RESEARCH ARTICLE

Conditions and calibration to obtain comparable grey values between different clinical cone beam computed tomography scanners

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Objectives: The objective of the present study was to examine the grey value parameters and their magnitudes produced by CBCT and whether they are influenced by different scanners with various scanning conditions.

Methods: An ATOM Max dental and diagnostic artificial head was scanned by two CBCT scanners (Planmeca and iCAT). Under full field of view with normal dose and ultralow-dose (ULD) conditions, the Planmeca scanner was examined for three scanning resolutions (200, 400, and 600 micron voxel sizes) and the iCAT scanner was tested for four scanning resolutions (200, 250, 300 and 400 micron voxel sizes). After 9 weeks, the artificial head was scanned again by the Planmeca scanner with the same scanning conditions. In addition, two hydroxyapatite phantoms (1220 and 1540 mg cm⁻³) were adhered on the artificial head and scanned using normal and ULD scanning conditions of 400 micron voxel size with both scanners. The grey value histogram of each region, which is proportional to the bone mineral density (BMD) histogram, was utilized to determine grey value distribution parameters and compare scanners (ANOVA, $p < 0.05$).

Results: The different scanning conditions and the bilateral locations of the artificial head did not have significant effects on measurements of the grey value parameters ($p > 0.436$) with excellent repeatability. However, the iCAT scanner produced significantly different grey values from the Planmeca scanner ($p < 0.001$).

Conclusions: CBCT can assess BMD, while calibration of absolute measures is necessary to obtain comparable values between different scanners that are currently used to assess oral bone quantity and quality.

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Introduction

CBCT has been widely used for the three-dimensional (3D) diagnosis and treatment planning of various

anatomical situations including oral maxillofacial surgery, dental implantation, temporomandibular joint (TMJ) disorder, orthodontic tooth movement, sleep apnoea and periodontal disease.¹⁻⁶ As the CBCT is an X-ray-based device, the dense materials of hard tissues (*i.e.* bone and tooth) absorb more radiation energy than soft tissues (*i.e.* skin, tongue and gingiva) producing

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various grey values in the 3D image, which can delineate their morphologies.² Thus, to date, most of the CBCT image-dependent diagnoses have been developed focusing on the visualization of morphological alteration resulting from the dental complications. However, despite the fact that fundamental information of the CBCT image produced by the grey value reflects material density, relatively fewer studies have been performed to quantify the density. This is mainly because reliability of CBCT to assess the grey value remains to be evaluated.^{7–9}

Bone mineral density (BMD) has been used as a surrogate for mechanical stability of bones.^{10,11} As the BMD can be measured by non-destructive X-ray-based technology, it is also utilized to diagnose bone disease and estimate bone quantity and quality of dental implantation sites in the clinical settings.^{6,12,13} Bone is a heterogeneous material consisting of minerals on a collagen matrix.^{14,15} The composition of bone changes by modelling and remodelling processes, which are activated at different time points. Bone mineralization continuously develops for years following the initial mineralization.^{14,16} Thus, active bone modelling and remodelling stimulated by the oral complications inherently alter the heterogeneity of BMD. In general, the BMD accounts for a mean of

mineral density in the bone. Recently, more parameters (variability and 5 percentile low and high) were introduced to describe the alteration of mineral distribution resulting from bone modelling and remodelling at the tissue level.^{17,18} However, it remains to be determined whether these parameters can be assessed using the CBCT-based BMD at the macro level.

It was indicated that the CBCT grey values of the edentulous human mandibular cadaver differ depending on device and scanning settings.¹⁹ Regarding the previous study, we hypothesize that the distribution of grey value may also be altered by different scanners with scanning conditions. Thus, the objective of the present study was to examine the grey value parameters and their magnitudes produced by CBCT and whether they are influenced by different scanners with various scanning conditions.

Methods and materials

Dental and diagnostic artificial head

An ATOM Max dental and diagnostic artificial head (Model 711-HN; CIRS, Norfolk, VA) was obtained (Figure 1). The size of this ATOM head

Figure 1 An ATOM Max dental and diagnostic artificial head mounted on the (a) Planmeca ProMax[®] 3D Mid (Planmeca, Roselle, IL), (b) iCAT CBCT machines (iCAT, Philadelphia, PA) and (c) with the four hydroxyapatite phantoms.

($18 \times 22.3 \times 27 \text{ cm}^3$) is comparable with the average male human head dimension. It includes detailed 3D anthropomorphic anatomy that is composed of human tissue-equivalent resin materials with different average densities for the spinal cord (1070 mg cm^{-3}), cortical bone (CB) (1930 mg cm^{-3}) and trabecular bone (1200 mg cm^{-3}).

CBCT

A CBCT machine (Planmeca ProMax[®] 3D Mid; Roselle, IL) was used to scan the ATOM head. Six different scanning conditions that are routinely used for patients in the clinic were examined (Table 1). Under the full field of view (FOV) option ($\text{Ø}200 \times 170 \text{ mm}$), the head phantom was scanned using normal dose and ultralow-dose (ULD) suboptions for three scanning resolutions (200, 400 and 600 micron voxel sizes) with the same voltage but different ampere and scanning durations (Planmeca first image set). Radiation dose was indicated by dose–area product (unit: milligray square centimetre). After scanning, seven regions of interest including the second cervical vertebra (C2) and bilateral positions of the TMJ condyle, alveolar bone (AB) and basal CB of the first premolar were digitally isolated from the CBCT image using imaging software (ImageJ; National Institutes of Health, Bethesda, MD) (Figure 2a,c). Non-bone voxels outside of these regions were removed using a heuristic segmentation algorithm, as described in the previous studies.^{20–22} The TMJ condyles were dissected parallel to the occlusal plane at 7 mm down from top surface. The first premolars were semi-automatically separated from the mandible using differences of grey values between these adjacent local regions. Then, the tooth was manipulated for 3D dilation up to approximately 1 mm from the surface of the tooth. An overlapped region between the dilated tooth and the mandibular segment surrounding the original tooth site provided the AB region. The CB region was determined by approximately 1 mm inward from basal endosteal surfaces of the mandibular segment. The gray value of each voxel in the isolated regions was obtained by adding 1000 to the Hounsfield Unit (HU) value. The CBCT machine companies utilize different calibrating methodologies to compute HU values using correlations between the gray values and corresponding known densities of reference materials. As the lowest HU value in the image provided by the scanners is -1000 for an air voxel, this process produced positive grey values for all voxels, which allows for absolute grey value comparisons between images. The grey value histograms of each region were utilized to determine the mean value (Mean) that was computed by dividing the sum of grey values by the total voxel counts in the region (Figure 2b). Standard deviation (SD) of the grey value histogram was obtained to account for variability of the grey values. Low and high grey values (Low₅ and High₅) were determined at the 5th and 95th percentiles of voxel counts in the histogram.

After 9 weeks following the first scanning, the same ATOM Max dental and diagnostic artificial head was

scanned again (Planmeca second image set) using the same scanning conditions as the Planmeca first image set (Table 1). In addition, the same artificial head was subject to scanning with the other clinical CBCT machine (iCAT, Hatfield, PA) using eight conditions of normal and ULD for full FOV ($\text{Ø}130 \times 160 \text{ mm}$) at 200, 250, 300 and 400 micron voxel sizes, which are the scanning ranges used in clinical practice (iCAT image set) (Table 1). For both CBCT image sets, all grey value parameters of the seven regions were obtained using the same process as performed for the Planmeca first image set. Finally, four hydroxyapatite phantoms were adhered on the right surface of the artificial head and scanned using the normal and ULD scanning conditions of 400 micron voxel size with both CBCT machines (Planmeca and iCAT), which are the most routinely used scanning conditions in clinical settings provided by both scanners (Figure 1c). Two smaller ($\text{Ø}2 \times 5.5 \text{ mm}$) and two bigger ($\text{Ø}4 \times 5.5 \text{ mm}$) size phantoms were used. In this study, grey values of the two bigger size phantoms were included to obtain sufficient voxels representing known physical density of 1220 and 1540 mg cm^{-3} , respectively.

Statistical analyses

ANOVA was performed to compare the grey value parameters between the scanning conditions and between bilaterally corresponding regions [right TMJ condyle (RC) vs left TMJ condyle (LC), AB and CB] for the Planmeca first and iCAT image sets as well as between the two image sets. *Post hoc* testing was performed using the Tukey–Kramer method. Intrarater reliability of the grey value parameters between the Planmeca first and second image sets was assessed using the intraclass correlation coefficient. Then, a paired *t*-test was used to compare the mean grey values of two phantoms between the 400 micron voxel size Planmeca and iCAT images. Pearson's correlation coefficients were used to examine the correlation of mean grey values between the Planmeca and iCAT images. Significance was set at <0.05 .

Results

All mean values of grey value parameters (Mean, SD, Low₅ and High₅) for the Planmeca first image sets were not significantly different between the scanning conditions (normal and ULD of 200, 400 and 600 micron voxel sizes) ($p > 0.436$) (Table 1, Figures 2d and 3a). Except for the SD between the RC and LC ($p = 0.032$), those values were not significantly different between bilateral regions of AB and CB ($p > 0.528$) (Figure 3b).

The intraclass correlation coefficient between Planmeca first and second image sets showed 0.73, 0.82, 0.88 and 0.44 for the Mean, SD, Low₅ and High₅, respectively.

As observed for the Planmeca first image sets, the mean values of grey value parameters (Mean, SD, Low₅

Table 1 Full field of view scanning conditions of Planmeca and iCAT machines and corresponding grey value parameters for seven regions

Scanning conditions		Grey value parameters				
		Regions	Mean	SD	Low ₅	High ₅
Planmeca ProMax® 3D Mid (Planmeca, Roselle, IL)						
200	200 micron voxel 90 kV 10 mA 36.402 s 3112 mGy cm ²	C2	2408.725	292.5089	2070	2925
		RC	2643.943	274.3328	2339	3171
		LC	2545.437	209.9583	2302	2977
		RAB	2334.416	138.8483	2161	2577
		LAB	2397.317	140.1666	2212	2568
		RCB	2807	381.1901	2254	3450
		LCB	2811.644	360.5732	2252	3440
200 ULD	200 micron voxel 90 kV 7.1 mA 12.389 s 648 mGy cm ²	C2	2444.723	286.8421	2104	2958
		RC	2620.517	279.7906	2268	3168
		LC	2887.687	219.9351	2626	3345
		RAB	2399.791	129.5463	2233	2597
		LAB	2457.914	136.6611	2275	2658
		RCB	2822.557	400.759	2244	3513
		LCB	2796.145	390.9682	2225	3486
400	400 micron voxel 90 kV 8 mA 27.508 s 1992 mGy cm ²	C2	2384.255	262.9602	2082	2870
		RC	2627.373	254.8465	2359	3126
		LC	2531.024	169.6098	2342	2898
		RAB	2342.034	115.4632	2198	2585
		LAB	2399.201	136.5388	2207	2592
		RCB	2706.882	341.3766	2249	3343
		LCB	2652.677	268.2131	2234	3080
400 ULD	400 micron voxel 90 kV 5.6 mA 9.356 s 410 mGy cm ²	C2	2423.627	259.8345	2116	2908
		RC	2664.125	264.3756	2370	3189
		LC	2567.89	173.4305	2361	2930
		RAB	2390.408	119.8324	2234	2660
		LAB	2462.064	133.707	2285	2728
		RCB	2703.47	343.8181	2233	3299
		LCB	2685.301	334.7058	2227	3287
600	600 micron voxel 90 kV 5.6 mA 18.496 s 878 mGy cm ²	C2	2385.187	252.5076	2083	2858
		RC	2613.502	234.2661	2344	3092
		LC	2541.726	161.3526	2336	2873
		RAB	2360.543	121.7565	2205	2633
		LAB	2416.331	118.0469	2255	2634
		RCB	2576.188	269.3043	2225	3049
		LCB	2550.24	244.3108	2228	2996
600 ULD	600 micron voxel 90 kV 2.2 mA 9.361 s 170 mGy cm ²	C2	2428.087	250.1332	2103	2891
		RC	2664.404	243.1591	2359	3145
		LC	2597.54	185.3289	2347	2964
		RAB	2422.687	105.4475	2285	2659
		LAB	2496.921	119.9092	2328	2749
		RCB	2504.339	234.0724	2213	2942
		LCB	2440.656	181.0978	2211	2766
iCAT (iCAT, Philadelphia, PA)						
200	200 micron voxel 120 kV 37.07 mA 26.9 s	C2	1548.752	355.3202	1125	2176
		RC	1489.597	294.3894	1147	2094
		LC	1422.423	246.1824	1120	1935
		RAB	1205.371	124.4894	1013	1414
		LAB	1276.249	119.0626	1107	1472
		RCB	1704.858	413.1376	997	2297
		LCB	1660.612	347.7658	1153	2239
200 ULD	200 micron voxel 120 kV 20.27 mA 14.7 s	C2	1419.085	311.7704	1020	1968
		RC	1302.285	324.8158	916	1963
		LC	1178.83	196.4394	902	1557
		RAB	1162.406	119.9121	974	1363
		LAB	1236.306	132.4839	1036	1435
		RCB	1625.799	338.3139	1079	2123
		LCB	1707.741	318.726	1256	2268
250	250 micron voxel 120 kV 37.07 mA 26.9 s	C2	1390.735	302.4715	1023	1919
		RC	1348.342	237.7135	1051	1819
		LC	1267.257	201.175	1008	1676
		RAB	1135.79	121.8397	966	1314
		LAB	1157.041	119.2809	994	1346
		RCB	1546.383	361.7451	1019	2094
		LCB	1483.546	286.2025	1095	1972
250 ULD		C2	1325.85	304.5235	927	1859

Table 1. Continued

Scanning conditions		Grey value parameters				
		Regions	Mean	SD	Low ₅	High ₅
300	250 micron voxel 120 kV 20.27 mA 14.7 s	RC	1299.619	322.7772	888	1931
		LC	1158.427	211.0231	846	1548
		RAB	1250.009	140.3536	1035	1449
		LAB	1242.144	158.9873	1020	1469
		RCB	1646.758	403.252	1058	2273
		LCB	1602.01	303.0877	1165	2128
	300 micron voxel 120 kV 18.54 mA 8.9 s	C2	1327.849	230.9333	1076	1769
		RC	1218.244	161.4779	1036	1536
		LC	1142.845	122.5026	994	1386
		RAB	1192.581	99.66327	1043	1373
		LAB	1220.684	104.4868	1085	1383
		RCB	1493.512	288.3869	1101	1979
300 ULD	300 micron voxel 120 kV 10.11 mA 4.8 s	LCB	1454.218	224.3088	1141	1856
		C2	1251.779	228.6965	989	1689
		RC	1288.181	229.0248	1015	1728
		LC	1143.706	137.9587	963	1415
		RAB	1294.137	112.7642	1105	1454
		LAB	1287.555	134.4956	1094	1551
	170 mGy cm ²	RCB	1611.982	271.8565	1225	2068
		LCB	1557.338	236.6948	1226	1981
	400 micron voxel 120 kV 18.54 mA 8.9 s	C2	1335.162	236.217	1078	1788
		RC	1331.449	178.4045	1125	1681
		LC	1277.144	136.6889	1113	1548
		RAB	1187.656	89.02696	1058	1335
		LAB	1198.432	99.67398	1058	1352
		RCB	1460.576	275.5242	1079	1929
400 ULD	400 micron voxel 120 kV 10.11 mA 4.8 s	LCB	1420.779	218.1306	1126	1822
		C2	1349.501	245.9785	1059	1812
		RC	1270.792	228.9728	990	1702
		LC	1205.945	136.9699	1021	1473
		RAB	1299.554	95.13246	1152	1441
		LAB	1250.91	125.8685	1078	1498
	600 micron voxel 120 kV 10.11 mA 4.8 s	RCB	1539.69	274.471	1140	2007
		LCB	1500.477	201.1662	1222	1845

C2, second cervical vertebra; LAB, left alveolar bone; LC, left temporomandibular joint condyle; LCB, left basal cortical bone; RAB, right alveolar bone; RC, right temporomandibular joint condyle; RCB, right basal cortical bone; SD, standard deviation; ULD, ultralow dose.

and High₅) for the iCAT were not significantly different between the scanning conditions (normal and ULD of 200, 250, 300 and 400 micron voxel sizes) ($p > 0.145$) (Table 1). However, those of grey value parameters in each region and overall average grey values were significantly different between the Planmeca first and iCAT image sets ($p < 0.001$) (Figure 4a) except for the SD ($p = 0.763$).

The mean grey values of the two phantoms were significantly higher for the Planmeca image sets than those for iCAT image sets ($p < 0.001$). Further, mean grey values were higher corresponding to higher physical densities independent of scanning conditions (normal and ULD of 400 micron voxel size) and scanners (Planmeca and iCAT) (Figure 4b). Averaged grey values of the artificial head and the phantoms had a strong positive correlation between Planmeca and iCAT image sets (Figure 4c).

Discussion

The scanning conditions with different voxel sizes and radiation dose options did not have a significant effect

on the measurement of the CBCT grey value parameters of the diagnostic artificial head. Comparable levels of grey value parameters were obtained between the bilateral regions. The reliability of measurements for those grey parameters was high using the same Planmeca scanner with different scanning time points. On the other hand, the iCAT scanner provided significantly different grey values from the Planmeca scanner. These results suggested that CBCT can measure a material density, while adjustment is needed to compare the measures from different scanners.

The dental diagnostic artificial head made it possible to examine several scanning conditions with different scanners, while also eliminating the individual variation of human patients. The anatomical regions investigated in the present study represent clinically important locations to measure BMD for the diagnoses of cervical vertebral maturation (C2), TMJ disorder (RC and LC), dental implantation site and periodontal disease (AB and CB).^{20,21,23–25} Alteration of BMD is associated with bone growth, bone disease and post-implantation bone healing. As the CBCT grey value is proportional to BMD, the grey value parameters account for the BMD distribution at the region of interest, which results from

Figure 2 (a) Isolated regions from three-dimensional CBCT full field of view image; (b) the grey value parameters defined in a histogram of grey values; (c) images around teeth and alveolar bone (AB) region; and (d) histograms of AB under different scanning conditions. C2, second cervical vertebra; CB, cortical bone; SD, standard deviation; ULD, ultralow dose.

bone modelling and remodelling activities observed in clinical settings.^{13,22,26}

As low as reasonably achievable radiation of CBCT is highly recommended for scanning patients.¹ While a higher resolution scanning with a smaller voxel size provides more precise image to delineate morphology (Figure 2c), it can be achieved only with a higher radiation dose. The current radiation dose of the highest resolution scanning (200 micron voxel size) was 18 times higher than that of the lowest resolution scanning (600 micron voxel size with ULD option). However, the grey value parameters were not significantly altered dependent on resolutions and bilateral locations. The excellent reliability of mean grey value measurement indicates that CBCT-based longitudinal analysis of BMD is available for patients. These findings suggest that CBCT scanning with the low radiation option can produce comparable information of regional BMD between different scanning time points, which is helpful to examine the progress of treatments for patients at the lower risk of radiation.

The grey values of the same material can vary when different CT systems are used to scan.

Thus, HU has been introduced to calibrate grey values relative to the attenuation coefficient (μ) of water [Equation (1)].²⁷

$$HU = (\mu_{\text{material}} - \mu_{\text{water}}) / \mu_{\text{water}} \times 1000. \quad (1)$$

However, the present study found that the HU-based grey values at each region of the artificial head and the same physical density phantoms were significantly different between Planmeca and iCAT scanners. These findings suggest that the HU should be calibrated in order to obtain consistent grey value distribution for the same patient using different CBCT systems. While the absolute grey values measured by the two scanners are different, they had a strong linear correlation. As such, conversion of those values using the correlation between the two scanners could minimize the difference of absolute values.

The limitation of the present study was that materials and anthropomorphic anatomy of the artificial head were not identical to those of real human patients. Its dimension is also limited to adult male size. These

Figure 3 The effects of (a) scanning conditions, (b) bilateral anatomical regions [right temporomandibular joint (TMJ) condyle (RC) and left TMJ condyle (LC), right alveolar bone (RAB) and left alveolar bone (LAB), right basal cortical bone (RCB) and left basal cortical bone (LCB)] and (c) different scan timing on measurements of the grey value parameters. No significant effects were found ($p > 0.436$), while the measurements were significantly repeatable ($p < 0.001$). The error bars represent standard deviation (SD) for each grey value parameter. ULD, ultralow dose.

components may influence the magnitude of X-ray energy absorption for different subjects to be scanned. Another limitation may arise from the use of only the full FOV scanning condition. It was reported that

limited FOV produced image artefacts.²⁸ Thus, further studies are needed to evaluate the CBCT-based grey value using various conditions of subjects and limited FOV images.

Figure 4 The effects of different CBCT scanners on measurements of the grey value parameters: (a) the Planmeca scanner provided significantly higher values for most of the grey value parameters with the iCAT scanner ($p < 0.001$), except for the standard deviation (SD) ($p = 0.763$); (b) the mean grey values of two phantoms corresponded to their physical densities; and (c) a strong positive correlation was found between the averaged grey values of the artificial head and the phantoms measured by the Planmeca and the iCAT scanners. ULD, ultralow dose.

Conclusion

The present study demonstrated that the CBCT image produced with the lowest resolution and radiation dose options can be used to measure grey value parameters comparable with those produced with the highest resolution option. While absolute grey values in the CBCT images obtained by the two scanners were significantly

different, the strong correlation of their grey values can be suggested to calibrate the differences.

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