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MINIREVIEWS

Bone mineral density in cone beam computed tomography: Only a few shades of gray

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Abstract

Cone beam computed tomography (CBCT) has often been used to determine the quality of craniofacial bone structures through the determination of mineral density, which is based on gray scales of the images obtained. However, there is no consensus regarding the accuracy of the determination of the gray scales in these exams. This study aims to provide a literature review concerning the reliability of CBCT to determine bone mineral density. The gray values obtained with CBCT show a linear relationship with the attenuation coefficients of the materials, Hounsfield Units values obtained with medical computed tomography, and density values from dual energy X-ray absorciometry. However, errors are expected when CBCT images are used to define the quality of the scanned structures because these images show inconsistencies and arbitrariness in the gray values, particularly when related to abrupt change in the density of the object, X-ray beam hardening effect, scattered radiation, projection data discontinuity-related effect, differences between CBCT devices, changes in the volume of the field of view (FOV), and changes in the relationships of size and position between the FOV and the object evaluated. A few methods of mathematical correction of the gray scales in CBCT have been proposed; however, they do not generate consistent values that are independent of the devices and their configurations or of the scanned objects. Thus, CBCT should not be considered the examination of choice for the determination of bone and soft tissue mineral density at the current stage, particularly when values obtained are to be compared to predetermined standard values. Comparisons between symmetrically positioned structures inside the FOV and in relation to the exomass of the object, as it occurs with the right and left sides of the skull, seem to be viable because the effects on the gray scale in the regions of interest are the same.

Key words: Tomography; Cone-Beam computed tomography; Bone mineral density; Reproducibility of results

Core tip: The development of cone beam computed tomography (CBCT) has allowed for more frequent use of these images in dentistry for the evaluation of dentomaxillofacial structures. Yet, there is no consensus regarding the accuracy of CBCT to determine mineral density of craniofacial bone structures, although this technique has been used for this purpose in several types of analyses. According to the studies available to date, it may be concluded that CBCT should not be considered the examination of choice for the determination of mineral density of osseous and soft tissues, especially when values obtained are compared with predetermined standard values.

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INTRODUCTION

Bidimensional radiographic methods (periapical, occlusal, panoramic and cephalometric radiographs) are widely used in dentistry; however, they do not provide visualization of the regions of interest without the superimposition of structures and consequent camouflage of anatomical details. The advent of images acquired from computed tomography (CT) has made more precise quantitative and qualitative evaluation of the adjacent structures possible[1,2].

Although the use of CT is routine in medical practice, this examination has not been extensively widespread in dentistry, due to the presence of image artifacts, high cost, complexity of the examination and high dose radiation[3].

The development of cone beam computed tomography (CBCT), used for the evaluation of dentomaxillofacial structures, has allowed for more frequent use of these images in dentistry because it is a less complex device that produces images with satisfactory resolution, with little artifact incidence and lower dose of radiation[4].

Multislice and cone beam CT images are frequently used to determine mineral density of craniofacial bone structures[5-10]. Yet, there is no consensus regarding the accuracy of CBCT for this type of analysis. While some studies advocate its use[10-15], others advocate that CBCT is not an adequate tool for this type of evaluation because the intensity values of CBCT are influenced by the characteristics of the system[4,13,16] and by the scanned object[16-18]. This study aims to provide a literature review concerning the reliability of CBCT for the determination of bone mineral density of craniofacial structures.

BONE MINERAL DENSITY

Mineral density is determined by the amount of mineral mass contained in a certain volume of a structure, described in units of mass per area (in bidimensional images) or per volume (in tridimensional images), where only mineral content is considered[19]. Several methods may be used to determine bone mineral density, including digital image analysis of microradiographs, single photon absorciometry, dual photon absorciometry, dual energy X-ray absorciometry (DEXA) and quantitative ultrasound[20-22]. However, these procedures present with limitations inherent to the techniques used because density is determined through images of superimposed structures, not producing tridimensional information[23,24].

Nowadays, multislice computed tomography (MSCT) is one of the most useful medical imaging techniques for the acquisition of data regarding not only bone density, but the density of all the tissues of the body. In these examinations, density is described in hounsfield units (HU) and represents the relative density of a body tissue according to a calibrated gray-level scale based on HU values of the air (-1000 HU), water (0 HU) and dense bone (+1000 HU)[25]. HU values are directly related to the mass absorption coefficient of different tissues[26] and, despite some variation[27], these values may be used for the determination of density of the tissues with a high degree of accuracy[10] and sensitivity, detecting density differences of 1% or less[28]. However, the gray scale can vary between different scanners and with different energies on the same MSCT scanner[25]. The factor with the highest influence on the determination of the gray scale is the energy of the X-ray beam (kVp), which is directly related to the capacity of penetration of the primary beam. The bigger the energy of the X-ray beam, the bigger and more uniform its penetration will be, resulting in smaller variation of attenuation, smaller contrast of images, and smaller density of the structures evaluated. The adequate setting of the energy applied allows for the determination of a correct density[29].

CONE BEAM CT

After the development of CBCT, a less complex device with low operational cost and reduced radiation emission[30-32] used for the acquisition of tridimensional images of dentomaxillofacial structures by Mozzo *et al*[33], the indication of medical CT for the evaluation of these structures decreased considerably, especially due to the higher radiation dose applied to the patient during image acquisition[10,32]. Thus, CBCT has been proposed as a diagnostic method for the determination of bone mineral density[10,11,18,34-36]. Gray values obtained with CBCT are used in an analog way as the HU values for the determination of mineral density[16] and show a linear relationship with the attenuation coefficients of the materials[13,15], HU values obtained with medical CT[11,12,37,38], and density values from DEXA[14].

Despite the correlation between gray values obtained with MSCT and CBCT, errors are expected when CBCT images are used to define the density of scanned structures[39] because these images present with inconsistencies and arbitrariness of gray values[16,40], especially when related to abrupt changes of density in the object[41,42], X-ray beam hardening effect[39,43], scattered radiation[43] and projection data discontinuity-related effect[16], making the validity of the measurements obtained questionable (Table 1).

In CBCT, the abrupt and discrepant variation of the attenuation coefficient of the X-rays in the scanned structures, as occurs in the presence of metallic structures, creates artifacts in the images, which are characterized by dark and bright streaks in the vicinity of the metal object. Once these artifacts exhibit a different color from that of the structure to be analyzed, they are responsible for the inconsistencies in the gray values in the areas where they are present[15,41,42].

Another source of artifacts in CBCT images is the

Table 1 Factors that might lead to inconsistencies and arbitrariness of grey values on cone beam computed tomography images

Ref.	Factors
Nackaerts *et al*[4]	Variation in the devices
	Image-acquisition settings
	Relationship between the object evaluated and FOV
	The position held by the region of interest
Mah *et al*[13]	Variation in the devices
Reeves *et al*[15]	Abrupt changes of density in the object
Katsumata *et al*[16]	Projection data discontinuity-related effect
	Variation in the CBCT devices
	Image-acquisition settings
	Relationship between the object evaluated and FOV
Bryant *et al*[17]	Projection data discontinuity-related effect
	Relationship between the object evaluated and FOV
	The amount of exomass
Katsumata *et al*[18]	The dimensions of the FOV
	The amount of exomass
Pauwels *et al*[39]	X-ray beam hardening effect
	Projection data discontinuity-related effect
	Variation in the devices
Schulze *et al*[41]	Abrupt changes of density in the object
	X-ray beam hardening effect
	Scattered radiation
Pauwels *et al*[42]	Abrupt changes of density in the object
Goodsitt *et al*[43]	X-ray beam hardening effect
	Scattered radiation
Liu *et al*[50]	The position held by the region of interest

CBCT: Cone beam computed tomography; FOV: Field of view.

phenomenon of X-ray beam hardening. In CBCT, when the beam of X-rays made up of broad spectrum photons reaches a certain material, the low energy photons are easily absorbed, altering the spectrum of the beam. Once the X-ray beam reaches a specific point or area of the object by different angles, varied alterations in the intensity of its energy spectrum occur before it strikes the detector, generating different readings of the attenuation coefficient of this point, and may produce dark streaks in the images obtained[41]. Besides causing artifacts in the images, when the low energy photons are absorbed, the X-ray beam gains energy, passing through the tissues more easily, causing an underestimation of the attenuation coefficient and producing dark areas in the images[42].

An underestimation of the attenuation coefficient due to the occurrence of darker gray values also occurs as a consequence of scattered radiation. When the X-ray beam interacts with the object being evaluated, some photons are diffracted from their original position and strike the detector in a random way. This scattered radiation is added to the primary radiation of the X-ray beam, overestimating the intensity measured by the system and underestimating the attenuation coefficient of the object, affecting the obtained values of density[41]. CBCT devices have bigger detectors than the MSCT because the X-ray beam of the former is conical and of the latter is in the shape of a fan, favoring the occurrence of scattered radiation[44].

Another type of artifact related to CBCT images is known as projection data discontinuity-related artifact, which occurs when FOV is smaller than the scanned object. First, during the system rotation for the image acquisition, the X-ray beam strikes the parts of the object located outside the FOV, creating peripheral bright-band near the boundary of the FOV[16,39], this effect being directly related to the mass and spatial distribution of materials or tissues outside the FOV[17].

Besides the presence of artifacts and the inconsistency of the gray values attributed to the characteristics of CBCT, variation in the devices[4,13,16], image-acquisition settings[4,16], and the relationship between the object evaluated and FOV[4,16-18] may also influence in the images obtained because alterations of these variables are associated with low reproducibility of gray values. Due mainly to the integration between some of these characteristics, in most instances, variables are not adequately controlled in the studies of reliability of values of density in CBCT.

At present, there are several models of CBCT devices in the market and significant fluctuations in gray values were demonstrated when different equipment was compared[4,13]. Each CBCT scanner has its own factors of exposition and image reconstruction (FOV, kVp, mA, voxel size, exposure time). Some are fixed, others are variable[13,39], making it difficult or even impossible for studies on determination of density in CBCT to draw conclusions for all the systems used[39].

According to Pauwels *et al*[39], some CBCT devices with specific protocols of exposition generate stable gray values which may be related to HU and density. However, as with medical CT, the determination of gray values is specific to the scanner, depending on the calibration of the devices.

The determination of the dimensions of the FOV in CBCT is very variable due to its different applicability in dentistry. This adaptation of the size of the FOV according to the demand of the examination is a great advantage of the system because it exposes the patient to a minimum amount of radiation in order to evaluate the region of interest. However, it may have significant implications in the gray values of the structures, with small volume FOVs associated with reduced values of density[18].

The decrease of gray values in the smallest FOV may be explained by the reduction of the diameter of the X-ray beam so as to irradiate only the region of interest[45-48]. This X-ray beam limitation may lead to the decrease of the amount of low-energy photons and to the increase in the capacity of penetration of X-rays[49], resulting in a relative reduction of the value of attenuation of X-rays and gray values[43].

The manipulation of the dimensions of the FOV may also alter the amount of exomass, mass present outside the FOV during image acquisition, which is associated with the variability of the gray values in CBCT examinations[17,18]. Katsumata *et al*[18] reported a significant variation of the gray values when objects of different mass were evaluated with different FOV volumes, where the greater volume FOV provided the elimination of the exomass, resulting in less variability of the gray values.

The variability of the gray values associated with the exomass may be explained by the projection data discontinuity caused by the variation of the superimpositions of the non-homogeneous and non-symmetrical tissues outside the FOV along the rotation of the X-ray beam during image acquisition[16,39].

Another factor that may be related to the variability of the gray values in CBCT is the position held by the region of interest (specific area of measurement of density) inside the FOV. This variability occurred when density was determined in various places of a homogeneous structure[4,50] and with more intensity when the same object was scanned repeatedly in different positions inside the FOV under the same exposure conditions[4].

Despite the many variables that may affect image quality and the determination of gray values in CBCT examinations, great effort has been made in obtaining valid gray values in these images. Studies have described methods for mathematical correction of gray levels in CBCT examination using as reference X-ray attenuation coefficients of standardized materials[13,15], gray values obtained in conventional CT examination[50,51], and even correction algorithms during or after image acquisition[51,52]. Yet, owing to different configurations of image acquisition, which may be specific for each CBCT device or altered for several applications of these examinations in dentistry, the correction methods of gray values obtained in CBCT still do not generate consistent values which are independent of the devices and their configurations or of the scanned objects[15,50].

CONCLUSION

According to the studies available to date, it may be concluded that CBCT should not be considered the examination of choice for the determination of mineral density of osseous and soft tissues, especially when values obtained are compared with predetermined standard values. Comparisons between symmetrically positioned structures inside the FOV and in relation to the exomass of the object, as with the right and left sides of the skull, seem to be viable because the effects on the gray values in the regions of interest are the same.

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