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Quantitative computed tomography of trabecular bone in the mandible

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Objective. To evaluate the potential use of quantitative computed tomography (QCT) for the assessment of bone mineral density of the edentulous mandible prior to implant placement.
Methods. Ten 2 mm thick CT slices of anterior and posterior edentulous sections from 15 mandibles were obtained perpendicular to the buccal and lingual plates. The bone mineral density, expressed as the amount of calcium hydroxyapatite (mg cm^{-3}) of the trabecular bone, was calculated using a method that takes into account the influence of fat.
Results. The variation of bone mineral density between mandibles was high. Anterior sections showed higher values than posterior sections and a variation was found within sections of the same mandible.
Conclusion. CT provides a site-related measure of the bone mineral density in the mandible and appears potentially useful as a non-invasive method to determine a parameter that may reflect bone quality prior to implant placement. Copyright © 1996 Elsevier Science Ltd for IADMFR.

Keywords: Mandible; tomography, X-ray computed; osteoporosis; dental implantation

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Bone quality is referred to in many follow-up studies of implant treatment as a factor of great importance in the outcome[1–5]. However, it is obvious that the term 'bone quality' is open to considerable interpretation and there is no real consensus in the literature[6]. Bone quality probably reflects a number of aspects of bone morphology of which the degree of mineralization may be one. The radiological methods that have been developed for determining the bone mineral density (BMD) are mainly used to study skeletal changes in osteoporosis and other metabolic bone diseases[7]. Densitometric measurements have been made from intra-oral and panoramic radiographs of the mandible to find signs of osteoporosis[8–10]. Dual photon absorptiometry[11,2] and dual energy X-ray absorptiometry[13] have been used to measure BMD of the mandible and to correlate it with that of other parts of the skeleton. Both these methods measure an integrated sum of cortical and trabecular bone density. However, the consistency of the trabecular bone is particularly significant in implant treatment, especially when the cortex is thin and the implant is inserted mainly in trabecular bone. Computed tomography (CT) is the only non-invasive pre-operative method where it is possible to obtain information on the degree of mineralization of trabecular bone as distinct from the cortex. At present, it is mainly used pre-operatively to evaluate jaw bone volume and to make measurements of bone height and width[14–17]. Although it has been suggested by a number of workers in this field that CT scans could provide radiological densitometric readings of the bone tissue in Hounsfield units[18–20], there are no previous reports on the measurement of BMD for the purpose of evaluation of bone quality in the jaws prior to implant treatment.

Quantitative computed tomography (QCT) has the major advantage of enabling trabecular and cortical bone density to be evaluated separately. Bone mineral content has been assessed in the mandible[11,12], but QCT of the trabecular bone density has been limited to correlating it with the degree of skeletal osteoporosis in postmenopausal women[21]. The aim of the present study was to evaluate the possible use of QCT for measuring the trabecular BMD in the edentulous mandible prior to implant placement.

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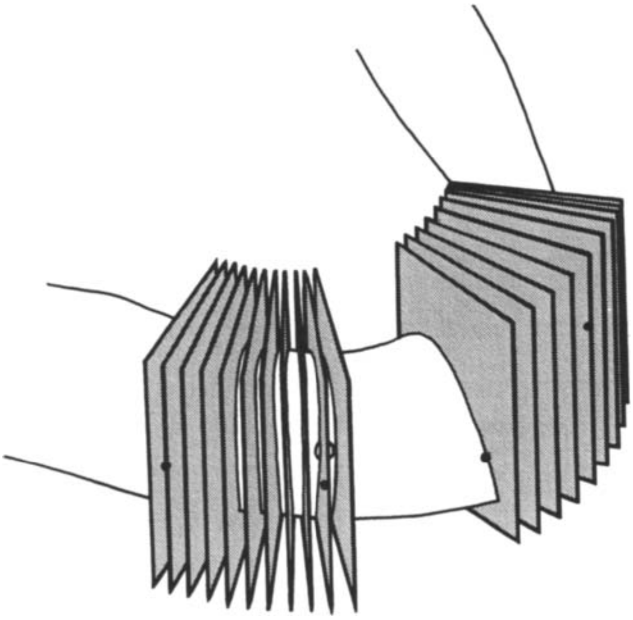

Figure 1 Schematic drawing of a mandible illustrating how the CT scans were obtained perpendicular to the mandible in the anterior and posterior sections as indicated by the tantalum pins

Material and methods

Material

The material consisted of 15 mandibles from individuals aged 62–94 years (mean 79 years) who before death had elected to donate their bodies to medical research. There was no history of disease or treatment that might have altered bone metabolism. The whole body was fixed in formalin using a mortal perfusion technique. The mandibles were later removed, degloved and post-fixed in 10% neutralized buffered formalin solution. This method preserves both the structure and tissues, including fat. The mandibles were wholly or partially edentulous, and sections without teeth, six anterior and 27 posterior, were examined. To obtain reference points, two tantalum pins (1.5 × 0.5 mm) were inserted at the buccal side of each edentulous section. In the posterior sections, one pin was inserted just beneath the mental foramen and the other 2 cm distally. In the anterior sections, the pins were inserted 1 cm from the midline on each side.

Production of CT images

CT images were obtained with a Somatom DRG scanner (Siemens, Erlangen, Germany) at 125 kV and 230 mA with a slice thickness of 2 mm using a standard convolution kernel. The mandibles were carefully positioned with the scanning planes perpendicular to the buccal and lingual plates. Ten direct CT images were obtained of the section between the tantalum pins (Figure 1), except for one mandible (no. 6), where there were seven. The accuracy of slice thickness and table feed was checked with a weekly quality assurance programme. The region of interest (ROI) was defined manually on each image as the trabecular bone 1–2 mm from the inner margin of the cortex (Figure 2, left). However, if there was a break in the inner cortex, the innermost part was included in the ROI (Figure 2, right). Every CT image was enlarged in order to increase the accuracy when the ROI was superimposed on the image using a graphic tablet. The enlargement procedure did not affect the quantitative data obtained.

Calibration of the CT scanner for BMD determination

The calibration procedure is described in detail by Nilsson *et al.*[22]. The CT scanner was calibrated for BMD determination using (i) BMD-simulating substance samples placed in a phantom simulating the skull, and (ii) the same samples placed in free air (simulating the mandibles in this study). Due to the very hard beam filtration of the Somatom DRG unit (added filtration 2.5 mm Al + 0.4 mm Cu), the beam hardening in the lower part of the skull phantom is not very pronounced. The calibration equation did therefore not significantly differ for these two situations and could be described by the equation:

$$\text{BMD (mg cm}^{-3}) = 0.960\,(\text{HU}_{\text{mean}} + 14) - 2.3 \times 10^{-4}\,(\text{HU}_{\text{mean}} + 14)^2$$

where HU_{mean} is the mean Hounsfield unit (HU) value in the trabecular part of the mandible. It must be stressed that this calibration is valid only for this type of CT scanner, for a slice thickness of 2 mm and using a specific convolution kernel.

The Somatom DRG scanner uses caesium iodide (CsI) scintillation detectors which are very sensitive to variations in temperature. Effects of drifting on the sensitivity of the detector, both as a whole and for individual detector elements, have to be corrected for at least every hour. This procedure, called 'air calibration', is performed with no object in the gantry. In this

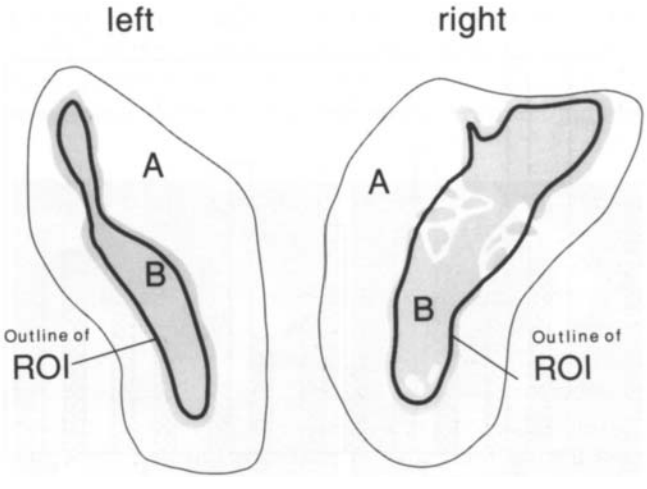

Figure 2 Schematic drawings of CT images illustrating how the region of interest (ROI) was allocated between the cortical (A) and trabecular (B) bone. The margin between A and B is well defined on the left but difficult to identify on the right

study, air calibration was always carried out immediately prior to scanning.

Statistical analysis

Differences in BMD between mandibles and different sections of the mandibles were investigated using analysis of variance with repeated measurements. A statistically significant difference was considered to be present when $p \leq 0.05$. The measurement of BMD was performed twice in 20 CT images. The second measurement was made at least one week after the first and the entire procedure with window-setting and enlargement was repeated. The precision of single measurements was expressed as the standard deviation $SD = \sqrt{\Sigma d^2/2n}$, where d is the difference between two measurements and n is the number of duplicate measurements. The measurement precision was estimated as SD = 17 mg cm^{-3}.

Results

The results of the measurements of BMD are shown in Table I. Significant differences ($p = 0.0001$) in mean BMD were found between the 15 mandibles. Measurements were performed in both anterior and posterior sections in six mandibles, and, with the exception of one (no. 8), the differences were significant ($p \leq 0.05$): values were higher in anterior than in posterior sections, as shown in Figure 3. The variation between different slices within a section was also large, as can be seen from the maximum and minimum values in Table I. The mean BMD for the first five slices were compared with those of the last five in the 12 mandibles where measurements were made on both left and right posterior sections; those for the first five slices were higher in 16 of the 24 sections examined (Figures 4 and 5). However, significant differences were found in only nine of these sections. An example of a CT image with a high BMD is shown in Figure 6 (left) and one with low BMD is shown in Figure 6 (right).

Table I Mean and standard deviation (sd) of BMD (amount of calcium hydroxyapatite; mg cm^{-3}) in 33 sections of 15 mandibles. Minimum and maximum values are given for the different slices within the mandibular sections

Mandible	*Section*	*Side*	*Mean value*	*sd*	*Minimum value*	*Maximum value*
1	Posterior	R	294	47	236	382
	Anterior		580	99	433	683
	Posterior	L	348	53	281	425
2	Posterior	R	177	56	112	271
	Anterior		457	115	351	700
	Posterior	L	341	161	72	543
3	Posterior	R	207	45	122	277
	Posterior	L	238	51	149	310
4	Posterior	R	134	53	41	200
	Anterior		349	93	214	440
	Posterior	L	207	170	−35	461
5	Posterior	R	479	58	379	541
	Posterior	L	410	77	244	484
6	Posterior	R	169	35	101	210
7	Posterior	R	176	55	78	261
	Anterior		444	86	308	563
	Posterior	L	107	151	−147	274
8	Posterior	R	194	46	139	260
	Anterior		233	77	113	394
	Posterior	L	213	38	169	271
9	Anterior	L	224	92	−3	303
	Posterior		354	60	257	452
10	Posterior	R	205	45	152	309
	Posterior	L	207	24	160	236
11	Posterior	R	11	35	−52	68
12	Posterior	R	162	78	64	281
	Posterior	L	132	80	42	281
13	Posterior	R	227	41	153	267
	Posterior	L	209	70	100	304
14	Posterior	R	197	34	142	249
	Posterior	L	181	19	154	216
15	Posterior	R	462	89	398	602
	Posterior	L	487	84	359	613

Discussion

We determined BMD by single-energy QCT. The precision is higher than that of dual-energy QCT but

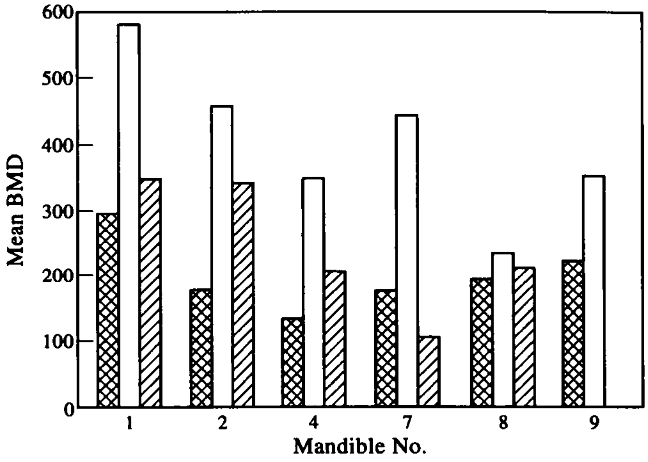

Figure 3 Histogram showing mean values for BMD in anterior and posterior sections of six mandibles: ▨ left posterior; ☐ anterior; ▩ right posterior

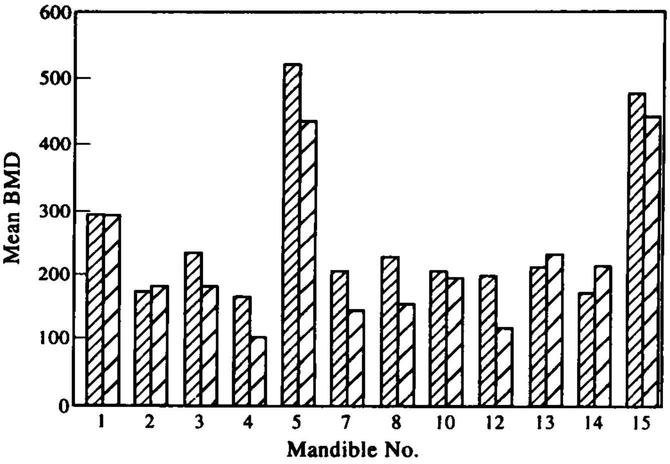

Figure 4 Histogram showing mean values for BMD of the first five and last five slices of the right posterior sections in 12 mandibles: ▨ first five scans; ▧ last five scans

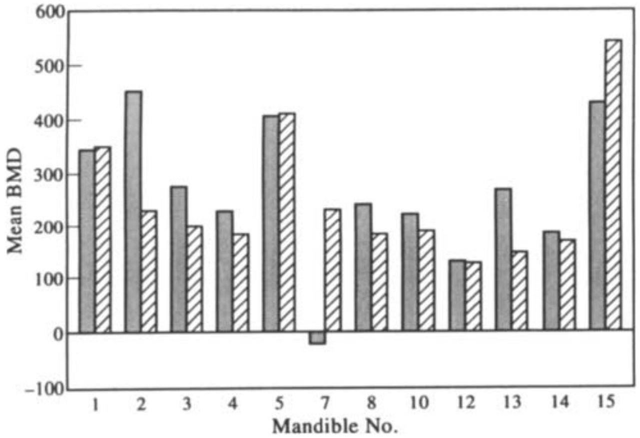

Figure 5 Histogram showing mean values of BMD of the first five and last five slices of the left posterior mandibular sections in 12 mandibles: ▩ last five scans; ▨ first five scans

the accuracy is lower due to the errors arising from the fat content of the trabecular bone[23,24]. The method used in our study reduces its influence on the derived values by taking into account the fact that, with few exceptions, trabecular bone is replaced by fatty bone marrow with increasing age[22]. This is illustrated by the negative BMD found at four sites, which indicates that there is no or very little mineral within these trabecular specimens. This affects both the density and atomic composition of the region being investigated. The effective atomic number of trabecular bone is reduced, mainly due to the higher proportion of carbon in fat and bone marrow and the relatively lower calcium hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] content. As a consequence, the BMD is reduced. The change in density as recorded by CT will therefore be a function of the reduction in both density and mean atomic number in individuals with a lower BMD. This will lead to a non-linear calibration curve that can be described by a two-degree polynominal. Different workers calibrate their CT units with different concentrations of bone mineral-simulating substances (for example K_2HPO_4 or $CaHPO_4$). However, the liquid in the sample is commonly of the same atomic composition, regardless of the 'BMD' concentration. Therefore, the variation in effective atomic number in such samples does not reflect that of human trabecular bone, and this will lead to erroneous results, especially for low and high BMDs. For instance, using a calibration based on K_2HPO_4 solutions in water for the Somatom CT unit will yield a correct BMD result for a human trabecular bone specimen with a mean value of about 320 HU, but will give results that are 6% too low and too high at 40 and 580 HU, respectively.

Taguchi *et al.*[24] studied the effect of the size of the ROI in QCT and found that an ROI < 1 cm^2 with a 2 mm slice thickness gave unacceptable results, but the values for ROI > 1 cm^2 were consistent. If axial scans are used, the buccal and lingual plates at a specific site limit the area that it is possible to measure. In contrast, none of our perpendicular slices was less than 1 cm^2, which gave a larger area to measure. The precision of a single measurement was also found to be high. However, direct CT scans perpendicular to the buccal and lingual bone plates are difficult to obtain clinically because of difficulties in patient positioning. We therefore intend to compare the results of BMD measurements in reformatted axial scans with those from the direct images in our study.

QCT has previously been used to measure mineral content in the trabecular bone of lumbar vertebrae[22]. However, results from measurements in other parts of the skeleton should not be compared with those in the mandible, as the latter seems to be subject to a more marked decrease in the amount of bone mineral through life[25]. This was confirmed by Klemetti *et al.*[21], who found no correlation between BMD in the trabecular bone of the mandible, femoral neck or lumbar spine. Using mandibular autopsy specimens gave us an opportunity to compare BMD with other measurements such as the trabecular bone volume at the same site which we will report subsequently.

We found higher values of BMD in the trabecular bone of anterior compared with posterior sections and also marked variations within the same section. This is in agreement with Klemetti *et al.*[21]. However, they found generally higher values of BMD. This could be due to the fact that their patients were younger than the individuals that we examined. There are also several other reports confirming that the bone in the anterior part of the mandible is denser than in the posterior and that variations in bone density are found in the same region[26–28]. However, it is not clear whether dense bone means the high quality required for successful implant treatment. In a clinical follow-up study, Friberg *et al.*[3] found the highest fixture loss in mandibles with the densest bone and in maxillae with low-density trabecular bone. They suggested that this failure may be due to overheating during drilling at bone sites with high density.

The future demands for implant treatment are difficult to predict but will probably increase in the partially dentate population. This, together with the fact that the anterior teeth in the mandible are usually retained the longest, makes it important to be able to estimate bone quality in the posterior parts of the jaw. In our view, bone quality must be described in a more detailed way, which should include not only mineral content but also

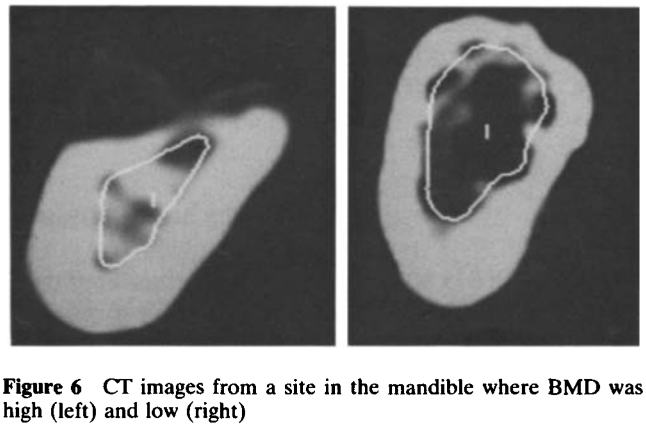

Figure 6 CT images from a site in the mandible where BMD was high (left) and low (right)

the volume and structure of both cortical and trabecular bone. BMD measurements of trabecular bone are needed because the skeleton undergoes age-related changes which affect trabecular bone, due to its higher turnover rate, more than they affect cortical bone[29]. QCT gives a site-related measure of BMD which could be an advantage since, as shown in our study, the state of the bone varies within a small area.

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