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ABSTRACT

Since edentate subjects have a reduced masticatory function, it can be expected that the morphology of the cancellous bone of their mandibular condyles has changed according to the altered mechanical environment. In the present study, the morphology of cylindrical cancellous bone specimens of the mandibular condyles of edentate subjects ($n = 25$) was compared with that of dentate subjects ($n = 24$) by means of micro-computed tomography and by the application of Archimedes' principle. Stiffness and strength were determined by destructive mechanical testing. Compared with dentate subjects, it appeared that, in edentate subjects, the bone was less dense and the trabecular structure was less plate-like. The regression models of stiffness and strength built from bone volume fraction and the trabecular orientation relative to the axis of the specimen were similar for both dentate and edentate subjects. This indicates that, under reduced mechanical load, the fundamental relationship between bone morphology and mechanical properties does not change.

KEY WORDS: cancellous bone, architecture, edentate, mandibular condyle.

Changed Morphology and Mechanical Properties of Cancellous Bone in the Mandibular Condyles of Edentate People

INTRODUCTION

A decreased masticatory function has been reported in relation to aging and loss of teeth (Boretti *et al.*, 1995). The decrease in function is associated with an atrophy of masticatory muscles (Newton *et al.*, 1993) and a reduction of bite force (Helkimo *et al.*, 1977). This implies a reduction of forces acting on the mandibular condyle. As bone reacts to its mechanical environment (*e.g.*, Turner, 1998; Huiskes, 2000), it is likely that the morphology of the condylar bone changes accordingly.

In previous studies, it has been shown that the cancellous bone of the mandibular condyle is adaptive, *i.e.*, in edentate subjects, the apparent density and bone volume fraction were found to be lower than in dentate subjects (Hongo *et al.*, 1989a; Kawashima *et al.*, 1997; Giesen *et al.*, 2003b). The mechanical consequence is a reduction (20-30%) in stiffness and strength (Giesen *et al.*, 2003b). Thus far, however, there is no information available on the nature of the morphological bone changes in edentate subjects. It has been demonstrated, for example, that the apparent density of the cancellous bone in the human tibia decreases during aging (Ding *et al.*, 1997), and that this decrease is accompanied by a change in bone structure type, from plate-like toward more rod-like (Ding and Hvid, 2000). Furthermore, the anisotropy of the bone and the bone surface-to-volume ratio has been demonstrated to increase with age (Ding *et al.*, 2002). In patients with hip fractures, a lower bone density has been found, accompanied by a higher degree of anisotropy (Ciarelli *et al.*, 2000).

For the mandibular condyles of dentate subjects, a close relationship between bone density and the type of trabecular structure has been shown (Giesen *et al.*, 2003a), *i.e.*, a higher apparent density is associated with more plate-like trabeculae, whereas a lower apparent density is associated with more rod-like trabeculae. It can be questioned whether the cancellous bone of edentate subjects exhibits the same kind of relationship. If the bone adapts similarly in dentate and edentate subjects, we would expect that, in edentate subjects, the changes in density are similarly accompanied by changes in the trabecular structure type and not by changes in, for instance, trabecular thickness or connectivity density.

In the present study, we investigated whether the stiffness of the bone of dentate and edentate subjects depended differently on the amount of bone and trabecular orientation. These measures were applied according to Giesen *et al.* (2003a) and were entered into linear regression analyses so that the variance in mechanical properties could be explained. It was hypothesized that, if only the amount of bone-related morphological parameters changed in the edentate subjects, the regression models to describe these mechanical properties are more or less the same for edentate and dentate subjects.

MATERIALS & METHODS

Cylindrical cancellous bone specimens were taken from the mandibular

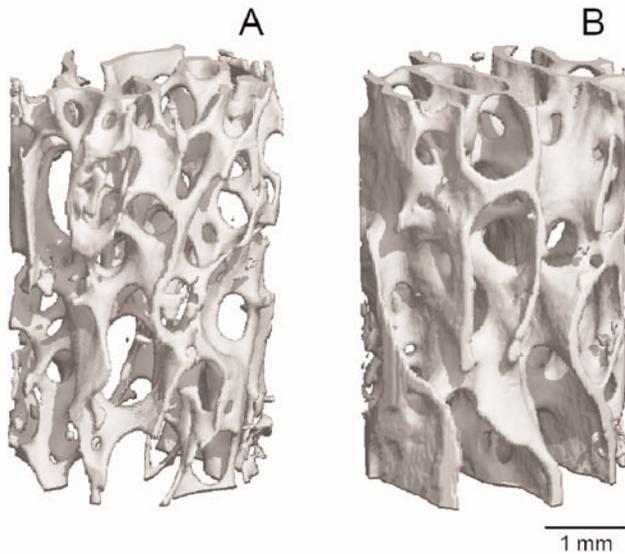


Figure 1. Examples of three-dimensional reconstructions of samples originating from the edentate (A) and dentate (B) groups. The structure changed from plate-like (dentate, SMI = 0.39) toward more rod-like (edentate, SMI = 1.26).

condyles of 49 embalmed human cadavers. Twenty-five of them were edentate (14 female, 11 male; mean age \pm SD, 85.2 \pm 8.5 yrs); we did not know the age at which they had lost their teeth. Twenty-four subjects were dentate or partially dentate (19 female, 5 male; mean age \pm SD, 74.8 \pm 11.7 yrs); their mean number of teeth was 8.5 (SD 3.6) in the upper jaw and 10.7 (SD 2.4) in the lower jaw. The use of human specimens conforms to a written

protocol that was reviewed and approved by the Department of Anatomy and Embryology of the Academic Medical Center of the University of Amsterdam. The specimens were taken from different directions, axial and transverse, and locations within the condyle (Giesen *et al.*, 2001). From each condyle, only one specimen was selected randomly. The specimens had a diameter of 3.65 \pm 0.14 (mean \pm SD) mm and a length of 4.87 \pm 0.07 mm. The specimens were stored in the embalming fluid prior to being tested.

To obtain their three-dimensional trabecular microstructure, we scanned the specimens in a micro-computed tomography (micro-CT) system (μ CT20, Scanco Medical AG, Zürich, Switzerland). The specimens were placed in embalming fluid to avoid dehydration during scanning. The scanning was performed at a resolution of 18 μ m. To distinguish bone from non-bone, we used a fixed threshold, which we had obtained experimentally by matching the bone volume fraction from the scans with the one that was measured according to a method based on Archimedes' principle (Ding *et al.*, 1999). Several bone morphology parameters were calculated (Software Revision 3.1, Scanco Medical AG): bone volume fraction, bone surface-to-volume ratio, trabecular thickness, trabecular separation, connectivity density, structure model index, and degree of anisotropy. The bone volume fraction is the ratio of the bone volume to the specimen's volume. Bone surface-to-volume ratio was the ratio of the bone surface to the bone volume. Trabecular thickness and trabecular separation were determined with use of a model-independent method (Hildebrand and Rüegsegger, 1997a). Connectivity density is a measure for the number of trabeculae per unit volume (Odgaard and Gundersen, 1993). The structure model index quantifies the characteristic form of the cancellous bone in terms of plate-like to rod-like. For an ideal plate and rod structure, this index is 0 and 3, respectively (Hildebrand and Rüegsegger, 1997b). The principal directions of the trabecular structure were estimated by the mean intercept length (MIL) ellipsoid. The degree of anisotropy was defined as the ratio between the MIL_{max} and MIL_{min}. Further, the orientation of the trabeculae was expressed by the angle between the main direction of the trabecular structure (MIL_{max}) and the axis of the cylindrical specimen (for more detail, see Giesen *et al.*, 2003a).

Table 1. Descriptive Statistics of Bone Parameters of the Edentate and Dentate Groups Determined by Micro-CT, a Method Based on Archimedes' Principle, and Mechanical Tests

	n ^a	Edentate Mean	SD	n ^a	Dentate Mean	SD	p-value ^b
Micro-CT							
Bone volume fraction [%]	25	14.7	4.8	24	17.3	3.4	0.016
Bone surface-to-volume ratio [mm ⁻¹]	25	19.22	2.98	24	17.85	2.38	0.042
Trabecular thickness [mm]	25	0.124	0.022	24	0.128	0.018	0.250
Trabecular spacing [mm]	25	0.679	0.110	24	0.641	0.093	0.102
Structure model index [-]	25	1.21	0.38	24	0.82	0.32	0.000
Connectivity density [trabec/mm ³]	25	4.03	1.86	24	4.28	1.58	0.306
Anisotropy 1/3 [-]	25	1.98	0.20	24	1.97	0.28	0.409
Angle [°]	25	45	30	24	50	29	0.305
Archimedes' principle							
Apparent density [g/cm ³]	21	0.30	0.07	18	0.35	0.06	0.006
Bone volume fraction [%]	21	14.4	3.2	18	16.5	2.7	0.017
Tissue density [g/cm ³]	21	2.08	0.07	18	2.13	0.05	0.013
Mechanical							
E-modulus [MPa]	22	290	230	23	373	197	
Ultimate stress [MPa]	22	2.4	2.1	23	3.3	2.0	

^a The numbers of specimens with valid test results are indicated.

^b One-tailed probability values of the differences between both groups are indicated (Student's *t* test).

Stiffness and strength were determined by destructive mechanical compression tests, carried out with a materials testing machine (858 Mini Bionix, MTS Systems Corporation, Minneapolis, MN, USA) equipped with a 1-kN load cell. The cylindrical specimens were compressed between parallel plates at a constant strain rate of 0.2% s⁻¹ until a strain of 3% was reached. The E-modulus (or stiffness) is defined as the maximum slope

of the stress-strain curve. The ultimate stress (or strength) is defined as the maximal stress during the test. For more details about the mechanical tests, refer to Giesen *et al.* (2001).

After the micro-CT scanning and mechanical testing, we applied Archimedes' principle to determine cancellous bone density parameters (Ding *et al.*, 1997). The marrow was removed from the specimens. Apparent density was defined as the ratio of the mass of specimen to its total volume. Bone volume fraction is the space occupied by mineral tissue relative to the specimen's volume. Tissue density was taken as the ratio between the mass of specimen and the space occupied by mineral tissue.

We applied Student's *t* tests to detect differences between dentate and edentate subjects. A *p*-value of less than 0.05 was considered statistically significant. To determine whether bone of dentate and edentate subjects had different relationships between bone morphology (bone volume fraction and the angle of the principal trabecular orientation) and mechanical properties (E-modulus and ultimate stress), we conducted linear regression analyses. The effects of age and number of absent teeth on the morphological parameters were investigated by multivariate analyses and correlation coefficients. SPSS 10.1.0 software (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses.

RESULTS

Typically, the samples originating from the edentate group had a less massive appearance than those obtained from the dentate group (Fig. 1). The descriptive statistics and the probability values for different statistical tests for the various parameters are summarized in Table 1. The apparent density, bone volume fraction, and tissue density were lower in the edentate group than in the dentate group. Since the structure model index was lower in the edentate group, the reduction of the amount of bone in this group was associated with a transition to more rod-like trabeculae. No gender differences or relationships between the number of teeth and the morphological parameters were found.

The E-modulus and the ultimate stress depended on the bone volume fraction and the trabecular orientation (Fig. 2). Both were proportional to the bone volume fraction and inversely proportional to the angle of the principal trabecular orientation relative to the direction of testing. On

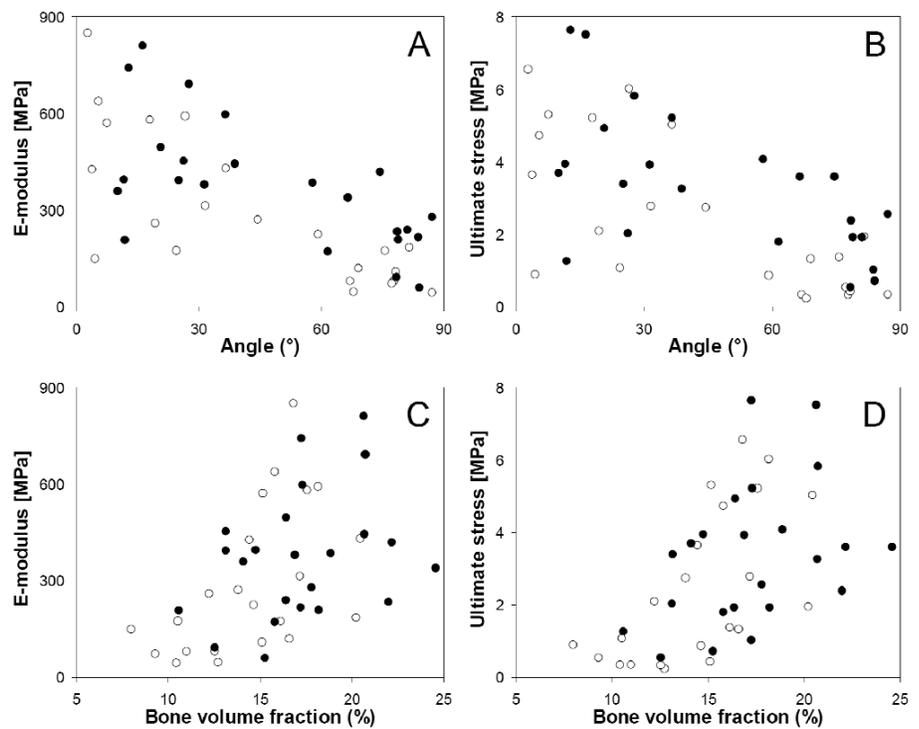


Figure 2. E-modulus and ultimate stress vs. angle (A,B) and E-modulus and ultimate stress vs. bone volume fraction (C,D) of both the edentate (open symbols) and dentate (closed symbols) subjects; angle (°) is the angle of the main trabecular direction relative to the direction of testing (see text).

average, E-modulus and ultimate stress were 25-30% lower in the edentate group than in the dentate group. The coefficients of the regression models to describe E-modulus and ultimate stress from angle and bone volume fraction were very similar for both groups (Table 2). The 95% confidence intervals for the coefficients indicated that the regression models for the dentate and edentate groups did not differ significantly.

Table 2. Regression Models of Mechanical Properties with Bone Volume Fraction and Angle

	Edentate (R ² = 0.81)		Dentate (R ² = 0.73)	
	Coefficients	(95% CI)	Coefficients	(95% CI)
E-modulus [MPa]				
Constant	66.02	(-166; 298)	75.42	(-168; 319)
BV/TV ^a	3195	(1748; 4643)	3297	(1841; 4751)
Angle	-5.45	(-7.06; -3.85)	-5.64	(-7.39; -3.90)
Ultimate Stress [MPa]				
	Edentate (R ² = 0.83)	(95% CI)	Dentate (R ² = 0.73)	(95% CI)
	Coefficients		Coefficients	
Constant	-0.66	(-2.69; 1.36)	-0.20	(-2.59; 2.19)
BV/TV	35.38	(22.76; 48.01)	35.51	(21.24; 49.79)
Angle	-0.046	(-0.060; -0.032)	-0.054	(-0.071; -0.037)

^a BV/TV [-] is the bone volume fraction, angle [°] is the angle of the main trabecular direction relative to the direction of testing, and 95% CI is the 95% confidence interval.

DISCUSSION

The present study aimed at characterizing the morphology of the cancellous bone of the mandibular condyles of edentate subjects. Since loss of teeth is associated with decreased masticatory function, it was hypothesized that the bone would react to the changed mechanical environment. It appeared that the morphology of the cancellous bone of the edentate subjects did differ from that of dentate subjects. In edentate subjects, the bone volume fraction was lower. The decrease in the amount of bone was associated with more rod-like trabeculae and not with a decrease in the number of trabeculae or with a thinning of the trabeculae. Thus, it seems that the fenestrations within bone plates become larger, without thinning of the bone plates. This is in contrast to the results reported by Hongo *et al.* (1998a) and Kawashima *et al.* (1997), who found a thinning of the trabeculae in edentate subjects. Although connectivity density and volume fraction have been reported to correlate negatively (Kinney and Ladd, 1998), we did not find a change in connectivity density, which is, in turn, consistent with the non-significant relationships found by Kabel *et al.* (1999). The association of a lower volume fraction with more rod-like trabeculae is consistent with the findings for cancellous bone of the mandibular condyles of dentate subjects (Giesen *et al.*, 2003a), for bone from other anatomic sites (Hildebrand *et al.*, 1999), and for tibial bone in aging subjects (Ding and Hvid, 2000).

The degree of anisotropy did not differ between the edentate and the dentate subjects, although in aging bone an increase in the degree of anisotropy has been reported (Ding *et al.*, 2002). Also, in patients with hip fractures, the degree of anisotropy increased with proportionally fewer trabecular elements transverse to the primary loading axis (Ciarelli *et al.*, 2000). In a previous study, we found an unchanged mechanical anisotropy in the edentate subjects (Giesen *et al.*, 2003b). This is consistent with the unchanged morphological anisotropy in the present study. It indicates that the changes in bone structure occurred equally in all directions.

The regression models to describe E-modulus and ultimate stress from the angle of the trabeculae relative to the testing direction and the bone volume fraction were very similar for both the dentate and the edentate groups. Since, in edentate subjects, the volume fraction was lower, the cancellous bone of the condyle was not as stiff and strong as in dentate subjects. The similar regression models indicate a similar dependence of mechanical properties on the trabecular structure. This is in line with the changes in morphology, *i.e.*, in edentate subjects the amount of bone was reduced, and this reduction was associated with a change toward more rod-like trabeculae. If the degree of anisotropy had changed, the mechanical properties would have depended differently on the trabecular orientation, which was not the case.

Some remarks have to be made about the material used. First, we did not know at what age the edentate subjects had lost their teeth, and whether they had worn dentures. Therefore, the time-period and the level of reduced mechanical loading were unknown. Further, we did not know if they had lost their teeth as a result of general osteoporosis, generating an overall lower bone density. Nevertheless, since it has been reported that edentate subjects have lower masticatory function (Boretti *et al.*, 1995) and produce lower bite forces (Helkimo *et al.*, 1977), we can safely assume that the mandibles of our edentate

group had been subjected to a reduced mechanical loading. Second, the edentate subjects were significantly older than the dentate subjects. Therefore, an age-related decrease of density and E-modulus (Ding *et al.*, 1997) could be expected in the edentate group. However, no age-related changes in density of the human mandibular condyle were previously found (Hongo *et al.*, 1989b). Also, in the present study, we found no correlations of aging and any of the morphological parameters for both the edentate and the dentate group. In addition, in the dentate group, no correlations were found between the number of absent teeth and any of these parameters. Third, the embalming procedure could have changed the mechanical properties, *i.e.*, a slight increase in stiffness (Linde, 1994). However, the major findings of this study—that is, the differences between dentate and edentate subjects—are not invalidated.

To conclude, the morphology of the cancellous bone in the mandibular condyles in edentate subjects was less dense than that in dentate subjects and had changed toward a more rod-like structure. The regression models of the mechanical properties built from the bone volume fraction and the trabecular orientation were similar for the two groups. Thus, mechanical properties depended similarly on morphology.

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