Low Bone Mineral Density and Its Predictors in Type 1 Diabetic Patients Evaluated by the Classic Statistics and Artificial Neural Network Analysis

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OBJECTIVE—To investigate factors associated with bone mineral density (BMD) in type 1 diabetes, by classic statistic and artificial neural networks.

RESEARCH DESIGN AND METHODS—A total of 175 eugonadal type 1 diabetic patients (age 32.8 ± 8.4 years) and 131 age- and BMI-matched control subjects (age 32.6 ± 4.5 years) were studied. In all subjects, BMI and BMD (as Z score) at the lumbar spine (LS-BMD) and femur (F-BMD) were measured. Daily insulin dose (DID), age at diagnosis, presence of complications, creatinine clearance (ClCr), and HbA1c were determined.

RESULTS—LS- and F-BMD levels were lower in patients (−0.11 ± 2.3 kg/m², DID >0.67 units/kg, and ClCr <88.8 mL/min). The presence of all of these risk factors had a positive predictive value, and their absence had a negative predictive value for low a BMD of 62.9 and 84.2%, respectively. Data were also analyzed using the TWIST system in combination with supervised artificial neural networks and a semantic connectivity map. The TWIST system selected 11 and 12 variables for F-BMD and LS-BMD prediction, which discriminated between high and low BMD with 67 and 68% accuracy, respectively. The connectivity map showed that low BMD at both sites was indirectly connected with HbA1c through chronic complications.

CONCLUSIONS—In type 1 diabetes, low BMD is associated with low BMI and low ClCr and high DID. Chronic complications negatively influence BMD.

Several studies reported a reduction of bone mineral density (BMD) in patients with type 1 diabetes (1). Potential pathogenic mechanisms of type 1 diabetes–related bone damage may include hyperglycemia (2), autoimmune inflammation (3), increased marrow adiposity through increased peroxisome proliferator–activated receptor γ activity (4,5), hypoinsulinemia and hypoamylinemia (6), a deficit of IGF-1 (7) and vitamin D (8), and the nonenzymatic glycosylation of type 1 collagen with subsequent formation of advanced glycation end products (9).

In some studies, the early-onset long duration of the disease has played a role in the type 1 diabetes–associated bone loss (10–14), whereas in other studies, chronic diabetes complications predicted the high risk of fractures in type 1 diabetic patients (12–14). These discordances are probably due to the not homogeneous samples studied (i.e., evaluating eugonadal and hypogonadal together). Moreover, osteoporosis is a multifactorial disease in which different factors and environments interact in nonlinear biological mechanisms, which probably need a special mathematical approach, such as artificial neural networks (ANNs), to be understood.

Because ANNs are artificial adaptive systems, able to modify their internal structure in relation to a function objective, they are particularly suited for solving nonlinear problems. The ability to learn through an adaptive way (i.e., extracting from the available data the information needed to gather a specific task and to generalize the acquired knowledge) makes the ANN model a powerful tool for data analysis (15). Although ANNs have been shown to improve the predictive value of classic statistics in many areas of medicine (16), no studies have investigated the ability of ANNs in predicting low bone mass in type 1 diabetes.

The aim of the current study was to investigate, in a homogeneous sample of type 1 diabetic patients, the factors associated with low BMD, by using ANNs and the classic statistic approach.

RESEARCH DESIGN AND METHODS

Patients
This cross-sectional study was performed in the Republic Clinical Hospital of Medical Rehabilitation (Minsk, Belarus) and the First Minsk City Clinical Hospital (Minsk, Belarus). From 2001 to 2007, 300 consecutive type 1 diabetic patients were evaluated. A total of 175 patients between the ages of 18 and 53 years were enrolled. The exclusion criteria were as follows: presence of severe chronic kidney disease; history of diseases and syndromes, other than type 1 diabetes; associated bone damage may include hyperglycemia (2), autoimmune inflammation (3), increased marrow adiposity through increased peroxisome proliferator–activated receptor γ activity (4,5), hypoinsulinemia and hypoamylinemia (6), a deficit of IGF-1 (7) and vitamin D (8), and the nonenzymatic glycosylation of type 1 collagen with subsequent formation of advanced glycation end products (9).

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diabetes, associated with low BMD (i.e., hyperthyroidism, hyperparathyroidism, intestinal malabsorption, and inflammatory bowel disease); intake of drugs that influence bone metabolism, pregnancy, and lactation period; and menopause or menstrual abnormalities. A total of 151 age-, sex-, and BMI-matched healthy subjects served as control subjects.

Methods

In all patients, height, weight, BMI, the presence and the degree of diabetes complications (neuropathy, retinopathy, and nephropathy), HbA1c, and BMD by dual-energy X-ray absorptiometry were assessed.

Diabetic neuropathy evaluation was based on symptoms, quantitative sensory testing (temperature, vibration, and pressure perception), and quantitative motor testing (patellar and ankle reflexes). On the basis of fundoscopic examination, diabetic retinopathy was categorized as nonproliferative, preproliferative, and proliferative (17). Diabetic nephropathy was assessed by measuring microalbumin in 24-h urine (normal values <30 mg/day) at the enrollment and after 3–6 months. Microalbuminuria and macroalbuminuria were diagnosed if albumin excretion rate was between 30 and 300 or >300 mg/day, respectively (17).

Blood samples were taken in the morning after a 10-h fast before the insulin injection, centrifuged, and stored at −70°C until analysis. HbA1c and serum creatinine were measured by high-performance liquid chromatography with a D10 autoanalyzer (Bio-Rad, Hercules, CA) and by an HITACHI 911 analyzer (Roche Diagnostics, Mannheim, Germany), respectively. Creatinine clearance (ClCr) was calculated with the Cockcroft-Gault equation (17).

BMD was assessed by dual-energy X-ray absorptiometry (Sophos L-XRA; Sophos, France) at the spine (L2–L4) and at the femur (coefficient of variation for both <1.5%) and was expressed as SD units (Z values) in relation to the age-matched reference population.

Statistical analysis

Classical statistics. Statistical analysis was performed using the SPSS version 17.0 statistical package (SPSS, Chicago, IL). The results are expressed as means ± SD. Categorical and continuous variables were compared by the χ² test and one-way ANOVA or Bonferroni test (as appropriate), respectively.

Correlation, as appropriate. Multivariate linear regression analysis assessed the association between lumbar spine (LS-BMD) and femur (F-BMD) BMD (expressed as Z score, dependent variable) and the following independent variables: BMI, age at diabetes diagnosis, daily insulin dose (DID), HbA1c, ClCr, and the sum of the chronic complications of diabetes. These variables were chosen since they were found to be associated with BMD by bivariate correlations. By receiver-operating characteristic (ROC) analysis, the cutoff values of the BMD predictors at any site were established. For each patient, the presence/absence of each predictor and a total predictor risk factor score (RFSc) for low BMD was calculated by summing the number of the predictors. P values <0.05 were considered significant.

ANN analysis. We applied supervised ANNs to develop a model able to predict with the maximal possible accuracy two separate targets as follows: low femoral and spinal (yes/no). The input variables for each model were as follows: age (years), female/male, height (cm), weight (kg), BMI (kg/m²), diabetes duration (years), age at diabetes diagnosis (years), DID (units/kg), HbA1c (%), nephropathy (presence/absence), nephropathy (presence/absence), nephropathy grade, serum creatinine (μmol/L), ClCr (mL/min), retinopathy (presence/absence), and retinopathy grade (grade).

Data analysis was performed using a resampling system (TWIST by Semeion Research Center). This system consists of an ensemble of two previously described systems, T&T and IS (18), based on a genetic algorithm, the Genetic Doping Algorithm (GenD), developed at Semeion Research Center (19) and previously applied in different medical contexts (20). After this processing, the most significant features for the classification were selected, and the training and testing set were created with a function of probability distribution similar to the one that provided the best results in the classification. Two series of supervised multi-layer perceptrons, with four hidden units, were created with a function of probability distribution similar to the one that provided the best results in the classification. Two series of supervised multi-layer perceptrons, with four hidden units, were then used for the classification task for each modeling target with a classic training and testing procedure as follows: training on subset A involving approximately half of the records and blind testing on subset B, involving the other half of the records and then training on subset B and testing on subset A. Results are given for each experiment (A vs. B and B vs. A) in terms of sensitivity, specificity, global accuracy, and ROC curves and for the average of cost functions as well. The final ANNs, which were trained and tested on the new dataset generated by the TWIST system, are “virgin” and operate independently and blindly from each other and from the TWIST system.

RESULTS—The general characteristics of diabetic patients and the control group are presented in Table 1. Age, BMI, and distribution of males and females were comparable between patients with diabetes and control subjects. Type 1 diabetic patients had a lower BMD than control subjects at both sites: spine and femur. The prevalence of low LS-BMD and F-BMD (Z score BMD less than or equal to −1.0) was higher in diabetic patients than in control subjects.

Because the spine and femur are constituted by different types of bone (prevalently trabecular and cortical, respectively), we evaluated the impact of type 1 diabetes on the spine and femur separately. All patients with diabetes were divided into groups on the basis of a Z score BMD less than or equal to −1.0 (low BMD) or more than −1.0 at both the spine and femur. Patients with diabetes with low LS-BMD and patients with low F-BMD showed lower BMI (22.7 ± 3.4 and 23.0 ± 3.3 kg/m², respectively) and higher DID (0.9 ± 0.3 and 0.8 ± 0.3 UI/kg, respectively) than their counterparts with normal BMD.
LS- but not F-BMD was inversely associated with BMI (P = 0.013, respectively). Patients with low F-BMD but not patients with low LS-BMD showed a younger age at diabetes diagnosis (17.3 ± 8.7 years) and lower ClCr (88.1 ± 31.3 mL/min) and tended to have higher HbA1c (8.6 ± 1.1%) than control subjects (age at diabetes diagnosis 21 ± 9.2 years, P = 0.013, ClCr 101.8 ± 31.3 mL/min, P = 0.007, and HbA1c 8.2 ± 1.2%, P = 0.052). Age, prevalence of males and females, duration of diabetes, and prevalence of complications were not different among the different groups.

In the whole group of patients, Z score BMD at both lumbar spine and femur was directly associated with age (r = 0.32, P = 0.001, and r = 0.2, P = 0.008, respectively), age at diabetes diagnosis (r = 0.15, P = 0.044, and r = 0.27, P = 0.001, respectively), and BMI (r = 0.3, P = 0.001, and r = 0.27, P = 0.001, respectively) and was inversely associated with DID (r = -0.3, P = 0.001, and r = -0.19, P = 0.014, respectively). F-BMD showed a positive correlation also with ClCr (r = 0.22, P = 0.004) and a negative correlation with HbA1c (r = -0.16, P = 0.036), which in turn was directly associated with DID (r = 0.22, P = 0.004). Disease duration was not correlated with BMD at both the lumbar spine and femur.

The presence of each diabetic chronic complication separately taken was not associated with BMD at both lumbar spine and femur. However, in each patient, the sum of the complications was inversely associated with BMD at the spine (r = -0.158, P = 0.036) and femur (r = -0.169, P = 0.025).

By multivariate regression, the independent associations of the sum of chronic complications, BMI, age at diabetes diagnosis, DID, HbA1c, and ClCr with LS- or F-BMD were tested. Both LS- and F-BMD were confirmed to be positively associated with BMI (β = 0.25, 95% CI 0.03–0.43, P = 0.002, and β = 0.16, 0.01–0.32, P = 0.04, respectively). LS- but not F-BMD was confirmed to be negatively associated with the DID (β = -0.21, 95% CI -1.88 to -0.3, P = 0.007), whereas F-BMD but not LS-BMD was positively associated with ClCr (β = 0.18, 0.01–0.01, P = 0.019). LS- and F-BMD were not associated with age at diabetes diagnosis, HbA1c, and sum of complications.

By ROC analysis, we determined the best cutoff of the statistically significant factors in predicting low BMD (less than or equal to −1.0) at the spine or femur. We found that BMI ≤23.5 kg/m², DID >0.67 units/kg, and ClCr <88.8 mL/min were the best predictors of low spinal BMD or F-BMD. After that, for each patient, the presence/absence of each risk factor and a total RFSc for low BMD was calculated by summing the number of the risk factors. For each unit of RFSc increase, the risk of having low BMD was twofold increased (OR 2.0, 95% CI 1.43–2.99, P = 0.000). In the presence of an RFSc = 0, the probability of having a normal BMD was 84.2% (negative predictive value 84.2%, sensitivity 95.8%, accuracy 48.6%), whereas in the presence of an RFSc = 3, the probability to have a low BMD was 62.9% (positive predictive value 62.9%, specificity 87.4%, accuracy 64%); in the presence of an RFSc ≤1 or ≤2, the negative predictive value, positive predictive value, sensitivity, specificity, and accuracy for predicting low BMD were identical (55.3, 72.2, 53.1, 74, and 62.3%, respectively).

Through the TWIST system, we established a discrete possibility to predict the status of having or not having a low BMD. For both low LS- and F-BMD, the following variables were selected: age, height, weight, and BMI. For low F-BMD, the selected variables were as follows: presence of neuropathy, absence and grade of nephropathy, serum creatinine, ClCr, and absence of retinopathy; for low LS-BMD, the selected variables were both sexes, diabetes duration, DID, absence of neuropathy, presence and grade of nephropathy, and presence of retinopathy.

Sensitivity, specificity, overall accuracy, and ROC values pertinent to femoral BMD target and lumbar BMD target are reported in Table 2 together with other information relative to experiments performed.

The neural networks were found easier to predict low femoral rather than low
lumbar BMD class (65.4 vs. 54.95%, respectively; \( P < 0.01 \)) and normal lumbar rather than normal femoral BMD class (76.8 vs. 68.76% respectively; \( P < 0.01 \)). The overall accuracy rate was not significantly different (area under the curve ROC = 0.66 for both targets). We tried to develop analog-predictive models with stepwise logistic regression, but because of the high nonlinearity and small sample size, the results were disappointing. No consistent model was generated.

Through the connectivity map (Fig. 1), we established the connections between the studied variables and the condition of low F-BMD and LS-BMD. The presence of retinopathy was the principle variable of the whole system that was directly connected with HbA1c, with the presence of nephropathy and neuropathy connected with HbA1c separately. The cluster formed by HbA1c and the presence of diabetes complications then was connected with low BMD at the femur and lumbar spine. Age of diagnosis, diabetes duration, BMI, or ClCr was not directly connected with low BMD at both sites. On the other hand, age of diagnosis, diabetes duration, BMI, and DID were connected with HbA1c separately.

**CONCLUSIONS**—In the current study, we found that BMD is reduced in type 1 diabetes. From classic statistics, low trabecular (spine) and cortical (femur) BMDs were associated with high DID and low ClCr, respectively. Low BMI was associated with both low trabecular and cortical BMD. The analyses with ANNs added the presence of diabetes complications, through poor metabolic control, to the list of contributors of low BMD in type 1 diabetes.

Several studies suggested several potential mechanisms responsible of low bone mass in type 1 diabetes, such as the inflammatory state, the local levels of insulin-like growth factors, the amylin deficit, and the nonenzymatic glycation of type 1 collagen with subsequent advanced glycation end product formation (6). However, almost all previous studies have relatively small and not homogeneous samples (i.e., evaluating eugonadal and hypogonadal subjects together). In addition, because osteoporosis is a multifactorial skeletal disease, the link between BMD and the risk factors may be hardly understandable using the classic statistics.

In this study, the factors associated with low BMD in type 1 diabetes were investigated in a large and homogeneous sample (all eugonadal individuals) using ANNs, which are considered particularly suited for solving nonlinear problems (15).

In the current study, after adjusting for the confounding factors, the age at diabetes diagnosis was not associated with BMD. This result is in contrast to some previous data showing the young onset of diabetes as a risk factor in adult life, possibly because of a low bone mass peak (7,22). This discordance may be
attributed to the different inclusion criteria of the current study with respect to the previous ones.

On the other hand, we found that BMD both at spine and femur was independently associated with BMI and that patients with low BMD were thinner than individuals with a normal BMD. Because body composition and lean mass may influence bone density, this finding suggests a possible link between BMD and muscle mass in type 1 diabetic patients.

Insulin is considered an anabolic agent for bone (6), and, therefore, one should expect BMD to increase with the increase of DID. On the contrary, in our study, patients with diabetes with low BMD had higher DID, which was independently associated with low spinal BMD. This result is in accordance with previous data, showing that large amounts of insulin had an independent deleterious effect on bone in type 1 diabetes (22). However, in poorly compensated patients with diabetes, the increased levels of inflammation markers and oxidative stress were shown to be inversely associated with BMD (23). The present finding of a correlation between DID and HbA1c suggests that the need of high insulin dose may reflect the presence of a more severe disease (i.e., a more pronounced inflammatory milieu), leading per se to bone damage (6). This hypothesis is supported by the connectivity map of the ANN (Fig. 1), showing that DID was strictly connected with HbA1c and then with low BMD, although through diabetes complications.

In keeping with previous studies (10,11,23,24), HbA1c levels were associated with BMD after adjusting for confounders. However, we measured HbA1c only at enrollment. Because HbA1c levels are representative of the metabolic status of the last 3 months, we could not exclude that, during the previous years in the individual subject, the metabolic status was different and therefore not reliably mirrored by the current HbA1c levels. Indeed, in those studies demonstrating the influence of metabolic control on BMD, HbA1c was also measured during the previous years of disease (10,11,23,24). However, the lack of a correlation between BMD and HbA1c may also depend on a nonlinear relationship between these variables, hardly detectable by the classic statistics. The connectivity map of ANN showed that HbA1c was connected with low BMD through the link with the diabetes complications (Fig. 1).

The chronic diabetes complications per se have been suggested to predict low BMD in type 1 diabetes. The reduced visual function and the presence of diabetic neuropathy may predispose patients to low physical activity, which, in turn, may cause bone loss (12,14). The presence of diabetic nephropathy with negative calcium balance and reduced vitamin D level was reported to be an early indicator of osteopenia in type 1 diabetes (13). However, because complications are the result of the chronic exposure to high blood glucose of target organs, the finding of an association between chronic complications and low BMD may also reflect the effect of chronic hyperglycemia on bone.

Finally, previous data suggested that even a mild impairment of kidney function may lead to bone loss (25), underlining the importance of estimation of CrCl when evaluating patients for fracture risk. A novel finding of the current study is that in type 1 diabetic patients, CrCl levels were independently associated with low F-BMD, showing the importance of mildly reduced kidney function for bone loss at the femur in type 1 diabetes.

Another novelty of our study is that we elaborated a RFSc (composed by ROC analysis–derived cutoffs for BMI, CrCl, and DID for low BMD). In the presence of RFSc = 0, the probability to have a normal bone mass is 84.2%; therefore, measuring BMD may not be necessary. On the contrary, in the presence of an RFSc = 3, the probability to have a low BMD is 62.9%, and the measurement of BMD might be considered, particularly if the chronic complications are present, as shown by ANNs (Fig. 1). The finding that the accuracy for predicting low BMD is similar for the classic statistics (64%) and ANNs (67%) suggests that other variables, not considered in our analyses, may be responsible for low BMD in type 1 diabetes.

The current study had several limitations. First, the cross-sectional design did not allow us to assess causality but only association between variables. Second, we did not measure bone turnover markers, which would have possibly helped us to better understand the mechanism of reduced BMD. Finally, the current study did not investigate the mechanisms for bone damage in type 1 diabetes.

A final comment is inherent to ANNs and their pros and cons. For the most part, most ANNs have few probabilistic underpinnings, unlike their more statistical or Bayesian counterparts in the more general field of machine learning. This result can be an advantage but also a problem, depending on the context. A significant part of using ANNs is training it. Training is an iterative process, where the data are repeatedly presented to the network, and training incrementally improves the model to match the data more closely. Training is difficult and requires a great deal of technical experience. However, when the underlying relation among the variables on study is complex and there is no reliable a priori statistical model to reference, ANNs can be the ideal solution, since they self-adjust their structure as they learn from their own errors and can simultaneously handle a high number of variables, irrespective of their underlying degree of nonlinearity.

In conclusion, the current study confirms that, in type 1 diabetes, BMD is reduced. Moreover, it shows that low BMI and the presence of chronic diabetes complications are associated with both LS- and F-BMD, whereas high insulin dose and low CrCl are associated with low LS- and F-BMD, respectively.

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C.E.-V. analyzed and interpreted the data and prepared the manuscript. V.V.Z. collected, analyzed, and interpreted the data and prepared the manuscript. Y.V.T. collected the data. S.S.K. and E.C. analyzed and interpreted the data. A.P.S. collected, analyzed, and interpreted the data. I.C. analyzed and interpreted the data and prepared the manuscript. A.P.S. collected, analyzed, and interpreted the data.

References


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22. Léger J, Marinovic D, Alberti C, et al. Lower bone mineral content in children with type 1 diabetes mellitus is linked to female sex, low insulin-like growth factor type 1 levels, and high insulin requirement. J Clin Endocrinol Metab 2006;91:3947–3953