Original paper

Questionable accuracy of CBCT in determining bone density: A comparative CBCT–CT in vitro study

Aayushi Gaur[1,A–D,F], Manu Dhillon[2,A,C,E,F], Nidhi Puri[1,A,E,F], Upasana Sethi Ahuja[1,E], Akshay Rathore[1,B,E]

[1] Department of Oral Medicine and Radiology, I.T.S. Centre for Dental Studies and Research, Muradnagar, India
[2] Department of Oral Medicine and Radiology, D.J. College of Dental Sciences and Research, Modinagar, India

A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

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Address for correspondence
Manu Dhillon
E-mail: drmanudhillon@yahoo.co.in

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Abstract

Background. The accuracy of the estimation of radiological bone density with the use of the cone-beam computed tomography (CBCT) grayscale is still questionable. Standardization and correlation with the gold standard computed tomography (CT) Hounsfield units (HU) is required prior to clinical application.

Objectives. The objective of the present study was to evaluate the reliability of the grayscale for the estimation of bone density, using samples with intact soft tissue in order to substantiate the clinical use of the scale.

Material and methods. A total of 240 sites in 20 goat heads were scanned to obtain radiological bone mineral density via Hounsfield units in CT and the grayscale in CBCT. The anatomical architecture of soft tissues was preserved for all samples. Two observers obtained the data, which consisted of 3 variables (mean, minimum and maximum) for both scales. The statistical analysis of the data was conducted using Cronbach's alpha, Pearson's correlation coefficients, the independent samples *t* tests, and regression analysis.

Results. Differences in the means of the mean, minimum and maximum values between the 2 scales were statistically highly significant ($p = 0.000$). The correlation coefficients for the mean, minimum and maximum values of the 2 scales were 0.496, 0.037 and 0.396, respectively. Regression analysis revealed that the R^2 values for the mean, minimum and maximum values were 29.79%, 21.05% and 19.45%, respectively.

Conclusions. The positive but weak correlation between the 2 scales and the low predictive reliability of the grayscale reveals its questionable applicability for the estimation of density in comparison with the standard HU.

Keywords: CT, CBCT, bone density, Hounsfield units, grayscale

Introduction

Constant remodeling due to physiological processes and aging phenomena have immensely increased the need to study bone quality and its importance while planning surgical and non-surgical procedures. The rehabilitative management of post-menopausal osteoarthritis and osteoporosis, fracture healing, orthodontic correction, and implant-supported occlusion rehabilitative surgeries include the radiological estimation of bone mineral density as an integral part of procedure planning and execution.[1]

The superimposition and consequent camouflage of the bony landmarks by anatomical structures compromise the visualization of regions of interest (ROI) in two-dimensional (2D) radiography. Such limitations are overcome by precise quantitative and qualitative imaging techniques, such as computed tomography (CT). Bone density is represented by Hounsfield units (HU) on CT scans, and is considered the standard for qualitative bone estimation.[2] The HU value depends on several factors, including the composition and nature of the tissue being imaged.[3]

Medical CT is commonly used for the imaging of several pathologies. This technique provides high precision and better visualization of hard tissues, making it a favorable approach for the evaluation of mineral density. High radiation exposure and the high cost of CT scans underscore the need for advances in this imaging modality. Comparable high resolution with low radiation exposure and cost-efficiency can be achieved by using cone-beam computed tomography (CBCT).

The calibration of the grayscale is done by taking HU as the standard base scale for the evaluation of mineral density. The HU value used in CT is calculated from the linear attenuation coefficient of each tissue and takes the linear attenuation coefficient of water into account. The grayscale also shows a linear relationship with the attenuation coefficient of the scanned material.[4] The reliability of the grayscale for the evaluation of mineral density has been a subject of discussion, as there have been many studies performed to assess the correlation between HU and the grayscale, with varying results.[5–7]

The available literature demonstrates the use of cortical and trabecular bone equivalent materials, along with the soft tissue simulations done by homogenous resin coverage, in experiments to derive mineral density. The homogeneity of the bio-like material, along with the absence of multi-level anatomical architecture in soft tissue imitations, fails to replicate heterogeneous human tissue, which can be a roadblock for the application of such bio-like materials in clinical scenarios.[8] It has been established that the attenuation of radiation is a direct linear function of the density of the matter. Furthermore, it is certain that the data formulated while working with dried preserved tissues cannot be compared with human tissues of variable densities due to their complex architecture. The varied densities of fat, vessels, hair and skin, and hard and soft connective tissues, are important variables, considering the attenuation of the radiation beam.[9] Even though a positive correlation has been revealed in previous studies, several authors have mentioned the need for the inclusion of living physiological tissue rather than using cadaveric mandibles and tissue equivalent materials for the sake of the attenuation offered by the adherent soft tissue in the actual patient.[8]

The present study aimed to evaluate the accuracy and applicability of the grayscale values of CBCT as compared to the HU of CT in estimating radiological bone mineral density. The study further aimed to obtain the conversion ratios for transmuting the available CBCT grayscale into the gold standard HU in order to establish a standardized scale for density estimation.

Material and methods

This study was conducted in the Department of Oral Medicine and Radiology at the I.T.S. Centre for Dental Studies and Research, Ghaziabad, India, and at the Advanced Diagnostic Center, Hargobind Enclave, Delhi, India, to evaluate the accuracy of the CBCT grayscale in determining bone density. The study was approved by the institutional Ethics Committee (ITSCDSR/IIEC/2018-21/OMR/OMR). The radiological mineral density of the specific anatomical areas in the goat mandible and maxilla at the same spatial coordinates was measured using CBCT (grayscale) and CT (HU).

Goat heads with intact physiological soft tissue were acquired from the local butcher. The goats were butchered for the purpose of consumption. To preserve the integrity of soft tissues, the goat heads were stored at a temperature of 4°C in an icebox. The scans were done on the same day when the samples were acquired.

The mean, minimum and maximum values were obtained for each ROI in the CBCT and CT scans. Two radiologists procured the data for both types of scans. A radiologist with an experience of more than 10 years obtained the initial values for both scales, which were then confirmed by another radiologist with 3 years of experience.

During scanning, the occlusal plane of the goat head was kept parallel to the floor. A customized wooden stool was made to standardize the position of the goat heads during CBCT. Sterilization was maintained by using a mackintosh sheet and a transparent cellophane sheet while the head was placed in the CBCT scanner.

A total of 20 samples were included in the study. The axial sections of each sample obtained with CBCT and CT were used for the evaluation. A total of 240 sites were evaluated in 20 samples (i.e., 12 sites for each sample; 6 in the maxillary arch and 6 in the mandibular arch).

The ROI in the maxilla were as follows: the region anterior to first premolar; the region posterior to first premolar; and the region distal to second molar. The ROI in the mandible were as follows: the region anterior to first premolar; the region posterior to first premolar; and the region distal to the last present molar.

The sites were evaluated bilaterally to obtain the grayscale values from the CBCT scan and HU from the CT scan.

First premolar was used as a standardized marker to ensure the overlapping of the focused sites from both the scans of an individual sample. The sections were adjusted to obtain the largest vertical dimension of first premolar in the sagittal and coronal sections bilaterally in the respective arch. The ROI was then analyzed for the grayscale values and HU from the CBCT and CT scans, respectively. To determine the bone density values of the ROI, a region of an area of 12 mm^2 was traced on to all sites adjacent to the respective tooth. In case of the absence of the reference tooth, the posterior tooth was used as a reference.

The CBCT scans were taken using the NewTom® GiANO scanner (model SN 70820432; Cefla, Imola, Italy,) with the following specifications: field of view (FoV) of 11 × 8 cm^2; slice thickness of 0.15 mm; tube voltage of 90 kVp; tube current of 32 mA; and exposure time of 9 s (pulsed). The CT scans were obtained using the Somaton® scanner (Siemens, Erlangen, Germany) with the following specifications: 120 kV; 118 mA; high-resolution kernel; slice thickness of 0.75 mm; interval of 0.5 mm; pitch of 0.5 mm; and gray density 31.78 bit.

Statistical analysis

The statistical analysis was carried out using the IBM SPSS Statistics for Windows software, v. 22.0 (IBM Corp., Armonk, USA). The inter-observer reliability was calculated using Cronbach's alpha and intraclass correlation coefficients (*ICC*). The means for the mean, minimum and maximum values of the grayscale from CBCT and HU from CT were compared using the independent samples *t* tests and Pearson's correlation coefficients. Scatter plots were prepared using the Minitab® statistical software, v. 19 (Minitab, State College, USA). Regression analysis was performed to examine the relationship between the grayscale (independent variable) and HU (dependable variable) in relation to the mean, minimum and maximum values.

Results

The present in vitro study comprised a total of 20 samples. For each sample, 12 sites (6 maxillary and 6 mandibular) were measured for the grayscale values from the CBCT scans and for HU from the CT scans with the aim of the qualitative estimation of radiological bone mineral density. For every site, the mean, minimum and maximum values for both scales were recorded (Fig. 1–3). Two researchers independently recorded the grayscale values and HU for each sample.

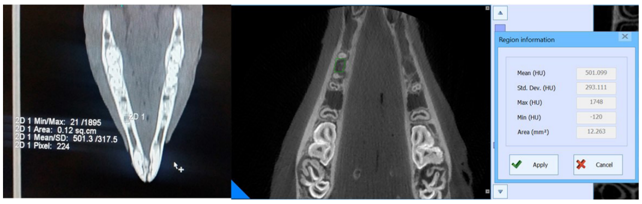

Fig. 1. Placement of the regions of interest (ROI) in the mandibular arch of sample I in the axial section of the computed tomography (CT) scan (left) and in the corresponding axial section of the cone-beam computed tomography (CBCT) scan (right)

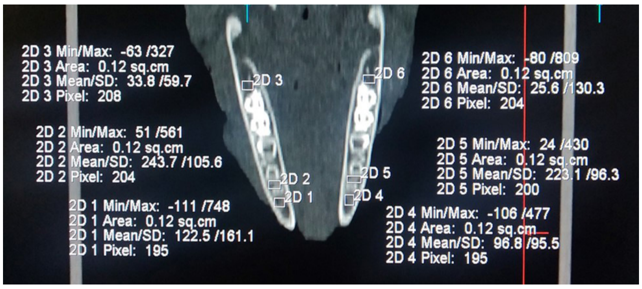

Fig. 2. Axial section of the CT scan of sample II, indicating multiple placements of regions of interest (ROI)

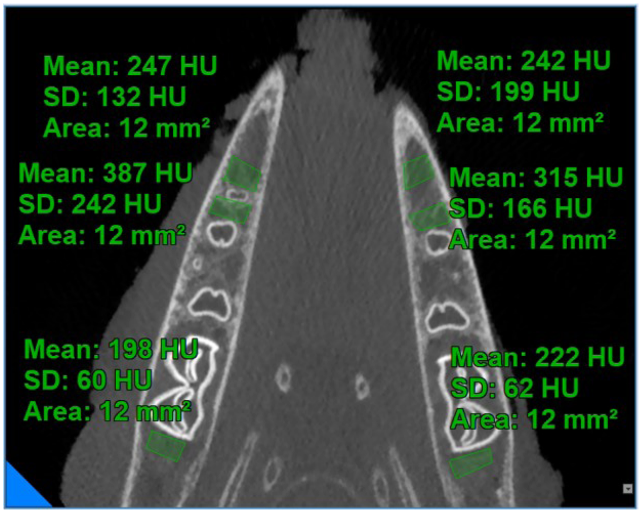

Fig. 3. Axial section of the CBCT scan of sample II indicating multiple placements of regions of interest (ROI)

The statistical analysis of the recorded values revealed an overall *ICC* of 0.979 (97.9%). The evaluation of the inter-observer data reliability with Cronbach's alpha revealed excellent agreement (99%).

The means for the mean, minimum and maximum values for the CT HU were 257.25 ±186.71, 15.18 ±122.61 and 720.98 ±338.07, respectively. The mean values for the mean, minimum and maximum values for the CBCT grayscale values were 355.14 ±188.13, −47.63 ±214.18 and 1,142.39 ±457.72, respectively (Table 1). The statistical analysis using the independent samples *t* test revealed statistically highly significant differences for all 3 sets ($p = 0.000$).

Table 1. Comparison of means between computed tomography (CT) and cone-beam computed tomography (CBCT) for different values

Value	CT *M* ±*SD*	CBCT *M* ±*SD*	*MD* ±*SD*	*t*-value	*p*-value
Minimum	15.18 ±122.61	−47.63 ±214.18	62.81 ±91.57	3.943	0.000*
Mean	257.25 ±186.71	355.14 ±188.13	97.89 ±1.42	5.722	0.000*
Maximum	720.98 ±338.07	1,142.39 ±457.72	421.41 ±119.65	11.473	0.000*

M – mean; *SD* – standard deviation; *MD* – mean difference; * statistically significant (independent samples *t* test).

Pearson's correlation analysis was applied to all 3 value sets (i.e., mean, minimum and maximum values) to establish the relationships between the 2 scales. The analysis revealed that the correlation coefficients for the mean, minimum and maximum values of the 2 scales were 0.496, 0.037 and 0.396, respectively. The analysis further revealed that the correlation between the maximum and mean values of the 2 scales was statistically significant (p = 0.000), but non-significant for the minimum values (p = 0.566). The correlations between the mean CBCT grayscale values and the mean, minimum and maximum CT HU were 0.496, 0.426 and 0.410, respectively, demonstrating a statistically significant correlation between the 2 scales in relation to the respective mean values (p = 0.000) (Table 2).

Table 2. Correlation between CT and CBCT

Correlation		CBCT min	CBCT mean	CBCT max
CT min	*r*	0.037	0.426	0.349
	p-value	0.566	0.000*	0.000*
CT mean	*r*	0.016	0.496	0.464
	p-value	0.804	0.000*	0.000*
CT max	*r*	0.117	0.410	0.396
	p-value	0.070	0.000*	0.000*

min – minimum; max – maximum; *r* – Pearson's correlation coefficient;
* statistically significant (two-tailed *t* test).

Furthermore, the scatter plot revealed a strong linear correlation between the HU minimum and the grayscale maximum and mean values, whereas the correlation with the grayscale minimum values was a non-linear relationship (Fig. 4). Similarly, the scatter plot for the HU mean values revealed a strong linear correlation with the grayscale maximum and mean values, and a weak correlation with respect to the minimum values (Fig. 5). The scatter plot for the HU maximum values revealed a strong linear correlation with the grayscale maximum and mean values, but a weak correlation with the minimum values (Fig. 6).

The weak correlation coefficients obtained here reveal the poor reliability of the grayscale for predictions, i.e., for the known CBCT grayscale values, the prediction of the standard CT HU for radiological mineral density is not very reliable.

The findings further reveal that, even though the grayscale accuracy is questionable in relation to the density estimation for all 3 registered variables, there is a comparatively higher reliability of the CBCT grayscale mean values for the prediction of all 3 (i.e., minimum maximum and mean) variables of CT HU.

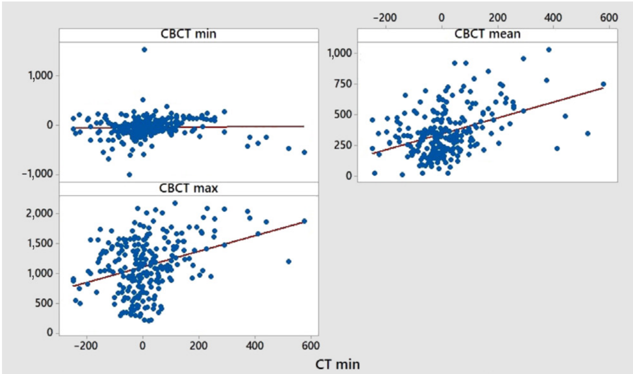

Fig. 4. Scatter plot of the CBCT minimum, CBCT maximum and CBCT mean values vs. the CT minimum values

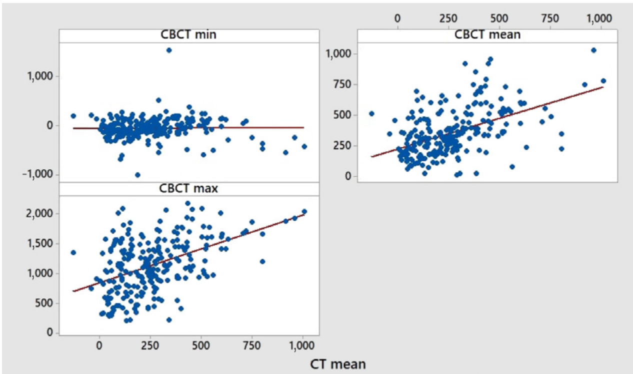

Fig. 5. Scatter plot of the CBCT minimum, CBCT maximum and CBCT mean values vs. the CT mean values

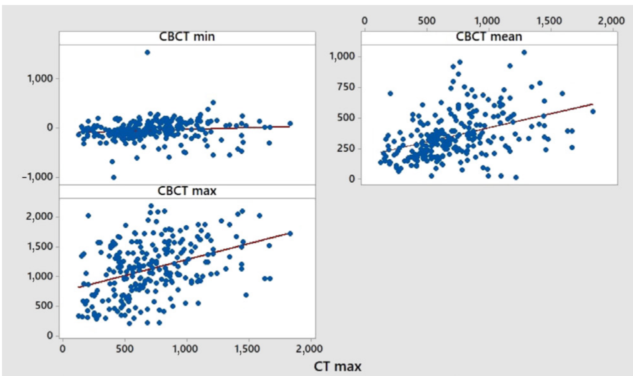

Fig. 6. Scatter plot of the CBCT minimum, CBCT maximum and CBCT mean values vs. the CT maximum values

Regression analysis was done to determine the coefficient of determination for all 3 variables (Table 3). The regression equations for the prediction of CT HU (dependable variable) from the available CBCT grayscale values were as follows (Equations 1–3):

$$\text{CT min} = -110.9 - 0.1028\ \text{CBCT min} + 0.3176\ \text{CBCT mean} + 0.0073\ \text{CBCT max}\ (R^2 = 21.05\%) \quad (1)$$

$$\text{CT mean} = 9.8 - 0.1816\ \text{CBCT min} + 0.4933\ \text{CBCT mean} + 0.0557\ \text{CBCT max}\ (R^2 = 29.79\%) \quad (2)$$

$$\text{CT max} = 366.9 - 0.014\ \text{CBCT min} + 0.484\ \text{CBCT mean} + 0.1590\ \text{CBCT max}\ (R^2 = 19.45\%) \quad (3)$$

As the mean values of the CBCT grayscale showed the highest prediction capability with the lowest chances of error for the prediction of the minimum, maximum and mean values of the CT HU, the regression equations in regard to the CBCT grayscale mean value were as follows (Equations 4–6):

$$\text{CT min} = -83.5 + 0.2777\ \text{CBCT mean}\ (R^2 = 18.16\%) \quad (4)$$

$$\text{CT mean} = 82.3 + 0.4927\ \text{CBCT mean}\ (R^2 = 24.65\%) \quad (5)$$

$$\text{CT max} = 459.5 + 0.736\ \text{CBCT mean}\ (R^2 = 16.79\%) \quad (6)$$

The low R^2 shows a low reliability of the predicted CT HU obtained from the available CBCT grayscale values for the minimum, maximum and mean.

Discussion

Non-physiological tissues or cadaveric samples without the preservation of the adherent soft tissues may produce grayscale values that deviate from the actual values. This is one of the significant concerns for the clinical applicability of CBCT for the estimation of radiological bone mineral density. The available literature has demonstrated a strong positive correlation between the standard protocols and several prediction models for estimating mineral density by means of CBCT. The samples used in such studies range from dried mandibles and phantoms to homogenous density inserts.[5,6] The present study used preserved physiological tissue and its anatomical architecture, addressing the substantial variation offered by the various components of biological tissues, which artificial simulations cannot duplicate. Parsa et al. emphasized that anatomical soft tissue simulations affected the attenuation values while measuring the mineral density.[5] Furthermore, the same authors expressed concern regarding the presence of high-density metal markers and restorative materials, leading to qualitative shortcomings, such as streaking, high noise ratios and beam-hardening artifacts, causing histogram shift and unreliable grayscale values. Previous studies have also stated that, if a varied range of background materials is used, it is quintessential to include the attenuation offered by soft tissues when correlating the 2 scales for clinical application,[7,10–12] which is the issue addressed in the current study.

Previous studies have used a varied array of restorative materials and metal markers to overlap the sections obtained via different imaging techniques. In the present study, an anatomical site was used as a landmark for overlapping ROI in both scans from the same sample, which is unique in comparison with the available literature. A CBCT scanner has a highly sensitive receptor, with the ability to differentiate subtle changes in attenuation,[9] and evidence indicates that the grayscale is subject to variabil-

Table 3. Regression analysis

Dependent variables	Regression equations	R^2 [%]
CT min	CT min = 16.19 + 0.0213 CBCT min	0.14
	CT min = −83.5 + 0.2777 CBCT mean	18.16
	CT min = −91.6 + 0.0935 CBCT max	12.18
	CT min = −110.9 – 0.1028 CBCT min + 0.3176 CBCT mean + 0.0073 CBCT max	21.05
CT mean	CT mean = 257.9 + 0.0141 CBCT min	0.03
	CT mean = 82.3 + 0.4927 CBCT mean	24.65
	CT mean = 41.1 + 0.1892 CBCT max	21.51
	CT mean = 9.8 – 0.1816 CBCT min + 0.4933 CBCT mean + 0.0557 CBCT max	29.79
CT max	CT max = 729.8 + 0.185 CBCT min	1.37
	CT max = 459.5 + 0.736 CBCT mean	16.79
	CT max = 387.1 + 0.2923 CBCT max	15.66
	CT max = 366.9 – 0.014 CBCT min + 0.484 CBCT mean + 0.1590 CBCT max	19.45

ity according to the density of objects in ROI.[4] There is great concern regarding the use of high-density objects and restorative materials as reference points, as they may cause a shift in the determined grayscale values of the sample.[5] The presence of implants and metal markers cause abrupt changes in densities. The variety of densities around the scanned object results in beam hardening, along with other possible associated phenomena, such as the scattered radiation and projection data-related effects, which make the applicability of the grayscale values questionable.[2,13] The use of an anatomical marker in our study assures that the retrieved values are more reliable.

The reliability of the CBCT grayscale has been depicted by either a coefficient of determination (R^2) or a correlation coefficient (r) in previous studies. The available literature mentions the presence of huge bias values and no agreement with regard to applicability, even with high correlation coefficients, due to non-observance for both the statistical tools.[5] In contrast, the present study considered values form both scales to derive relevant evidence for the suitability of the CBCT grayscale for estimating bone mineral density. The r coefficient for the mean, minimum and maximum values was 0.496, 0.037 and 0.396, respectively, and the R^2 coefficient for the mean, minimum and maximum variables were 29.79%, 21.05% and 19.45%, respectively.

In their review, Pauwels et al. mentioned the questionable potential of considering the correlation coefficient alone, for there can be a significant deviation from the linear fit (coefficient of determination) for statistically significant correlations.[4] It has also been mentioned that for substantiating the clinical use of the grayscale values, both r and R^2 have to be taken into account, and the values are not interchangeable. Both the values of Pearson's correlation coefficient (r) and the coefficient of determination (R^2) considered in our study further validate the disputed use of the grayscale for density estimation.

In contrast to the current results, Casetta et al. reported that differences between the CBCT voxel values (VV) and the CT (HU) gray density values were statistically significant ($p < 0.05$).[14] In addition, an r-value of 0.978 demonstrated a statistically significant linear correlation between VV and HU gray density values.[14]

The current study shows a positive but weak correlation between the 2 scales, not per the previous literature. The statistical analysis showed that among the 3 variables that were compared, the highest correlation ($r = 0.496$, $R^2 = 29.79\%$) was observed for the relationship between the mean values of the 2 scales, which implies that the mean values of the grayscale are the most reliable for the evaluation of density.

According to de Carvalho Crusoé Silva et al., the mean HU value obtained using CBCT (418.06) was significantly higher than that obtained using multi-slice computed tomography (MSCT) (313.13).[15] Thus, the authors concluded that bone density in HU obtained from the CBCT images proved unreliable, since it was higher than that obtained using MSCT.[15] Similarly, the differences between the minimum, mean and maximum values noted in our study were 62.81 ±91.57, 97.89 ±1.42 and 421.41 ±119.65, respectively. Differences between all the variable values were statistically significant, and thus question the applicability of the grayscale for density estimation.

Challenges regarding the applicability of the grayscale are also likely due to shortcomings in the basic radiation physics principle, beam geometry, and the assumptions and limitations of the available reconstruction algorithms. The artifacts resulting from variability in the axial plane (e.g., cupping and doming artifacts), beam hardening, the concepts of endomass and exomass, the divergence of the beam, and a high noise ratio in CBCT scans are also a matter of concern in terms of measuring radiological bone mineral density.[4]

Similar to the present study, comparative studies performed for the standardization of the grayscale used a limited number of scanning protocols and a limited variety of machine models.[3–7,11,12,14] In addition, the array of scanning protocols and the models used fluctuate in the literature. Varshowsaz et al. conducted an in vitro study to compare the density values of different tissue phantoms, with 2 different thicknesses, 2 different image acquisition settings and 3 locations in the phantoms.[16] The analysis found significant differences between the density values obtained from the CBCT and CT scans in most situations. Furthermore, the CBCT values were not similar to the CT values in any of the phantoms using different thicknesses and acquisition parameters, or the 3 different sites, which is analogous to our findings. The abovementioned authors also stated that machine-related factors could be responsible for the questionable reliability reported in the literature, supporting the applicability of the grayscale for radiological bone density estimation.[16]

The use of a single scanning protocol and a single machine model can be considered as shortcomings of the present study, and may provide a scope for future detailed studies. The obtained data, even when showing a strong positive correlation, cannot be applied to multiple available models due to the characteristic variation in device calibration and the scanning protocol used for imaging.[16,17] Even for the same machine, the imaging protocol has a varied range according to the required radiological insights. Image acquisition requires different settings and changes in calibration, which can be manually adjusted or automatically applied, depending upon the model in use.[2]

The accuracy of density estimation with a smaller FoV is greater than with a larger FoV due to the high resolution of the target area. The largest FoV available was used while scanning the goat heads, which is a shortcoming of the present study. On the other hand, a small FoV can result in reduced density values, as the diameter of the X-ray beam decreases. This may lead to a decrease in the number of low-energy photons and an increase in the penetration of radiation, which leads to a reduction in the attenuation of X-rays, and finally the gray values.[2]

Another way in which FoV affects the evaluation of density involves the concept of exomass. The exomass is the mass that is present outside the dimensions of FoV during image acquisition. The literature shows that variability in the amount of exomass evaluated in different FoV sizes is related to the gray values.[4] Preserved physiological tissue architecture provides a non-homogenous exomass in close proximity to ROI, which can produce variation in the grayscale values and HU provided by natural tissue. Candemil et al., while studying the effects of non-homogenous hyperdense artifacts in homogenous regions, concluded that not only was there a great discrepancy in the data obtained by 3 machines, but also in the distribution of hyperdense artifacts from the exomass that followed the inherent gray value dispersion of CBCT images, with less homogeneity in the inner zone of FoV.[18] This is exacerbated when metal objects are in the exomass. Katsumata et al. found that a greater FoV eliminates the exomass, resulting in less variability in the gray values,[19] which can justify the use of a large FoV in the present study.

Conclusions

The mean and maximum variables of the grayscale were positively but weakly correlated with HU, whereas the minimum values showed a non-significant correlation. While the correlation is positive, the predictive reliability of the grayscale is low for HU. With the current results as evidence and a review of the available literature, it can be concluded that the accuracy of the CBCT grayscale in measuring bone density, in contrast to CT HU, is questionable and needs to be standardized before clinical application.

Ethics approval and consent to participate

The study was approved by the institutional Ethics Committee at the I.T.S. Centre for Dental Studies and Research, Ghaziabad, India (ITSCDSR/IIEC/2018-21/OMR/OMR).

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

ORCID iDs

Aayushi Gaur https://orcid.org/0000-0002-6404-9394
Manu Dhillon https://orcid.org/0000-0002-7034-4162
Nidhi Puri https://orcid.org/0000-0003-2682-1539
Upasana Sethi Ahuja https://orcid.org/0000-0003-4829-1735
Akshay Rathore https://orcid.org/0000-0002-6455-9247

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