Bone density does not reflect mechanical properties in early-stage arthrosis

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ABSTRACT – Subchondral cancellous bone specimens were removed from 10 human postmortem early-stage arthrotic proximal tibiae (mean age 73 (63–81) years) and 10 age- and gender-matched normal proximal tibiae. The early-stage arthrosis was confirmed histologically and the specimens were divided into 4 groups: medial arthrosis, lateral control, normal medial and normal lateral controls. The specimens were tested in compression to determine mechanical properties and then physical/compositional properties.

Compared to the normal medial control, we found reductions in ultimate stress, Young's modulus, and failure energy, and an increase in ultimate strain of arthrotic cancellous bone. Bone volume fraction, apparent density, apparent ash density, and collagen density were higher in cancellous bone with arthrosis, but no differences were found in tissue density, mineral and collagen concentrations between arthrotic cancellous bone and the 3 controls. None of the mechanical properties of arthrotic cancellous bone could be predicted by the physical/compositional properties measured. The increase in bone tissue in early-stage arthrotic cancellous bone did not make up for the loss of mechanical properties, which suggests a deterioration in the quality of arthrotic cancellous bone.

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Changes in arthrosis occur in all parts of the joint, with cartilage surface disruption as a constant factor. Recent studies have shown that subchondral cancellous bone may be involved primarily, and plays a large role in cartilage degeneration in arthrosis (Burr and Schaffler 1997). Despite research efforts, the pathogenesis of arthrosis remains unknown, and it is uncertain whether bone changes precede cartilage changes or vice versa.

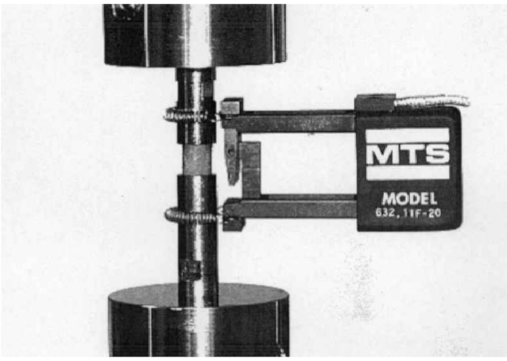
We tested the hypothesis that the mechanical and physical properties and quality changes even occur in early-stage arthrotic subchondral cancellous bone and determined whether the normal relationship between mechanical and physical/compositional properties can be applied to early-stage arthrotic cancellous bone.

Material and methods

Material

Early-stage arthrosis was defined as macroscopically-fibrillated cartilage, and this finding was confirmed histologically, using Mankin's (1971) criteria. Mankin's histological-histochemical grading ranges between 0 and 14 (for structure 0–6, cells 0–3, Safranin-O staining 0–4, and tidemark integrity 0–1), where 0 is normal and 14 is severe arthrosis. This was seen as degeneration, with slight fissures in the cartilage surface (superficial zone) of the medial condyle in arthrotic tibiae, but the cartilage surface of the lateral condyle was intact. The medial arthrosis was graded as 4.9 (3–7), lateral control as 1.7 (1.5–3). The normal tibiae had no macroscopic pathology or history of musculoskeletal diseases and normal medial was graded as 0.8 (0–2), and normal lateral as 0.5 (0–1) (Ding et al. 1998). The donors all died suddenly of trauma or acute disease.

Cylindrical cancellous bone specimens were removed from 10 human postmortem early-stage arthrotic proximal tibiae (mean age 73 (63–81)



Mechanical testing set-up. The specimen was tested in compression between the upper and lower testing columns. A static strain gauge extensometer was attached to both columns close to the specimen. The force-deformation data were collected and converted to stress-strain data (Ding et al. 1997).

years, 7 males), and 10 normal human age- and gender-matched proximal tibiae (mean age 72 (58–85) years, 7 males). The donors were Caucasian. 3 specimens were drilled out from each medial and lateral condyle of a tibia (one tibia from each donor), and a total of 120 specimens were obtained. The axis of the cylindrical specimens corresponded to the longitudinal axis of the tibia. The specimens were also cut 1 mm below the subchondral bone plate and at the distal end to create specimens with a diameter and length of 7.5 mm (Ding et al. 1997). They were stored in plastic tubes at –20 °C, and divided into 4 groups: medial arthrosis, lateral control, normal medial, and normal lateral controls (Ding et al. 1998). Thus, 30 specimens were examined in each group.

Mechanical testing

The specimens were tested in compression on an 858 Bionix MTS hydraulic material-testing machine (MTS Systems Cooperation, Minneapolis, Minnesota, USA). A 1 kN load cell was used and a static strain gauge extensometer (Model 632.11F-20, MTS) was attached to both upper and lower testing columns close to the specimen (Figure). The testing machine was computer-controlled by the software TestStar II Operation System (MTS Systems Cooperation). The force-deformation data were collected and converted to stress and strain data using the cross-sectional area of the specimens for normalization of load to stress and the original length of the specimens for normalization of deformation to strain. All the specimens were tested to failure in compression, with a strain rate of 0.002 per second. We determined Young's modulus, ultimate stress, ultimate strain, and the failure energy of each specimen (Ding et al. 1997).

Physical/compositional properties

After testing, an accurate protocol was made for measuring the Archimedes-based volume fraction (Ding et al. 1997). Bone volume fraction (bone volume per total specimen volume), bone apparent density (bone dry weight of the specimen per total volume of specimen), tissue density (bone dry weight of the specimen per total volume of bone matrix excluding marrow space), mineral concentration (total mineral content of the specimen per total dry weight of the specimen), apparent ash density (mineral weight of the specimen per total volume of specimen), collagen concentration (total collagen weight of the specimen per total dry weight of the specimen), and collagen density (collagen weight of the specimen per total volume of specimen) were determined by the techniques described in detail elsewhere (Ding et al. 1997, Neuman and Logan 1950).

Statistics

The statistical analyses (SPSS, SPSS Inc. Chicago, Illinois) were based on the entire data set and the average value of the 3 specimens from each condyle was used as the variable in the analyses. Normality and equal variance were checked first, then paired or 2-sample t-tests, as appropriate, were done to assess the differences in mechanical and physical/compositional properties between the arthrosis and 3 control groups. Linear regression analyses were used to assess the associations between mechanical properties and physical/compositional properties. Stepwise multiple linear regression analyses were used to evaluate the associations between each of the mechanical properties as dependent variables and all physical/compositional properties measured as independent variables. The determination coefficient (r^2) was used to express proportional variation due to linear or multiple regression, and a p-value <0.05 was considered significant.

Descriptive statistics (mean) of the mechanical and physical/compositional properties in arthrosis and 3 controls

	Arthrosis	95% CI	Lateral control	95% CI	Normal medial	95% CI	Normal lateral	95% CI
Mechanical								
Ultimate stress (MPa)	4.11	3.18–5.04	4.38	3.04–5.72	6.84 [b]	4.87–8.81	4.35	2.54–6.13
Young's modulus (MPa)	275	211–339	293	187–401	475	257–693	297	208–386
Ultimate strain (%)	2.65	2.40–2.90	2.73	2.20–3.26	2.23 [b]	2.06–2.51	2.42	1.87–2.98
Failure energy (kJ/cm^3)	63.8	53.9–73.7	71.0	40.8–101	86.7	63.9–110	59.9	45.7–74.1
Physical/compositional								
Bone volume fraction (–)	0.24	0.22–0.26	0.18 [c]	0.15–0.20	0.20 [a]	0.18–0.23	0.16 [c]	0.14–0.18
Apparent density (g/cm^3)	0.52	0.47–0.57	0.39 [c]	0.35–0.42	0.43 [c]	0.37–0.49	0.35 [c]	0.30–0.40
Apparent ash density (g/cm^3)	0.33	0.30–0.37	0.24 [c]	0.20–0.28	0.27 [c]	0.23–0.31	0.22 [c]	0.19–0.25
Collagen density (g/cm^3)	0.13	0.11–0.14	0.10 [c]	0.08–0.11	0.11 [c]	0.09–0.12	0.09 [c]	0.08–0.10
Tissue density (g/cm^3)	2.23	2.22–2.24	2.23	2.22–2.24	2.21	2.20–2.22	2.19	2.16–2.22
Mineral concentration (–)	0.63	0.63–0.64	0.63	0.62–0.64	0.63	0.62–0.63	0.62	0.61–0.63
Collagen concentration (–)	0.25	0.24–0.26	0.25	0.24–0.25	0.25	0.24–0.26	0.25	0.24–0.26

95% CI = 95% confidence interval of mean. (–) indicates no unit. Mechanical and physical/compositional properties of OA and three controls were compared, using paired or two sample t–tests, as appropriate.
[a] p = 0.04
[b] p = 0.02
[c] p = 0.01

Results

We found reductions in ultimate stress (p= 0.01), Young's modulus (p= 0.06) and f ailure energy (p= 0.05) and an increase in ultimate strain (p= 0.02) in arthrotic cancellous bone, when compared with those of the normal medial control. The mechanical properties of arthrotic cancellous bone did not differ significantly from those of the lateral control and normal lateral control (Table).

Bone volume fraction, apparent density, apparent ash density, and collagen density of arthrotic cancellous bone were higher than those of the 3 controls (p= 0.04–0.001). The mean tissue density, mineral and collagen concentrations of arthrotic cancellous bone did not differ significantly from those of normal controls (Table).

Linear and multiple linear regression analyses showed that variances of neither ultimate stress nor Young's modulus nor failure energy of arthrotic cancellous bone could be explained by the physical/compositional properties measured. The association between bone apparent density and ultimate stress, Young's modulus or failure energy for arthrotic cancellous bone was $r^2 = 0.22$, p= 0.18, $r^2 = 0.30$, p= 0.10, and $r^2 = 0.35$, p= 0.07, respectively. Variances of ultimate stress could be explained by collagen density alone in the normal medial control ($r^2 = 0.62$, p= 0.01) or by apparent density together with collagen content ($r^2 = 0.79$, p= 0.01). Variances of Young's modulus could be explained by bone apparent density alone in the normal medial control ($r^2 = 0.59$, p= 0.01). Variance of failure energy showed a significant relation to collagen density together with collagen content in the normal medial control ($r^2 = 0.85$, p= 0.01).

Discussion

The main findings were that the mechanical properties of arthrotic cancellous bone were reduced, despite the greater density of arthrotic bone tissue. Variation in ultimate stress, Young's modulus, and failure energy of arthrotic cancellous bone were not due to bone density. Our data showed that the mechanical properties of arthrotic cancellous bone could not be predicted by measuring density alone. These findings suggest that the quality of early-stage arthrotic cancellous bone had become significantly worse.

Most previous studies of changes in cancellous bone properties have focused on moderate- and late-stage arthrosis. They have shown that bone mineral density increases in the axial and peripheral skeleton with progression of arthrosis (Dequeker 1997). Subchondral bone plate sclerosis although not necessary for initiation of cartilage fibrillation, may be needed for progression, and changes only in bone and calcified cartilage close to the joint are essential for to the disease process (Burr and Schaffler 1997). Arthrosis may have an abnormally low mineralization pattern, despite a thicker subchondral bone plate (Grynpas et al. 1991). In late-stage arthrosis, both stiffness and density increase in subchondral cancellous bone (Li and Aspden 1997a), but decrease in the subchondral bone plate (Li and Aspden 1997b).

In our study on early-stage arthrosis, ultimate stress, Young's modulus, and failure energy of cancellous bone were recuced by 26–42%, but ultimate strain was increased by 19%, when compared to the normal medial control. These results were consistent with our previous findings from testing of cartilage and bone simultaneously (Ding et al. 1998). In late-stage arthrosis, Young's modulus and failure energy were significantly higher than those of the normal control, and ultimate stress tended to be higher (Li and Aspden 1997a). In normal cancellous bone, the variation in mechanical properties can be reliably predicted by bone density (Ciarelli et al. 1991). The losses observed in mechanical properties predicted from bone density may be interpreted as deterioration of bone quality in arthrotic cancellous bone.

Bone volume fraction and apparent density of early-stage arthrotic cancellous bone were higher (23% and 16%) than those of the normal medial control. In late-stage arthrosis, apparent density was increased by 51%, and mineral concentration was reduced by 12% (Li and Aspden 1997a). Comparing early- and late-stage arhtrosis, a trend to an increase in the amount of bone tissue at both stages to compensate for the reduction in mechanical properties was apparent. However, the increased amount of defective bone tissue could not entirely counteract the loss of mechanical properties in both early- and late-stage arthrosis.

Cancellous bone quality is reflected by the amount of bone tissue present, the mechanical properties of the tissue, and its trabecular architecture. In this study we have shown that a reduction occurred in the mechanical properties, despite higher density in arthrotic bone tissue, and we have recently reported a deterioration in the microstructure in early-stage arthrotic cancellous bone (Ding et al. 2000). These findings indicate that bone density is not a good parameter for predicting mechanical properties in diseased cancellous bone, such as arthrosis.

Bone-quality deterioration in arthrotic cancellous bone may be multifactorial—i.e., in accord with the microfracture repair hypothesis that healing of a microfracture in subchondral cancellous bone results in overloaded articular cartilage (Radin and Paul 1970). Microdamage accumulation has been shown to impair the mechanical properties of cortical bone. Such accumulation is detectable only when the elastic modulus is reduced by more than 15% (Burr 1998). Our results suggest that it may even occur in early-stage arthrotic cancellous bone, which reduces the mechanical properties. In late-stage arthrosis, microdamage accumulation has been found (Fazzalari et al. 1998), suggesting an increase in the amount of unrepaired fatigue microdamage and a reduction in cancellous bone quality.

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