J Clin Endocrinol Metab* 2010; **95**: 5045-5055 [PMID: 20719835 DOI: 10.1210/jc.2010-0226]

15 **Yu EW**, Putman MS, Derrico N, Abrishamanian-Garcia G, Finkelstein JS, Bouxsein ML. Defects in cortical microarchitecture among African-American women with type 2 diabetes. *Osteoporos Int* 2015; **26**: 673-679 [PMID: 25398431 DOI: 10.1007/s00198-014-2927-7]

16 **Samakkarnthai P**, Sfeir JG, Atkinson EJ, Achenbach SJ, Wennberg PW, Dyck PJ, Tweed AJ, Volkman TL, Amin S, Farr JN, Vella A, Drake MT, Khosla S. Determinants of Bone Material Strength and Cortical Porosity in Patients with Type 2 Diabetes Mellitus. *J Clin Endocrinol Metab* 2020; **105** [PMID: 32556277 DOI: 10.1210/clinem/dgaa388]

17 **Samelson EJ**, Demissie S, Cupples LA, Zhang X, Xu H, Liu CT, Boyd SK, McLean RR, Broe KE, Kiel DP, Bouxsein ML. Diabetes and Deficits in Cortical Bone Density, Microarchitecture, and Bone Size: Framingham HR-pQCT Study. *J Bone Miner Res* 2018; **33**: 54-62 [PMID: 28929525 DOI: 10.1002/jbmr.3240]

18 **Paccou J**, Ward KA, Jameson KA, Dennison EM, Cooper C, Edwards MH. Bone Microarchitecture in Men and Women with Diabetes: The Importance of Cortical Porosity. *Calcif Tissue Int* 2016; **98**: 465-473 [PMID: 26686695 DOI: 10.1007/s00223-015-0100-8]

19 **Shanbhogue VV**, Hansen S, Frost M, Jørgensen NR, Hermann AP, Henriksen JE, Brixen K. Compromised cortical bone compartment in type 2 diabetes mellitus patients with microvascular disease. *Eur J Endocrinol* 2016; **174**: 115-124 [PMID: 26537860 DOI: 10.1530/EJE-15-0860]

20 **Farr JN**, Drake MT, Amin S, Melton LJ 3rd, McCready LK, Khosla S. In vivo assessment of bone quality in postmenopausal women with type 2 diabetes. *J Bone Miner Res* 2014; **29**: 787-795 [PMID: 24123088 DOI: 10.1002/jbmr.2106]

21 **Shu A**, Yin MT, Stein E, Cremers S, Dworakowski E, Ives R, Rubin MR. Bone structure and turnover in type 2 diabetes mellitus. *Osteoporos Int* 2012; **23**: 635-641 [PMID: 21424265 DOI: 10.1007/s00198-011-1595-0]

22 **Furst JR**, Bandeira LC, Fan WW, Agarwal S, Nishiyama KK, McMahon DJ, Dworakowski E, Jiang H, Silverberg SJ, Rubin MR. Advanced Glycation Endproducts and Bone Material Strength in Type 2 Diabetes. *J Clin Endocrinol Metab* 2016; **101**: 2502-2510 [PMID: 27115060 DOI: 10.1210/jc.2016-1437]

23 **Nilsson AG**, Sundh D, Johansson L, Nilsson M, Mellström D, Rudäng R, Zoulakis M, Wallander M, Darelid A, Lorentzon M. Type 2 Diabetes Mellitus Is Associated With Better Bone Microarchitecture But Lower Bone Material Strength and Poorer Physical Function in Elderly Women: A Population-Based Study. *J Bone Miner Res* 2017; **32**: 1062-1071 [PMID: 27943408 DOI: 10.1002/jbmr.3057]

24 **Starup-Linde J**, Vestergaard P. Biochemical bone turnover markers in diabetes mellitus - A systematic review. *Bone* 2016; **82**: 69-78 [PMID: 25722065 DOI: 10.1016/j.bone.2015.02.019]

25 **Tonks KT**, White CP, Center JR, Samocha-Bonet D, Greenfield JR. Bone Turnover Is Suppressed in Insulin Resistance, Independent of Adiposity. *J Clin Endocrinol Metab* 2017; **102**: 1112-1121 [PMID: 28324004 DOI: 10.1210/jc.2016-3282]

26 **Starup-Linde J**. Diabetes, biochemical markers of bone turnover, diabetes control, and bone. *Front Endocrinol (Lausanne)* 2013; **4**: 21 [PMID: 23482417 DOI: 10.3389/fendo.2013.00021]

27 **Starup-Linde J**, Lykkeboe S, Handberg A, Vestergaard P, Høyem P, Fleischer J, Hansen TK, Poulsen PL, Laugesen E. Glucose variability and low bone turnover in people with type 2 diabetes. *Bone* 2021; **153**: 116159 [PMID: 34461287 DOI: 10.1016/j.bone.2021.116159]

28 **Starup-Linde J**, Lykkeboe S, Gregersen S, Hauge EM, Langdahl BL, Handberg A, Vestergaard P. Differences in biochemical bone markers by diabetes type and the impact of glucose. *Bone* 2016; **83**: 149-155 [PMID: 26555635 DOI: 10.1016/j.bone.2015.11.004]

29 **Hygum K**, Starup-Linde J, Harsløf T, Vestergaard P, Langdahl BL. MECHANISMS IN ENDOCRINOLOGY: Diabetes mellitus, a state of low bone turnover - a systematic review and meta-analysis. *Eur J Endocrinol* 2017; **176**: R137-R157 [PMID: 28049653 DOI: 10.1530/EJE-16-0652]

30 **Chen Y**, Zhang W, Chen C, Wang Y, Wang N, Lu Y. Thyroid and bone turnover markers in type 2 diabetes: results from the METAL study. *Endocr Connect* 2022; **11** [PMID: 35196256 DOI: 10.1530/EC-21-0484]

31 **Zha KX**, An ZM, Ge SH, Cai J, Zhou Y, Ying R, Zhou J, Gu T, Guo H, Zhao Y, Wang NJ, Lu YL. FSH may mediate the association between HbA1c and bone turnover markers in postmenopausal women with type 2 diabetes. *J Bone Miner Metab* 2022; **40**: 468-477 [PMID: 35059887 DOI: 10.1007/s00774-021-01301-7]

32 **Barrett EJ**, Liu Z, Khamaisi M, King GL, Klein R, Klein BEK, Hughes TM, Craft S, Freedman BI, Bowden DW, Vinik AI, Casellini CM. Diabetic Microvascular Disease: An Endocrine Society Scientific Statement. *J Clin Endocrinol Metab* 2017; **102**: 4343-4410 [PMID: 29126250 DOI: 10.1210/jc.2017-01922]

33 **Bartl R**, Moser W, Burkhardt R, Sandel P, Kamke W, Mähr G, Adelmann BC. [Diabetic osteomyelopathy: histobioptic data of bone and bone marrow in diabetes mellitus (author's transl)]. *Klin Wochenschr* 1978; **56**: 743-754 [PMID: 682529 DOI: 10.1007/BF01476763]

34 **Cirovic A**, Jadzic J, Djukic D, Djonic D, Zivkovic V, Nikolic S, Djuric M, Milovanovic P. Increased Cortical Porosity, Reduced Cortical Thickness, and Reduced Trabecular and Cortical Microhardness of the Superolateral Femoral Neck Confer the Increased Hip Fracture Risk in Individuals with Type 2 Diabetes. *Calcif Tissue Int* 2022 [PMID: 35871240 DOI: 10.1007/s00223-022-01007-6]

35 **Maamar El Asri M**, Pariente Rodrigo E, Díaz-Salazar de la Flor S, Pini Valdivieso S, Ramos Barrón MC, Olmos Martínez JM, Hernández Hernández JL. Trabecular bone score and 25-hydroxyvitamin D levels in microvascular complications of type 2 diabetes mellitus. *Med Clin (Barc)* 2022; **158**: 308-314 [PMID: 34238580 DOI: 10.1016/j.medcli.2021.04.027]

36 **Chen J**, Hendriks M, Chatzis A, Ramasamy SK, Kusumbe AP. Bone Vasculature and Bone Marrow Vascular Niches in Health and Disease. *J Bone Miner Res* 2020; **35**: 2103-2120 [PMID: 32845550 DOI: 10.1002/jbmr.4171]

37 **Stabley JN**, Prisby RD, Behnke BJ, Delp MD. Type 2 diabetes alters bone and marrow blood flow and vascular control mechanisms in the ZDF rat. *J Endocrinol* 2015; **225**: 47-58 [PMID: 25817711 DOI: 10.1530/JOE-14-0514]

38 **Matsumoto T**, Ando N, Tomii T, Uesugi K. Three-dimensional cortical bone microstructure in a rat model of hypoxia-induced growth retardation. *Calcif Tissue Int* 2011; **88**: 54-62 [PMID: 20848090 DOI: 10.1007/s00223-010-9415-7]

39 **Delaisse JM**, Andersen TL, Kristensen HB, Jensen PR, Andreasen CM, Søe K. Re-thinking the bone remodeling cycle mechanism and the origin of bone loss. *Bone* 2020; **141**: 115628 [PMID: 32919109 DOI: 10.1016/j.bone.2020.115628]

40 **Shanbhogue VV**, Hansen S, Frost M, Brixen K, Hermann AP. Bone disease in diabetes: another manifestation of microvascular disease? *Lancet Diabetes Endocrinol* 2017; **5**: 827-838 [PMID: 28546096 DOI: 10.1016/S2213-8587(17)30134-1]

41 **Singh R**, Barden A, Mori T, Beilin L. Advanced glycation end-products: a review. *Diabetologia* 2001; **44**: 129-146 [PMID: 11270668 DOI: 10.1007/s001250051591]

42 **Strollo R**, Rizzo P, Spoletini M, Landy R, Hughes C, Ponchel F, Napoli N, Palermo A, Buzzetti R, Pozzilli P, Nissim A. HLA-dependent autoantibodies against post-translationally modified collagen type II in type 1 diabetes mellitus. *Diabetologia* 2013; **56**: 563-572 [PMID: 23160643 DOI: 10.1007/s00125-012-2780-1]

43 **Hernandez CJ**, Tang SY, Baumbach BM, Hwu PB, Sakkee AN, van der Ham F, DeGroot J, Bank RA, Keaveny TM. Trabecular microfracture and the influence of pyridinium and non-enzymatic glycation-mediated collagen cross-links. *Bone* 2005; **37**: 825-832 [PMID: 16140600 DOI: 10.1016/j.bone.2005.07.019]

44 **Ahmed N**. Advanced glycation endproducts--role in pathology of diabetic complications. *Diabetes Res Clin Pract* 2005; **67**: 3-21 [PMID: 15620429 DOI: 10.1016/j.diabres.2004.09.004]

45 **Epstein S**, Defeudis G, Manfrini S, Napoli N, Pozzilli P; Scientific Committee of the First International Symposium on Diabetes and Bone. Diabetes and disordered bone metabolism (diabetic osteodystrophy): time for recognition. *Osteoporos Int* 2016; **27**: 1931-1951 [PMID: 26980458 DOI: 10.1007/s00198-015-3454-x]

46 **Manigrasso MB**, Juranek J, Ramasamy R, Schmidt AM. Unlocking the biology of RAGE in diabetic microvascular complications. *Trends Endocrinol Metab* 2014; **25**: 15-22 [PMID: 24011512 DOI: 10.1016/j.tem.2013.08.002]

47 **Huebschmann AG**, Regensteiner JG, Vlassara H, Reusch JE. Diabetes and advanced glycoxidation end products. *Diabetes Care* 2006; **29**: 1420-1432 [PMID: 16732039 DOI: 10.2337/dc05-2096]

48 **Sanguineti R**, Puddu A, Mach F, Montecucco F, Viviani GL. Advanced glycation end products play adverse proinflammatory activities in osteoporosis. *Mediators Inflamm* 2014; **2014**: 975872 [PMID: 24771986 DOI: 10.1155/2014/975872]

49 **Saito M**, Fujii K, Soshi S, Tanaka T. 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* 2006; **17**: 986-995 [PMID: 16552468 DOI: 10.1007/s00198-006-0087-0]

50 **Sanguineti R**, Storace D, Monacelli F, Federici A, Odetti P. Pentosidine effects on human osteoblasts in vitro. *Ann N Y Acad Sci* 2008; **1126**: 166-172 [PMID: 18448811 DOI: 10.1196/annals.1433.044]

51 **McCarthy AD**, Uemura T, Etcheverry SB, Cortizo AM. Advanced glycation endproducts interefere with integrin-mediated osteoblastic attachment to a type-I collagen matrix. *Int J Biochem Cell Biol* 2004; **36**: 840-848 [PMID: 15006636 DOI: 10.1016/j.biocel.2003.09.006]

52 **Kume S**, Kato S, Yamagishi S, Inagaki Y, Ueda S, Arima N, Okawa T, Kojiro M, Nagata K. Advanced glycation end-products attenuate human mesenchymal stem cells and prevent cognate differentiation into adipose tissue, cartilage, and bone. *J Bone Miner Res* 2005; **20**: 1647-1658 [PMID: 16059636 DOI: 10.1359/JBMR.050514]

53 **Piccoli A**, Cannata F, Strollo R, Pedone C, Leanza G, Russo F, Greto V, Isgrò C, Quattrocchi CC, Massaroni C, Silvestri S, Vadalà G, Bisogno T, Denaro V, Pozzilli P, Tang SY, Silva MJ, Conte C, Papalia R, Maccarrone M, Napoli N. Sclerostin Regulation, Microarchitecture, and Advanced Glycation End-Products in the Bone of Elderly Women With Type 2 Diabetes. *J Bone Miner Res* 2020; **35**: 2415-2422 [PMID: 32777114 DOI: 10.1002/jbmr.4153]

54 **McCarthy AD**, Etcheverry SB, Cortizo AM. Effect of advanced glycation endproducts on the secretion of insulin-like growth factor-I and its binding proteins: role in osteoblast development. *Acta Diabetol* 2001; **38**: 113-122 [PMID: 11827431 DOI: 10.1007/s005920170007]

55 **Kanazawa I**, Yamaguchi T, Sugimoto T. Serum insulin-like growth factor-I is a marker for assessing the severity of vertebral fractures in postmenopausal women with type 2 diabetes mellitus. *Osteoporos Int* 2011; **22**: 1191-1198 [PMID: 20532480 DOI: 10.1007/s00198-010-1310-6]

56 **Khosla S**, Farr JN, Tchkonia T, Kirkland JL. The role of cellular senescence in ageing and endocrine disease. *Nat Rev Endocrinol* 2020; **16**: 263-275 [PMID: 32161396 DOI: 10.1038/s41574-020-0335-y]

57 **Alcorta DA**, Xiong Y, Phelps D, Hannon G, Beach D, Barrett JC. Involvement of the cyclin-dependent kinase inhibitor p16 (INK4a) in replicative senescence of normal human fibroblasts. *Proc Natl Acad Sci U S A* 1996; **93**: 13742-13747 [PMID: 8943005 DOI: 10.1073/pnas.93.24.13742]

58 **Beauséjour CM**, Krtolica A, Galimi F, Narita M, Lowe SW, Yaswen P, Campisi J. Reversal of human cellular senescence: roles of the p53 and p16 pathways. *EMBO J* 2003; **22**: 4212-4222 [PMID: 12912919 DOI: 10.1093/emboj/cdg417]

59 **Wissler Gerdes EO**, Zhu Y, Tchkonia T, Kirkland JL. Discovery, development, and future application of senolytics: theories and predictions. *FEBS J* 2020; **287**: 2418-2427 [PMID: 32112672 DOI: 10.1111/febs.15264]

60 **Coppé JP**, Desprez PY, Krtolica A, Campisi J. The senescence-associated secretory phenotype: the dark side of tumor suppression. *Annu Rev Pathol* 2010; **5**: 99-118 [PMID: 20078217 DOI: 10.1146/annurev-pathol-121808-102144]

61 **Acosta JC**, Banito A, Wuestefeld T, Georgilis A, Janich P, Morton JP, Athineos D, Kang TW, Lasitschka F, Andrulis M, Pascual G, Morris KJ, Khan S, Jin H, Dharmalingam G, Snijders AP, Carroll T, Capper D, Pritchard C, Inman GJ, Longerich T, Sansom OJ, Benitah SA, Zender L, Gil J. A complex secretory program orchestrated by the inflammasome controls paracrine senescence. *Nat Cell Biol* 2013; **15**: 978-990 [PMID: 23770676 DOI: 10.1038/ncb2784]

62 **Aguayo-Mazzucato C**, Andle J, Lee TB Jr, Midha A, Talemal L, Chipashvili V, Hollister-Lock J, van Deursen J, Weir G, Bonner-Weir S. Acceleration of β Cell Aging Determines Diabetes and Senolysis Improves Disease Outcomes. *Cell Metab* 2019; **30**: 129-142.e4 [PMID: 31155496 DOI: 10.1016/j.cmet.2019.05.006]

63 **Eckhardt BA**, Rowsey JL, Thicke BS, Fraser DG, O'Grady KL, Bondar OP, Hines JM, Singh RJ, Thoreson AR, Rakshit K, Lagnado AB, Passos JF, Vella A, Matveyenko AV, Khosla S, Monroe DG, Farr JN. Accelerated osteocyte senescence and skeletal fragility in mice with type 2 diabetes. *JCI Insight* 2020; **5** [PMID: 32267250 DOI: 10.1172/jci.insight.135236]

64 **Figeac F**, Tencerova M, Ali D, Andersen TL, Appadoo DRC, Kerckhofs G, Ditzel N, Kowal JM, Rauch A, Kassem M. Impaired Bone Fracture Healing in Type 2 Diabetes Is Caused by Defective Functions of Skeletal Progenitor Cells. *Stem Cells* 2022; **40**: 149-164 [PMID: 35257177 DOI: 10.1093/stmcls/sxab011]

65 **Heilmeier U**, Hackl M, Schroeder F, Torabi S, Kapoor P, Vierlinger K, Eiriksdottir G, Gudmundsson EF, Harris TB, Gudnason V, Link TM, Grillari J, Schwartz AV. Circulating serum microRNAs including senescent miR-31-5p are associated with incident fragility fractures in older postmenopausal women with type 2 diabetes mellitus. *Bone* 2022; **158**: 116308 [PMID: 35066213 DOI: 10.1016/j.bone.2021.116308]

66 **Brunetti G**, D'Amato G, Chiarito M, Tullo A, Colaianni G, Colucci S, Grano M, Faienza MF. An update on the role of RANKL-RANK/osteoprotegerin and WNT-ß-catenin signaling pathways in pediatric diseases. *World J Pediatr* 2019; **15**: 4-11 [PMID: 30343446 DOI: 10.1007/s12519-018-0198-7]

67 **Kim JY**, Lee SK, Jo KJ, Song DY, Lim DM, Park KY, Bonewald LF, Kim BJ. Exendin-4 increases bone mineral density in type 2 diabetic OLETF rats potentially through the down-regulation of SOST/sclerostin in osteocytes. *Life Sci* 2013; **92**: 533-540 [PMID: 23357248 DOI: 10.1016/j.lfs.2013.01.001]

68 **Nuche-Berenguer B**, Moreno P, Portal-Nuñez S, Dapía S, Esbrit P, Villanueva-Peñacarrillo ML. Exendin-4 exerts osteogenic actions in insulin-resistant and type 2 diabetic states. *Regul Pept* 2010; **159**: 61-66 [PMID: 19586609 DOI: 10.1016/j.regpep.2009.06.010]

69 **Gennari L**, Merlotti D, Valenti R, Ceccarelli E, Ruvio M, Pietrini MG, Capodarca C, Franci MB, Campagna MS, Calabrò A, Cataldo D, Stolakis K, Dotta F, Nuti R. Circulating sclerostin levels and bone turnover in type 1 and type 2 diabetes. *J Clin Endocrinol Metab* 2012; **97**: 1737-1744 [PMID: 22399511 DOI: 10.1210/jc.2011-2958]

70 **Gaudio A**, Privitera F, Battaglia K, Torrisi V, Sidoti MH, Pulvirenti I, Canzonieri E, Tringali G, Fiore CE. Sclerostin levels associated with inhibition of the Wnt/β-catenin signaling and reduced bone turnover in type 2 diabetes mellitus. *J Clin Endocrinol Metab* 2012; **97**: 3744-3750 [PMID: 22855334 DOI: 10.1210/jc.2012-1901]

71 **Yamamoto M**, Yamauchi M, Sugimoto T. Elevated sclerostin levels are associated with vertebral fractures in patients with type 2 diabetes mellitus. *J Clin Endocrinol Metab* 2013; **98**: 4030-4037 [PMID: 23894157 DOI: 10.1210/jc.2013-2143]

72 **Heilmeier U**, Carpenter DR, Patsch JM, Harnish R, Joseph GB, Burghardt AJ, Baum T, Schwartz AV, Lang TF, Link TM. Volumetric femoral BMD, bone geometry, and serum sclerostin levels differ between type 2 diabetic postmenopausal women with and without fragility fractures. *Osteoporos Int* 2015; **26**: 1283-1293 [PMID: 25582311 DOI: 10.1007/s00198-014-2988-7]

73 **Wang Y**, Liu Y, Huang Z, Chen X, Zhang B. The roles of osteoprotegerin in cancer, far beyond a bone player. *Cell Death Discov* 2022; **8**: 252 [PMID: 35523775 DOI: 10.1038/s41420-022-01042-0]

74 **Takegahara N**, Kim H, Choi Y. RANKL biology. *Bone* 2022; **159**: 116353 [PMID: 35181574 DOI: 10.1016/j.bone.2022.116353]

75 **Wittrant Y**, Gorin Y, Woodruff K, Horn D, Abboud HE, Mohan S, Abboud-Werner SL. High d(+)glucose concentration inhibits RANKL-induced osteoclastogenesis. *Bone* 2008; **42**: 1122-1130 [PMID: 18378205 DOI: 10.1016/j.bone.2008.02.006]

76 **Duan P**, Yang M, Wei M, Liu J, Tu P. Serum Osteoprotegerin Is a Potential Biomarker of Insulin Resistance in Chinese Postmenopausal Women with Prediabetes and Type 2 Diabetes. *Int J Endocrinol* 2017; **2017**: 8724869 [PMID: 28255300 DOI: 10.1155/2017/8724869]

77 **Dede AD**, Tournis S, Dontas I, Trovas G. Type 2 diabetes mellitus and fracture risk. *Metabolism* 2014; **63**: 1480-1490 [PMID: 25284729 DOI: 10.1016/j.metabol.2014.09.002]

78 **Secchiero P**, Corallini F, Pandolfi A, Consoli A, Candido R, Fabris B, Celeghini C, Capitani S, Zauli G. An increased osteoprotegerin serum release characterizes the early onset of diabetes mellitus and may contribute to endothelial cell dysfunction. *Am J Pathol* 2006; **169**: 2236-2244 [PMID: 17148684 DOI: 10.2353/ajpath.2006.060398]

79 **Sassi F**, Buondonno I, Luppi C, Spertino E, Stratta E, Di Stefano M, Ravazzoli M, Isaia G, Trento M, Passera P, Porta M, Isaia GC, D'Amelio P. Type 2 diabetes affects bone cells precursors and bone turnover. *BMC Endocr Disord* 2018; **18**: 55 [PMID: 30089481 DOI: 10.1186/s12902-018-0283-x]

80 **Panezai J**, Altamash M, Engstrӧm PE, Larsson A. Association of Glycated Proteins with Inflammatory Proteins and Periodontal Disease Parameters. *J Diabetes Res* 2020; **2020**: 6450742 [PMID: 31998807 DOI: 10.1155/2020/6450742]

81 **Cherian P**, Al-Khairi I, Jamal M, Al-Sabah S, Ali H, Dsouza C, Alshawaf E, Al-Ali W, Al-Khaledi G, Al-Mulla F, Abu-Farha M, Abubaker J. Association Between Factors Involved in Bone Remodeling (Osteoactivin and OPG) With Plasma Levels of Irisin and Meteorin-Like Protein in People With T2D and Obesity. *Front Endocrinol (Lausanne)* 2021; **12**: 752892 [PMID: 34777249 DOI: 10.3389/fendo.2021.752892]

82 **Kiechl S**, Wittmann J, Giaccari A, Knoflach M, Willeit P, Bozec A, Moschen AR, Muscogiuri G, Sorice GP, Kireva T, Summerer M, Wirtz S, Luther J, Mielenz D, Billmeier U, Egger G, Mayr A, Oberhollenzer F, Kronenberg F, Orthofer M, Penninger JM, Meigs JB, Bonora E, Tilg H, Willeit J, Schett G. Blockade of receptor activator of nuclear factor-κB (RANKL) signaling improves hepatic insulin resistance and prevents development of diabetes mellitus. *Nat Med* 2013; **19**: 358-363 [PMID: 23396210 DOI: 10.1038/nm.3084]

83 **Miranda C**, Giner M, Montoya MJ, Vázquez MA, Miranda MJ, Pérez-Cano R. Influence of high glucose and advanced glycation end-products (ages) levels in human osteoblast-like cells gene expression. *BMC Musculoskelet Disord* 2016; **17**: 377 [PMID: 27582133 DOI: 10.1186/s12891-016-1228-z]

84 **Rosset EM**, Bradshaw AD. SPARC/osteonectin in mineralized tissue. *Matrix Biol* 2016; **52-54**: 78-87 [PMID: 26851678 DOI: 10.1016/j.matbio.2016.02.001]

85 **Boskey AL**, Moore DJ, Amling M, Canalis E, Delany AM. Infrared analysis of the mineral and matrix in bones of osteonectin-null mice and their wildtype controls. *J Bone Miner Res* 2003; **18**: 1005-1011 [PMID: 12817752 DOI: 10.1359/jbmr.2003.18.6.1005]

86 **Delany AM**, Amling M, Priemel M, Howe C, Baron R, Canalis E. Osteopenia and decreased bone formation in osteonectin-deficient mice. *J Clin Invest* 2000; **105**: 915-923 [PMID: 10749571 DOI: 10.1172/JCI7039]

87 **Dole NS**, Kapinas K, Kessler CB, Yee SP, Adams DJ, Pereira RC, Delany AM. A single nucleotide polymorphism in osteonectin 3' untranslated region regulates bone volume and is targeted by miR-433. *J Bone Miner Res* 2015; **30**: 723-732 [PMID: 25262637 DOI: 10.1002/jbmr.2378]

88 **Xu L**, Niu M, Yu W, Xia W, Gong F, Wang O. Associations between FGF21, osteonectin and bone turnover markers in type 2 diabetic patients with albuminuria. *J Diabetes Complications* 2017; **31**: 583-588 [PMID: 27916484 DOI: 10.1016/j.jdiacomp.2016.11.012]

89 **Afkarian M**, Zelnick LR, Hall YN, Heagerty PJ, Tuttle K, Weiss NS, de Boer IH. Clinical Manifestations of Kidney Disease Among US Adults With Diabetes, 1988-2014. *JAMA* 2016; **316**: 602-610 [PMID: 27532915 DOI: 10.1001/jama.2016.10924]

90 **Zhou Z**, Chaudhari P, Yang H, Fang AP, Zhao J, Law EH, Wu EQ, Jiang R, Seifeldin R. Healthcare Resource Use, Costs, and Disease Progression Associated with Diabetic Nephropathy in Adults with Type 2 Diabetes: A Retrospective Observational Study. *Diabetes Ther* 2017; **8**: 555-571 [PMID: 28361464 DOI: 10.1007/s13300-017-0256-5]

91 **Jepson C**, Hsu JY, Fischer MJ, Kusek JW, Lash JP, Ricardo AC, Schelling JR, Feldman HI; Chronic Renal Insufficiency Cohort (CRIC) Study Investigators. Incident Type 2 Diabetes Among Individuals With CKD: Findings From the Chronic Renal Insufficiency Cohort (CRIC) Study. *Am J Kidney Dis* 2019; **73**: 72-81 [PMID: 30177484 DOI: 10.1053/j.ajkd.2018.06.017]

92 **Ball AM**, Gillen DL, Sherrard D, Weiss NS, Emerson SS, Seliger SL, Kestenbaum BR, Stehman-Breen C. Risk of hip fracture among dialysis and renal transplant recipients. *JAMA* 2002; **288**: 3014-3018 [PMID: 12479766 DOI: 10.1001/jama.288.23.3014]

93 **Daya N**, Voskertchian A, Schneider ALC, Ballew S, McAdams DeMarco M, Coresh J, Appel LJ, Selvin E, Grams ME. Kidney Function and Fracture Risk: The Atherosclerosis Risk in Communities (ARIC) Study. *Am J Kidney Dis* 2016; **67**: 218-226 [PMID: 26250781 DOI: 10.1053/j.ajkd.2015.06.020]

94 **Alshayeb HM**, Josephson MA, Sprague SM. CKD-mineral and bone disorder management in kidney transplant recipients. *Am J Kidney Dis* 2013; **61**: 310-325 [PMID: 23102732 DOI: 10.1053/j.ajkd.2012.07.022]

95 **Romero-Díaz C**, Duarte-Montero D, Gutiérrez-Romero SA, Mendivil CO. Diabetes and Bone Fragility. *Diabetes Ther* 2021; **12**: 71-86 [PMID: 33185853 DOI: 10.1007/s13300-020-00964-1]

96 **Hofbauer LC**, Busse B, Eastell R, Ferrari S, Frost M, Müller R, Burden AM, Rivadeneira F, Napoli N, Rauner M. Bone fragility in diabetes: novel concepts and clinical implications. *Lancet Diabetes Endocrinol* 2022; **10**: 207-220 [PMID: 35101185 DOI: 10.1016/S2213-8587(21)00347-8]

97 **Kidney Disease: Improving Global Outcomes (KDIGO) CKD-MBD Work Group**. KDIGO clinical practice guideline for the diagnosis, evaluation, prevention, and treatment of Chronic Kidney Disease-Mineral and Bone Disorder (CKD-MBD). *Kidney Int Suppl* 2009: S1-130 [PMID: 19644521 DOI: 10.1038/ki.2009.188]

98 **Kidney Disease: Improving Global Outcomes (KDIGO) CKD-MBD Update Work Group**. KDIGO 2017 Clinical Practice Guideline Update for the Diagnosis, Evaluation, Prevention, and Treatment of Chronic Kidney Disease-Mineral and Bone Disorder (CKD-MBD). *Kidney Int Suppl (2011)* 2017; **7**: 1-59 [PMID: 30675420 DOI: 10.1016/j.kisu.2017.04.001]

99 **Ketteler M**, Block GA, Evenepoel P, Fukagawa M, Herzog CA, McCann L, Moe SM, Shroff R, Tonelli MA, Toussaint ND, Vervloet MG, Leonard MB. Executive summary of the 2017 KDIGO Chronic Kidney Disease-Mineral and Bone Disorder (CKD-MBD) Guideline Update: what's changed and why it matters. *Kidney Int* 2017; **92**: 26-36 [PMID: 28646995 DOI: 10.1016/j.kint.2017.04.006]

100 **Ray S**, Beatrice AM, Ghosh A, Pramanik S, Bhattacharjee R, Ghosh S, Raychaudhury A, Mukhopadhyay S, Chowdhury S. Profile of chronic kidney disease related-mineral bone disorders in newly diagnosed advanced predialysis diabetic kidney disease patients: A hospital based cross-sectional study. *Diabetes Metab Syndr* 2017; **11** Suppl 2: S931-S937 [PMID: 28728874 DOI: 10.1016/j.dsx.2017.07.019]

101 **Ribeiro AL**, Mendes F, Carias E, Rato F, Santos N, Neves PL, Silva AP. FGF23-klotho axis as predictive factors of fractures in type 2 diabetics with early chronic kidney disease. *J Diabetes Complications* 2020; **34**: 107476 [PMID: 31708378 DOI: 10.1016/j.jdiacomp.2019.107476]

102 **Yeung SMH**, Bakker SJL, Laverman GD, De Borst MH. Fibroblast Growth Factor 23 and Adverse Clinical Outcomes in Type 2 Diabetes: a Bitter-Sweet Symphony. *Curr Diab Rep* 2020; **20**: 50 [PMID: 32857288 DOI: 10.1007/s11892-020-01335-7]

103 **Desbiens LC**, Sidibé A, Ung RV, Fortier C, Munger M, Wang YP, Bisson SK, Marquis K, Agharazii M, Mac-Way F. FGF23-klotho axis, bone fractures, and arterial stiffness in dialysis: a case-control study. *Osteoporos Int* 2018; **29**: 2345-2353 [PMID: 29959497 DOI: 10.1007/s00198-018-4598-2]

104 **Jadoul M**, Albert JM, Akiba T, Akizawa T, Arab L, Bragg-Gresham JL, Mason N, Prutz KG, Young EW, Pisoni RL. Incidence and risk factors for hip or other bone fractures among hemodialysis patients in the Dialysis Outcomes and Practice Patterns Study. *Kidney Int* 2006; **70**: 1358-1366 [PMID: 16929251 DOI: 10.1038/sj.ki.5001754]

105 **Nakashima A**, Yokoyama K, Kawanami D, Ohkido I, Urashima M, Utsunomiya K, Yokoo T. Association between resistin and fibroblast growth factor 23 in patients with type 2 diabetes mellitus. *Sci Rep* 2018; **8**: 13999 [PMID: 30228288 DOI: 10.1038/s41598-018-32432-z]

106 **Takashi Y**, Kawanami D. The Role of Bone-Derived Hormones in Glucose Metabolism, Diabetic Kidney Disease, and Cardiovascular Disorders. *Int J Mol Sci* 2022; **23** [PMID: 35216490 DOI: 10.3390/ijms23042376]

107 **Titan SM**, Zatz R, Graciolli FG, dos Reis LM, Barros RT, Jorgetti V, Moysés RM. FGF-23 as a predictor of renal outcome in diabetic nephropathy. *Clin J Am Soc Nephrol* 2011; **6**: 241-247 [PMID: 20966122 DOI: 10.2215/CJN.04250510]

108 **Silva AP**, Mendes F, Fragoso A, Jeronimo T, Pimentel A, Gundlach K, Büchel J, Santos N, Neves PL. Altered serum levels of FGF-23 and magnesium are independent risk factors for an increased albumin-to-creatinine ratio in type 2 diabetics with chronic kidney disease. *J Diabetes Complications* 2016; **30**: 275-280 [PMID: 26750742 DOI: 10.1016/j.jdiacomp.2015.11.006]

109 **Chen CD**, Podvin S, Gillespie E, Leeman SE, Abraham CR. Insulin stimulates the cleavage and release of the extracellular domain of Klotho by ADAM10 and ADAM17. *Proc Natl Acad Sci U S A* 2007; **104**: 19796-19801 [PMID: 18056631 DOI: 10.1073/pnas.0709805104]

110 **Sakan H**, Nakatani K, Asai O, Imura A, Tanaka T, Yoshimoto S, Iwamoto N, Kurumatani N, Iwano M, Nabeshima Y, Konishi N, Saito Y. Reduced renal α-Klotho expression in CKD patients and its effect on renal phosphate handling and vitamin D metabolism. *PLoS One* 2014; **9**: e86301 [PMID: 24466013 DOI: 10.1371/journal.pone.0086301]

111 **Castellano G**, Intini A, Stasi A, Divella C, Gigante M, Pontrelli P, Franzin R, Accetturo M, Zito A, Fiorentino M, Montinaro V, Lucarelli G, Ditonno P, Battaglia M, Crovace A, Staffieri F, Oortwijn B, van Amersfoort E, Pertosa G, Grandaliano G, Gesualdo L. Complement Modulation of Anti-Aging Factor Klotho in Ischemia/Reperfusion Injury and Delayed Graft Function. *Am J Transplant* 2016; **16**: 325-333 [PMID: 26280899 DOI: 10.1111/ajt.13415]

112 **Mezzolla V**, Pontrelli P, Fiorentino M, Stasi A, Pesce F, Franzin R, Rascio F, Grandaliano G, Stallone G, Infante B, Gesualdo L, Castellano G. Emerging biomarkers of delayed graft function in kidney transplantation. *Transplant Rev (Orlando)* 2021; **35**: 100629 [PMID: 34118742 DOI: 10.1016/j.trre.2021.100629]

113 **Infante B**, Bellanti F, Correale M, Pontrelli P, Franzin R, Leo S, Calvaruso M, Mercuri S, Netti GS, Ranieri E, Brunetti ND, Grandaliano G, Gesualdo L, Serviddio G, Castellano G, Stallone G. mTOR inhibition improves mitochondria function/biogenesis and delays cardiovascular aging in kidney transplant recipients with chronic graft dysfunction. *Aging (Albany NY)* 2021; **13**: 8026-8039 [PMID: 33758105 DOI: 10.18632/aging.202863]

114 **Tataranni T**, Biondi G, Cariello M, Mangino M, Colucci G, Rutigliano M, Ditonno P, Schena FP, Gesualdo L, Grandaliano G. Rapamycin-induced hypophosphatemia and insulin resistance are associated with mTORC2 activation and Klotho expression. *Am J Transplant* 2011; **11**: 1656-1664 [PMID: 21672148 DOI: 10.1111/j.1600-6143.2011.03590.x]

115 **Gigante M**, Lucarelli G, Divella C, Netti GS, Pontrelli P, Cafiero C, Grandaliano G, Castellano G, Rutigliano M, Stallone G, Bettocchi C, Ditonno P, Gesualdo L, Battaglia M, Ranieri E. Soluble Serum αKlotho Is a Potential Predictive Marker of Disease Progression in Clear Cell Renal Cell Carcinoma. *Medicine (Baltimore)* 2015; **94**: e1917 [PMID: 26559258 DOI: 10.1097/MD.0000000000001917]

116 **Kuro-O M**. The Klotho proteins in health and disease. *Nat Rev Nephrol* 2019; **15**: 27-44 [PMID: 30455427 DOI: 10.1038/s41581-018-0078-3]

117 **Hu MC**, Kuro-o M, Moe OW. Klotho and chronic kidney disease. *Contrib Nephrol* 2013; **180**: 47-63 [PMID: 23652549 DOI: 10.1159/000346778]

118 **Poole KE**, van Bezooijen RL, Loveridge N, Hamersma H, Papapoulos SE, Löwik CW, Reeve J. Sclerostin is a delayed secreted product of osteocytes that inhibits bone formation. *FASEB J* 2005; **19**: 1842-1844 [PMID: 16123173 DOI: 10.1096/fj.05-4221fje]

119 **Figurek A**, Rroji M, Spasovski G. Sclerostin: a new biomarker of CKD-MBD. *Int Urol Nephrol* 2020; **52**: 107-113 [PMID: 31612420 DOI: 10.1007/s11255-019-02290-3]

120 **Kim SH**, Yoon SY, Lim SK, Rhee Y. The effect of renal dysfunction on circulating sclerostin level in patients with type 2 diabetes. *Int J Endocrinol* 2014; **2014**: 715908 [PMID: 25053944 DOI: 10.1155/2014/715908]

121 **Yoshimura N**, Hashimoto T, Sakata K, Morioka S, Kasamatsu T, Cooper C. Biochemical markers of bone turnover and bone loss at the lumbar spine and femoral neck: the Taiji study. *Calcif Tissue Int* 1999; **65**: 198-202 [PMID: 10441650 DOI: 10.1007/s002239900682]

122 **Lee NK**, Sowa H, Hinoi E, Ferron M, Ahn JD, Confavreux C, Dacquin R, Mee PJ, McKee MD, Jung DY, Zhang Z, Kim JK, Mauvais-Jarvis F, Ducy P, Karsenty G. Endocrine regulation of energy metabolism by the skeleton. *Cell* 2007; **130**: 456-469 [PMID: 17693256 DOI: 10.1016/j.cell.2007.05.047]

123 **Wei J**, Ferron M, Clarke CJ, Hannun YA, Jiang H, Blaner WS, Karsenty G. Bone-specific insulin resistance disrupts whole-body glucose homeostasis *via* decreased osteocalcin activation. *J Clin Invest* 2014; **124**: 1-13 [PMID: 24642469 DOI: 10.1172/JCI72323]

124 **Ye X**, Yu R, Jiang F, Hou X, Wei L, Bao Y, Jia W. Osteocalcin and Risks of Incident Diabetes and Diabetic Kidney Disease: A 4.6-Year Prospective Cohort Study. *Diabetes Care* 2022; **45**: 830-836 [PMID: 35090006 DOI: 10.2337/dc21-2113]

125 **Bacchetta J**, Boutroy S, Guebre-Egziabher F, Juillard L, Drai J, Pelletier S, Richard M, Charrié A, Carlier MC, Chapurlat R, Laville M, Fouque D. The relationship between adipokines, osteocalcin and bone quality in chronic kidney disease. *Nephrol Dial Transplant* 2009; **24**: 3120-3125 [PMID: 19515806 DOI: 10.1093/ndt/gfp262]

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**Table 1 Mechanisms of bone fragility in type 2 diabetes**

|  |  |  |
| --- | --- | --- |
| **Cytokines/factors** | **Mechanisms** | **Bone effect** |
| Microvascular disease | Reduced bone vasculature, blood flow and oxygen supply | Increased fracture risk |
| AGEs | Osteoclast and osteoblast alterations | Poor bone quality, impaired biomechanical properties, and occurrence of fracture |
| Senescence pathways | Osteocyte impairment | Reduced biomechanical strength, defective bone microarchitecture and increased risk of fracture |
| Wnt/β-catenin pathway | High levels of sclerostin and DKK1 in T2D. Involvement in CKD-MBD | Impairment of bone cell activity in murine and human models |
| OPG/RANKL | Decreased OPG/RANKL ratio | Suppressed bone turnover |
| Osteonectin | High levels of osteonectin | Albuminuria is linked to higher levels of osteonectin |
| Osteocalcin | Reduced levels in T2D | Decreased bone formation. Bone fracture, involved in T2D and kidney complication |
| FGF23/klotho | High FGF23 and low klotho levels in T2D | Dysregulation of mineral metabolism, bone fractures. FGF23 is linked to bone fragility; reduced klotho levels are predictors for CKD-MBD |

AGEs: Advanced glycation end products; CKD-MBD: Chronic kidney disease-mineral and bone disorder; DKK1: Dickkopf-related protein 1; FGF23: Fibroblast growth factor 23; OPG/RANKL: Osteoprotegerin/receptor-activator of nuclear factor kappa B ligand; T2D: Type 2 diabetes.



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