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REVIEW ARTICLE

Bone quality and quantity measurement techniques in dentistry

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A B S T R A C T

In dentistry, finding a reliable method for measurement mineral density of bone and bone strength in jaw bones is not only beneficial for implant planning, but also benefical in early diagnosis of diseases which effects the mineral density of bone like osteoporosis. Dual-energy X-ray absorptiometry (DXA) method is considered as a gold standard for measurement of bone mineral density in medicine. DXA yields quantitative information on bone structure. In addition DXA, imaging methods which given detailed qualitative information have been developed. Finding a method, which can be also applied on jaw bones and will not damage to the patient and offering a correct information that might be contrubute in dentistry especially with respect to implant and periodontal operations.

The aim of the present article, is to provide basic information to reader from past to present about main procedures on assessment of bone structure also including jaw bones and the advantages and disadvantages of these methods.

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INTRODUCTION

The clinical use of noninvasive methods to determine bone quality and quantity is a crucial issue.[1] Bone mass, structural properties (macro-microarchitecture, size), and material properties (modulus of elasticitiy, mineral density or densitometric) constitute mechanical competence of bone.[2] Mechanical behavior of bone is a critical factor in the attainment and maintenance of osseointegration[3,4] and bone strenght.[5] The preferred method to measure bone mineral density (BMD) is Dual Energy X-ray Absorptiometry (DXA). It is a method that directly measures the density of bone and is considered as a "gold standard" of measurement. However, DXA does not yield any information on structural characteristics of the bone[6] and it has been indicated that bone quantity can not explain bone fragility alone.[7,8] With the developments in technology, quantitative computerized tomography (QCT), quantitative ultrasound (QUS) and micro-computed tomography demonstrating the structural characteristics of the bone have started to be used.[9-13] In dentistry, investigations on methods ranging from morphometric methods to advanced imaging methods are still in progress for finding a method practical enough to be used in daily clinical practice. Such a method will affect the success of treatment by providing a healthy evaluation of bone quality before both periodontal and implant applications. In addition, a more practical and economic method will enable the detection of diseases such as osteoporosis from mandibula before fractures occur. The methods in the literature which are quality and quantitatively determine the bone changes are summerized in this article.

TECHNIQUES OF DETERMINING BONE QUALITY AND QUANTITY IN JAW BONES

Radiomorphometric indexes

Due to their ease of application, radiomorphometric indexes have been the most commonly investigated method. They are not used for the measurement of density directly. Radiomorphometric indexes depend on the measurement of the thickness and evaluation of the mandibular cortical bones in certain parts of jaw bones. The method has been used predominantly in osteoporosis research to determine the diagnostic validity of possible morphological changes in jaw bone that may be related to osteoporosis symptoms. DXA measurements have been the most common reference technique in this context. Radiomorphometric indexes studied include the following: mandibular cortical index (MCI; qualitatively considering the endosteal margin of the mandibular cortex) as follows: C1: normal (even and sharp) endosteal margin; C2 osteopenia (with semilunar defects); and C3 osteoporosis (presence of porosity and reduced cortical thickness).[14-19] Antegonial index (AI; mandibular cortical thickness over the C), Gonial index (GI; mandibular cortical thickness over the E), Mental index (MI; mandibular cortical thickness over the F), Panoramic mandibular index (PMI; the ratio of the thickness of the inferior mandibular cortex over the line C, the distance between the lower border of the mandible and the foramen mentale over the same line).[19-22] The measurement of these indexes relies on the guidelines drew on panoramic radiograms (Figure 1).

Fractal dimension analysis (FD)

This is a method of analysis based upon the idea that bone strength does not only

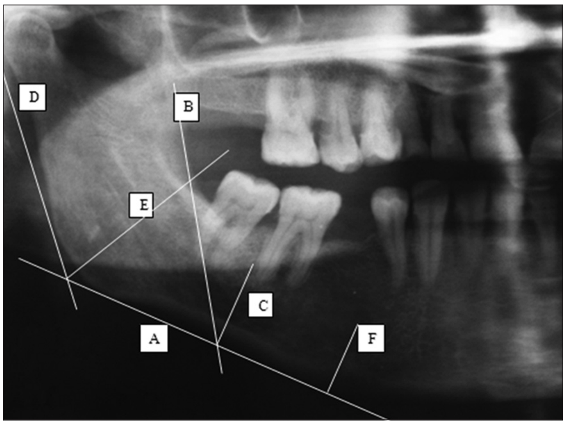

Figure 1. A, tangent lined to the bottom of the mandible; B, tangent lined to the anterior border of the branch; C, perpendicular to A, at the intersection of B with the bottom of the mandible; D, tangent lined to the posterior border of the branch; E, bisectrix of the angle between A and D; F, perpendicular to A, at the middle of the mental foremen (unpublished figure by Dr.Yalçın Yeler D)

depend on bone mass but also on bone structure and morphology. It is therefore necessary to evaluate bone quality as well as bone mass. It is a mathematical method used to identify complex shapes and structural models that provides numerical results.[23] X-rays are affected by trabecular dispersion and fractural developments as they move along a certain tissue. When bone mass is lost, bone trabecules get thinner and their integrity is impaired, which increases the number of bone marrow cavities. FD can also measure of cavity dimensions.[21] Measurements are obtained by translating the digital or digitalized periapical or panoramic images into binary and outline images and converting them into numerical results through a special computer software[23] (Figure 2).

Densitometric analysis (DA)

This is the measurement of bone density in radiographic films in terms of optical density. In this technique, optic density of the bone investigated is compared with step-wedge utilized as reference. Optical density is a degree of transparency in selected areas in radiography and is expressed as radiodensity. When the DA value is zero, this means that the entire light has passed.[21] In this method, a metal "step-wedge" of some thickness is placed on film or cassette and is become with the selected object. In this way, the density of the object is defined in terms of the thickness of the metal. Different degrees of thickness absorb x-rays in different amounts, and different density values appear on films after bathing, depending on the thickness. These different values are measured by the densitometry device.[24,25]

DXA

It is the most practical method in daily clinical practice to measure the bone mineral density (BMD) of bones such as vertebra, femur and forearm due to its speed and accuracy.[24,26-28] It is defined today as the "gold standard".[29] In DXA, x-ray tube, which gives double-energy x rays, is used as the energy source. Two x-ray beams are used, one low and the other high (between 40-140 keV), to eliminate the effect of surrounding soft tissues on measurements. While passing through soft tissues, the absorption of the two beams of low and high energy is disproportionate. This difference makes it possible to determine only the absorption value of the bone by eliminating the value of the other structures that enter the frame along with the target bone. The result values are given in gr/cm^2.[24]

DXA with suitable software can be used in other anatomical areas.[24] In clinical studies, determining BMD in mandible by DXA became possible through the efforts of Corten et al.[30] In the 90s, studies on mandible using DXA then gained speed.[9,24,26,31,32] However, utility of DXA in mandible measurement has been limited. Because

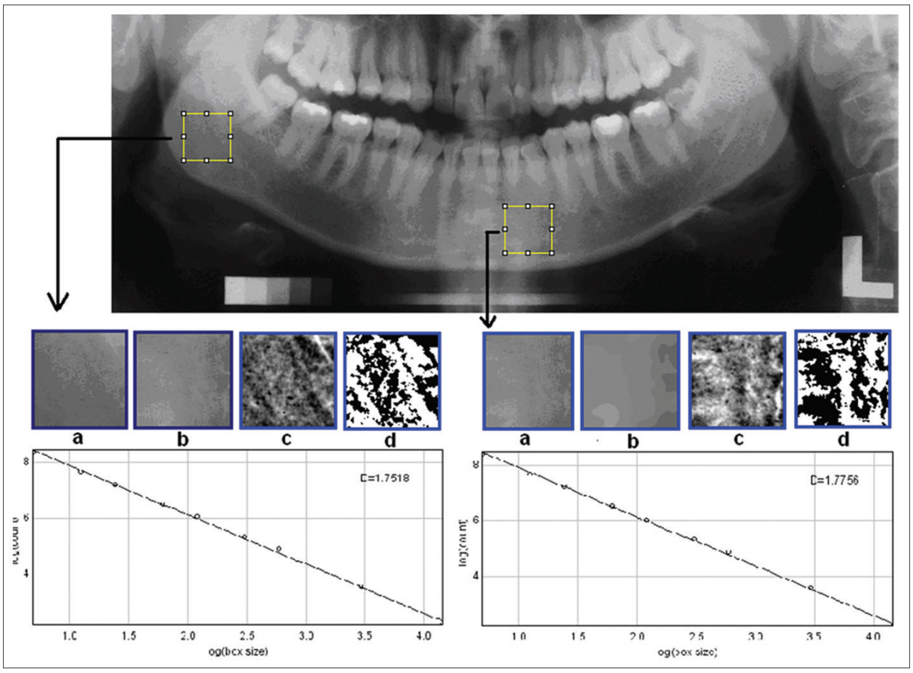

Figure 2. Fractal analysis of two different regions in the mandibula. Row to binary (a, d) images of the regions of interest and relating graphics show fractal dimensions (unpublished data by Dr.T.E.)

mandible contains contralateral sections. Because of the controlateral sections we can not prevent superposition. Limitations result from positioning patients requires skill and experience of the operator, patients find it hard to remain still in the same position and feel uncomfortable.[16,26,27,30] Orthopedic physicians commonly employ DXA to measure the bone mineral content (BMC, in gr) or BMD (in gr/cm2) of the femoral neck or spine as a method for determining patients bone strength.[1,33,34] However, the strength of bone is affected by both its material (or densitometric) properties and its geometric parameters (size, shape and macroarchitecture). Nevertheless, BMD acquired through the use of DXA is the local BMD, and is unable to acquire bone shape to provide structural stiffness characteristics.[5,35] Advantages of DXA include low cost, low radiation doses, and high accuracy.[36] Yet, DXA can not differentiate between, cortical and trabecular bone density.[9] In addition, DXA doesn't provide the cross-sectional image and determination of the positioning is difficult; hence, it is not appropriate for implant placement.[37]

Quantitative CT (QCT)

Macroscopic assesment of three-dimensional (3D) bone geometry can be performed by using QCT. Unlike DXA, QCT measures volumetric density with resulting values expressed in gr/cm.[9,16] BMD determined by QCT or peripheral QCT (pQCT) through the appropriate conversion of the Hounsfield (or grayscale) units(HU) of the bone.[6] The HU values varies according to the density of the tissue. Higher values are denser. The mean HU values decreases according to the amount of mineral. Hence, the HUs can be used directly to determine bone quality alterations.[38] The best feature of QCT is the capability of evaluating cortical and cancellous bone mineral densities separately. Trabecular bone is approximately eight times more metabolically active than cortical bone.[39] QCT, which measures trabecular bone, is therefore highly sensitive to show changes in skeletal density.[38] An important drawback of QCT is the delivery of ionizing radiation to patients.[40] It is also expensive and is not widely available.[38]

CT

CT has a capacity of preventing the superposition of irrelevant structures, high definition, and images can show axial, coronal, sagittal or any section. Because of these reasons CT a frequently used imaging.[41] However, due to the high radiation dose of traditional CTs, researchers have turned toward alternatives such as CBCT for evaluating bone density prior to implant practices.[42] Pixel size of CT is approximately 200-300 μm, whereas the average trabecular size is approximately 100 μm. Therefore, the bone density shown by CT limited. Despite these limitations, several specific programs were developed for the measurement of bone density before the implant procedure (i.e. Vimplant;Korea, SimPlant;Belgium). These programs contain diverse functions such as the measurement of bone quantity and bone density of implant placement site, tracing of the mandibular canal etc.[37]

CBCT

It is based on volumetric tomography using a two-dimensional extended digital array providing an area detector. This is combined with a 3D x-ray beam. Two-dimensional images are made three-dimensional using software programs. CBCT offers advantages such as the lower dose of radiation, image accuracy, rapid scan time, and reduced costs.[43,44] Despite the excellent spatial resolution of CBCT for hard tissues during the measurement of bone density, the compatibility with HUs of conventional CT remains a problem to be solved in all types of equipment. Regardless of the type of equipment, conventional CT methods can be presented at constant value. But the density value measured by CBCT varies depending on the type of equipment, and the values do not concur with the density values of conventional CT methods.[37] CBCT data have a larger amount of scattered x-rays than conventional spiral-CT. This may enhance the noise of reconstructed images and thus affect the low contrast detectability.[45] Because of scatter and artefact, HU values in CBCT are not valid and therefore the method of correlating BMD to HU values from CBCT is not ideal. Moreover, the scatter and artefact in CBCT worsen around the inhomogeneous tissues with reduced HU values up to 200 HU.[46] This information confirms that the HU in CBCT is not a valid method for bone quality assessment.[47]

QUS

QUS measurements of bone have been proposed as a radiation-free, non-invasive technique to screen and identify patients at risk for osteoporosis.[48] The advantages for the use of QUS in the assessment of bone status in children and adolescents lie in its lack of ionizing radiation, ease of use, portability, and low cost. Despite its proven advantages, the use of QUS remains controversial, due to scarce knowledge of the physical mechanism of ultrasound in assessing bone characteristics and the difficulty in comparing the results obtained by QUS with those acquired by DXA.[49] QUS presents the advantage to be modified not only by bone density, but also by bone architecture and quality.[12] The calcaneus is chosen for measurements because it is an easily accessible site rich in trabecular bone, evolving with age in parallel to lumbar vertebrae.[50] This site would be particularly interesting in patients with vertebral deformities, aortic or paravertebral calcifications, or even in the elderly in whom DXA of the spine is less accurate.[51]

Micro-computed tomography (micro-CT)

In the past 10 years, micro-CT has been commonly used in laboratories to examine the trabecular and cortical bone measurements.[52-55] Bouxsein et al.[55] indicated that micro-CT scans can be considered the gold standard for evaluating the trabecular bone structure.[55] It provide a spatial representation of bone formation at the implant surface and peri-implant region up to a few microns or even better, and can evaluate both qualitative and quantitative morphometry of bone integration around dental implant.[13] In another study, human cadaveric maxillary and mandibular trabecular bone with 3D morphometric data acquired through micro-CT were analyzed and correlated with bone density measurement in HU scale and Lekholm-Zarb bone classification.[2,3] This device offers a much better image resolution than CBCT, but the long scanning time, high radiation dosage and size limitations hinder its clinical use.[6] In addition, it is quite costly.[56]

High resolution-MR (HR-MRI)

HR-MRI allows nonionizing 3D imaging of the trabecular network at peripheral sites. During scanning, a strong magnetic field and a series of radiofrequency (RF) pulses are applied to the specimen to generate 3D images of the hydrogen in water within skeletal tissues. Bone tissue generates no signal in standart MR images as a result of the low water content of the tissue and the chemical environment of the protons within the bone matrix. When the marrow is imaged, trabeculae appear as a dark space within the bright marrow.[57] Resolutions as small as approximately 50x50x200 micron have been achieved ex vivo[58] and resolution of 156x156x300 micron are typical in vivo.[59] Consequently MRI based trabecular morphologic parameters are also affected by partial volume effects.[60] The MRI based trabecular measures are correlated with their counterparts measured by micro-CT and MRI can detect age and disease induced changes in trabecular morphology.[61] A critical advantage of this technique is the ability to generate 3D images of bone geometry and microarchitecture without ionizing radiation. Disadvantages of the tecnique include the long scan times required for high-resolution images of trabecular bone.[40]

Studies using various densitometry methods

In most studies on radiomorphometric indexes, the study group is composed of postmenopausal osteoporotic women whose bone densities are considerably diminished. Some researchers stated that radiomorphometric indexes could be useful in determining low bone density. Mahl et al. reported that, PMI specifity is found to be low, in normal, osteopenic and osteoporotic individuals, all indexes can be useful.[20] Vlasiadis et al. reported that in postmenopausal patients indexes can be beneficial in the early diagnosis of osteoporosis.[14] Ledgerton et al. reported that among the radiomorphometric analyses, MCI had excellent reliability and repeability.[17] Bollen et al. and Taguchi et al. demonstrated that MCI could be used as an indicator of skeletal BMD, the risk of osteoporotic fractures or bone turnover.[62-64] None the less, other researchers, who encountered problems associated with the repeatability and accuracy of these evaluations, considered these problems as a barrier to the practical use of indexes.[17,65] There are also researchers who claim that the indexes used with this purpose cannot be able to distiguish between osteoporotic/osteopenic individuals.[16] In the study of Drozdzowska et al. no statistically significant correlation was found between MCI and PMI values on panoramic radiographs and DXA and QUS measurements on patients without teeth.[16] Çakur et al. used indexes with mandibular DXA. No relation between skeletal and mandibular bone mineral density was identified using indexes or mandibular DXA.[27]

Radiographic densitometry of the mandible has been performed in a number of studies, using both intra-oral[66-69] and panoramic radiographs.[69,70] Devlin and Homer showed that panoramic radiographs taken with a cassette fitted with a nickel step wedge, could be used to provide a quantitative measure of mandibular bone mineral content in vitro.[71] In the in vivo study of the same investigators, panoramic densitometric measurements were compared with DXA and were not found to be related to mandibular BMC.[24] It was stated that these disappointing results are due to superposition of anatomic structures on step wedge. In the study of Mohajery and Brooks[69], it was concluded that panoramic densitometric analysis can not be used in mandibuler BMD measurements.[69] In another study, the value of both maxilla and mandible in osteoporosis diagnosis with densitometry was investigated. The results showed that premolar area can be useful in density evaluations.[31]

FD method is useful for detecting and quantifying changes in alveolar process bone mineral content[72-74] and is unaffected by variations in exposure, alignment, and choice of regions of interest (ROI).[75,76] Khosrovi et al.[77] reported lower FD values in a periodontally compromised population, and Otis et al.[78] have used FD values to investigate the effects of the quality and quantity of the bone on the extent of apical root resorption. Shrout et al.[75] confirmed that FDs of digitized radiographs of mandibular alveolar bone in periodontitis patients were different from those in healthy controls.[75] However, FD analysis is less predictive than CT's in the differentiation of type II and type III bones in Lekholm ve Zarb classification.[37]

FD analyses are also used to investigate the effect of systemic diseases on the density of mandible. However, some authors have reported increased FD with decalcification/osteoporosis[76,79,80], whereas others determined decreasing values for the FD with decalcification.[81,82] In contrast, Yaşar and Akgünlü[83] argued the difference in FD values in osteoporotic and non-osteoporotic individuals who do not have any statistical significance.[83]

Mandibular measurements can be a reliable indicator for osteoporosis, suggested that mandible and other skeletal areas can be related in terms of bone density. Corten et al. suggested using DXA as a means of investigating bone density in the mandible.[30] Horner et al.[26] showed positive correlation between mandible and overall skeleton. Çakur et al. performed similar studies but found no correlation between mandible and other areas.[27] Bone mineral content of mandible has been studied with dual photon absorptiometry (DPA) as well. In the study of Von Wovern[32], both the forearm and mandible measurements were carried out with DPA, and a significant correlation between both bones was demonstrated.[32] Drozdzowska et al., demonstrated that there was significant correlation between hip DXA measurements and mandibular BMD on edentulous patients (except for trochanteric BMD).[16] In the same study, it was stated that mandibular BMD can be a suitable measurement tool in the diagnosis of patients with osteoporosis.[16] Drage et al., found in their study on edentulous patients that mandibular BMD and hip BMD values were compatible.[84] In this study, it was stated that, hip and lumbar spine BMD's are not reliable in the prediction of maxillar bone density.[84] In a study examining the dentate state and lumbar spine BMD dentate women had a higher lumbar BMD.

They concluded that edentulous patients may be more susceptible to osteoporosis or that a functioning dentition inhibits or delays the progress of osteoporosis (presumably because of better nutritional status of dentate subjects).[85] However, other workers have shown that there is no relationship between the number of teeth present and skeletal BMD.[86,87] In a QMRI study comparing mandibular trabecular bone quality between edentulous and dentate patients, any relationship between dental status and bone quality could not be shown.[88]

In addition, bone densitometric parameters (volumetric BMD), QCT and pQCT are able to acquire geometric parameters (cross-sectional area[CSA],cross-sectional moment of inertia [CSMI],and bone strength index[BSI]).[10,11] CSMI, which is derived from bone density and geometric models, has been reported to give a slightly better estimation of bone strength than bone mass measured by DXA.[5,35,89-91] QCT was stated to be more practical than DXA for implant theraphy, since it provides accurate infromation on bone quality and quantity.[92,93] Lindh et al. examined trabecular bone in mandible and stated that QCT can be useful in determining bone mineral density in mandible before placing the implant.[9]

CT is the most objective method for use in evaluating bone quality, despite basic limits caused by pixel size; the values obtained more strongly correlated with actual bone quality as HUs than those provided by any other method. Bassi et al. claimed that correct results can be obtained from CTs in trabecular bone evaluations on bone density of mandible with and without teeth.[94]

CBCT has been widely used to evaluate alveolar bone density prior to dental implant placement.[95-97] Ferrare et al. reported that the regions of thin bone tissue may not be visualized on CBCT images.[98] There are risks of underestimating bone measurements with CBCT and assuming bone loss that does not exist clinically. Although the difference of the bone high measurement was small, the clinical relevance must be analyzed in the interpretation of CBCT. Bilhan et al. concluded that HU values could be a misleading diagnostic tool for the determination of bone density alone.[47] However, Nomura et al.stated that it may be possible to evaluate the BMC from the voxel values of dental CBCT.[99]

Micro-CT is currently the most accurate method for measuring BMD, the shape of bones, and the structural parameters of trabecular bone; however, size limitations mean that this technique can only be applied to animal models.[6] The ability of micro-CT to accurately analyze the bone microstructure has been assessed by direct comparison with conventional histomorphometry, with the results showing a correlation coefficient exceeding 0,7.[100] This indicates that micro-CT is an ideal method for evaluating the morphology and microstructure of bones.[100]

In conclusion nowadays, it is stated that the quantitative evaluation is important on bone measurement and qualitative evaluation as well. However, a device that collects all of the appropriate equipment with multiple advantages for clinical use is not available, which can make both evaluation of bone quality and quantity and prevent damage to the patient. The present methods offers with these requirements separately. Especially CBCT is often used in the assessment of bone structure in dentistry with less radiation advantages. But CBCT has artefact and scatter problems which give rise to unreliable HU assessments. Therefore the method of correlating BMD to HU values from CBCT is not ideal. CT is currently considered to be the best method of radiographic evaluation.

and has the potential to be developed for use in conjunction with different software systems. Yet, HR-MRI's can also be a more promising method since it is non-invasive.

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