Accuracy of CBCT Measurements of a Human Skull

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Abstract The purpose of this study is to assess the accuracy and reproducibility of cone-beam computed tomography (CBCT) measurements of a human dry skull by comparing them to direct digital caliper measurements. Heated gutta-percha was used to mark 13 specific distances on a human skull, and the distances were directly measured using a digital caliper and on CBCT images obtained with Iluma (3M Imtec, OK, USA) and 3D Accuitomo 170 (3D Accuitomo; J Morita Mfg. Corp., Kyoto, Japan) CBCT imaging systems. Iluma images were obtained at 120 kVp and 3.8 mA and reconstructed using voxel sizes of 0.2 and 0.3 mm³. Accuitomo images were obtained at 60 kVp and 2 mA and a voxel size of 0.250 mm³. In addition, 3-D reconstructions were produced from images obtained from both systems. All measurements were made independently by three trained observers and were repeated after an interval of 1 week. Agreement between observers and

image type was assessed by calculating Pearson correlation coefficients, with a level of significance set at $p < 0.05$. Pearson correlation coefficients between readings ranged from 0.995 to 1 for all image types. Correlations among observers were also very high, ranging from 0.992 to 1 for the first reading and from 0.992 to 1 for the second reading for the different image types. All CBCT image measurements were identical and highly correlated with digital caliper measurements. Accuracy of measurements of various distances on a human skull obtained from different CBCT units and image types is comparable to that of digital caliper measurements.

Keywords CBCT · Direct measurement · Radiography · 3-D imaging (imaging, three-dimensional) · 3-D reconstruction · Automated measurement · Computed tomography

Introduction

Since the initial introduction of cone-beam computed tomography (CBCT) dedicated to dentomaxillofacial imaging, several novel systems offering different technical specifications and settings have become commercially available. CBCT is now commonly used for a variety of purposes in implantology, dentomaxillofacial surgery, image-guided surgical procedures, orthodontics, periodontics, and endodontics [1, 2]. Recently, the use of digital CBCT models has come to replace traditional dental casts in diagnosis, treatment planning, and simulation [3]. With CBCT, multiple single-frame images are acquired by a process of rotational scanning of an X-ray source and a reciprocating 2-D planar X-ray detector—either an amorphous silicon flat panel or an image intensifier/CCD detector. Images can be acquired with only one pass or less

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Fig. 1 Schematic drawing of the mandible and specific distances measured

around the patient's head and are recorded in a cylindrical or spherical volume of data with a field of view (FOV) ranging from 4 to 30 cm. Voxels are isotropic and typically range in size from 0.08 to 0.4 mm³. Images can be generated in orientations other than the conventional axial plane through the use of special algorithms that can produce multi-planar, reformatted two-dimensional (2-D), three-dimensional (3-D), and panoramic reconstructions on a personal computer [4–7]. In comparison to traditional medical computed tomography (CT) systems, dental CBCT units offer reduced effective radiation doses, shorter acquisition scan times, easier imaging, and lower costs [8–10]. Disadvantages associated with dental CBCT include scatter radiation, a limited dynamic range, minimal soft tissue detail, and beam hardening artifacts caused by dental care material and implants [11–14]. CBCT image quality is influenced by detector quality, imaging setting, voxel size, and hardware/software characteristics [15]. The present study assessed the accuracy and reproducibility of CBCT measurements obtained from specific distances on a human dry skull using 2-D tomographic slices and 3-D images and compared these with direct caliper measurements in order to provide clinically relevant data.

Materials and Methods

Gutta-percha was heated and glued to mark 13 points on a dry human skull in order to measure the following specific mandibular, maxillary, and skull-base distances: (1) distance between left and right foramen mentales, (2) distance between left and right distal tubercles of mandibular second molars, (3) distance between left and right angulus mandibulae, (4) distance between left and right coronoid process, (5) distance

between left and right incisura mandibulae, (6) distance between left and right fovea pterygoidea, (7) distance between spina nasalis anterior and spina nasalis posterior, (8) distance between left and right foramen infraorbitalis, (9) distance between left and right infraorbital suture, (10) distance between left and right foramen palatinum majus, (11) distance between left and right foramen ovale, (12) distance between left and right canalis caroticus, and (13) distance between left and right occipital condyle. Figures 1 and 2 show schematic drawing of mandible and human skull along with specific distances measured, respectively.

The Frankfurt line (a line from the center of the ear through the lowest point of the eye socket) was held parallel to the horizontal plane. The skull was imaged using two different CBCT units: the Iluma CBCT (3M Imtec, OK, USA) and the 3D Accuitomo 170 CBCT (3D Accuitomo; J Morita Mfg. Corp., Kyoto, Japan). The Iluma CBCT has a 24.4×19.5 cm amorphous silicon flat-panel image detector and offers a cylindrical volume of reconstruction up to 21.1×14.2 cm. The 3D Accuitomo 170 CBCT has a flat-panel detector offering five different FOVs—40×40, 60×60, 80×80, 100×100, and 170×120 mm. With the Iluma system, images were obtained at 120 kVp and 3.8 mA with an exposure time of 40 s and were reconstructed using voxel sizes of 0.2 mm³ (high resolution) and 0.3 mm³ (low resolution). With the Morita system, images were obtained at 65 kVp, 2 mA with an exposure time of 30.8 s using a 170×170×120 mm FOV (0.250 mm³ voxel size). With both CBCT systems, axial scans and multi-planar reconstructions were obtained, and dedicated software was used to produce volumetric data and create 3-D reconstructions. A total of six image sets were obtained, as follows: (1) Accuitomo, 170×120 mm

Fig. 2 Schematic drawing of the human skull and specific distances measured

Fig. 3 3-D reconstructed image obtained by Iluma CBCT

FOV 2-D (0.250 mm³); (2) Accutomo, 170×120 mm FOV 3-D (0.250 mm³); (3) Iluma, high-resolution 2-D (0.2 mm³); (4) Iluma, high-resolution 3-D (0.2 mm³); (5) Iluma, low-resolution 2-D (0.3 mm³); (6) Iluma, low-resolution 3-D (0.3 mm³). Figure 3 shows 3-D reconstruction digital tomographic image obtained by Iluma CBCT.

An Absolute Digimatic (Mitutoyo Corp., Kawasaki, Japan) digital caliper accurate to 0.01 mm was used to directly measure the mandibular, maxillary, and skull-base distances described above, and the same distances were measured on the CBCT images using the built-in measurement tools provided. One Data Viewer is a unique Morita software feature which is a stand-alone, executable appli-

Fig. 4 Photography of the digital caliper used for direct measurements. An Absolute Digimatic (Mitutoyo Corp., Kawasaki, Japan)

Table 1 Intra-observer correlations

	Pearson correlation		
	Observer 1	Observer 2	Observer 3
Caliper	1.000*	0.999*	0.999*
Iluma 0.3	0.997*	0.999*	0.999*
Iluma 0.3 3-D	1.000*	0.999*	0.999*
Iluma 0.2	0.999*	1.000*	0.999*
Iluma 0.2 3-D	0.998*	0.998*	0.998*
Morita	1.000*	0.995*	0.999*
Morita 3-D	0.999*	0.999*	0.999*

* $p < 0.001$

cation. It allows 3-D images to be viewed on any computer without installing special software. One Data Viewer is made by exporting the data files with the execution file of One Data Viewer, from i-Dixel. Data files can be taken from anywhere and viewed on all computers within the clinic network, including 3-D images and patient data. Functions to measure distances and angles, zoom, invert the gray scale, adjust brightness, contrast, and gamma are also available options. ILUMA Vision is a software application used for the display and 3-D visualization of medical image files from scanning devices, such as the ILUMA scanner. Additionally, ILUMA Vision is a preoperative software application used for the simulation and evaluation of dental implants, orthodontic planning, and surgical treatments. The ILUMA software suite provides all the capabilities needed for thorough image analysis and treatment planning. An image from one scan can be reconstructed at different levels of resolution, as many times as needed, without rescanning the patient. With a wide array of preset formats, a variety of full, multi-sectional and cross-sectional views

Table 2 Inter-observer correlations for first reading

	Pearson correlation		
	Observer 1–observer 2	Observer 1–observer 3	Observer 2–observer 3
Caliper	0.996*	0.996*	0.995*
Iluma 0.3	0.993*	0.999*	0.995*
Iluma 0.3 3-D	0.997*	1.000*	0.998*
Iluma 0.2	0.998*	0.998*	0.999*
Iluma 0.2 3-D	0.999*	0.998*	0.998*
Morita	0.992*	0.998*	0.995*
Morita 3-D	0.998*	0.998*	0.999*

* $p < 0.001$

Table 3 Inter-observer correlations for second reading

	Pearson correlation		
	Observer 1–observer 2	Observer 1–observer 3	Observer 2–observer 3
Caliper	0.994*	0.998*	0.993*
Iluma 0.3	0.992*	0.997*	0.994*
Iluma 0.3 3-D	0.996*	0.998*	0.998*
Iluma 0.2	0.998*	0.999*	0.997*
Iluma 0.2 3-D	0.994*	0.994*	0.995*
Morita	0.998*	0.998*	0.999*
Morita 3-D	0.997*	0.998*	0.999*

* $p < 0.001$

can be accessed. The digital caliper measurements were considered the “gold standard” to which all CBCT measurements were compared. Figure 4 shows the caliper utilized for direct measurements.

All caliper and CBCT measurements (millimeter) were separately recorded in a random order by three independent trained observers. Reproducibility of measurements was assessed by having each observer separately repeat both caliper and CBCT measurements after a 1-week interval to eliminate memory bias. No time restriction was placed on the observers. Images were viewed in a dimly lit room on a 22-in. LG Flatron monitor (LG, Seoul, Korea) with a screen resolution of 1,440×900 pixels and 32-bit color depth.

Agreement between observers and image type was assessed by calculating Pearson correlation coefficients with a level of significance set at $p < 0.05$.

Results

Pearson correlation coefficients for each observer and correlations between observers for the first and second readings are given in Tables 1, 2, and 3, respectively. Almost perfect intra- and inter-observer correlation coefficients were found ($p < 0.001$). Pearson correlation coef-

Table 4 Observer 1: first reading

Correlations		Caliper	Iluma 0.3 mm ³	Iluma 0.3 mm ³ 3-D	Iluma 0.2 mm ³	Iluma 0.2 mm ³	Accutomo	Accutomo 3-D
Caliper	Pearson correlation	1	0.999 ^a	1.000 ^a	1.000 ^a	1.000 ^a	0.999 ^a	1.000 ^a
	Sig. (two-tailed)		0.000	0.000	0.000	0.000	0.000	0.000
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³	Pearson correlation	0.999 ^a	1	0.999 ^a	0.999 ^a	0.999 ^a	0.998 ^a	0.999 ^a
	Sig. (two-tailed)	0.000		0.000	0.000	0.000	0.000	0.000
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³ 3-D	Pearson correlation	1.000 ^a	0.999 ^a	1	0.999 ^a	1.000 ^a	0.999 ^a	1.000 ^a
	Sig. (two-tailed)	0.000	0.000		0.000	0.000	0.000	0.000
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³	Pearson correlation	1.000 ^a	0.999 ^a	0.999 ^a	1	1.000 ^a	0.999 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000		0.000	0.000	0.000
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³ 3-D	Pearson correlation	1.000 ^a	0.999 ^a	1.000 ^a	1.000 ^a	1	0.999 ^a	1.000 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000		0.000	0.000
	<i>N</i>	13	13	13	13	13	13	13
Accutomo	Pearson correlation	0.999 ^a	0.998 ^a	0.999 ^a	0.999 ^a	0.999 ^a	1	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000		0.000
	<i>N</i>	13	13	13	13	13	13	13
Accutomo 3-D	Pearson correlation	1.000 ^a	0.999 ^a	1.000 ^a	0.999 ^a	1.000 ^a	0.999 ^a	1
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13

^a Correlation is significant at the 0.01 level (two-tailed)

ficients ranged from 0.995 to 1 for the first and second measurements of each observer and from 0.992 to 1 for the first reading and from 0.992 to 1 for the second reading for different image types. In addition, correlation coefficients for all image types were identical and highly correlated with the gold standard direct digital caliper measurements ($p < 0.01$). Given the near perfect intra-observer correlation coefficients, only the correlations for the first readings of observers 1, 2, and 3 are given in Tables 4, 5, and 6, respectively.

Discussion

The present study showed CBCT measurements of specific distances on a human dry skull to be highly accurate and reproducible. The similarities in measurements among imaging units, image types, and observers indicate the effectiveness of both the 2-D and 3-D reconstructions obtained from the Iluma and Accutomo systems studied. One limitation of the present study is that no soft tissue or

soft tissue equivalent was utilized since the main focus of the study was to assess the versatility of the measurement tools of both CBCT systems tested in measuring anatomical bone structures in the dentomaxillofacial region.

Our findings regarding accuracy are in line with those of a previous study that found two different CBCT systems, the NewTom QR DVT 9000 (Aperio Inc., Sarasota, FL) and the Hitachi MercuRay (Hitachi Medico Technology, Tokyo, Japan), to provide similar, highly accurate data with $<1\%$ error when compared to physical measurements [16]. Our results are also in line with another study that showed increasing voxel resolution did not affect the accuracy of surface model measurements [17].

While our study found both CBCT units tested yielded highly accurate and reproducible results for mandibular, maxillary, and skull-base measurements, a similarly designed previous study in which 13 sites on human dry skulls were measured using a NewTom 9000 CBCT (Quantitative Radiology, Verona, Italy) found CBCT images underestimated the real distances between skull sites; however, the differences between CBCT and direct

Table 5 Observer 2: first reading

Correlations		Caliper	Iluma 0.3 mm ³	Iluma 0.3 mm ³ 3-D	Iluma 0.2 mm ³	Iluma 0.2 mm ³ 3-D	Accutomo	Accutomo 3-D
Caliper	Pearson correlation	1	0.994 ^a	0.996 ^a	0.997 ^a	0.997 ^a	0.992 ^a	0.998 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³	Pearson correlation	0.994 ^a	1	0.998 ^a	0.998 ^a	0.996 ^a	0.990 ^a	0.996 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³ 3-D	Pearson correlation	0.996 ^a	0.998 ^a	1	0.999 ^a	0.999 ^a	0.993 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³	Pearson correlation	0.997 ^a	0.998 ^a	0.999 ^a	1	0.999 ^a	0.992 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³ 3-D	Pearson correlation	0.997 ^a	0.996 ^a	0.999 ^a	0.999 ^a	1	0.994 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Accutomo	Pearson correlation	0.992 ^a	0.990 ^a	0.993 ^a	0.992 ^a	0.994 ^a	1	0.995 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Accutomo 3-D	Pearson correlation	0.998 ^a	0.996 ^a	0.999 ^a	0.999 ^a	0.999 ^a	0.995 ^a	1
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13

^a Correlation is significant at the 0.01 level (two-tailed)

Table 6 Observer 3: first reading

Correlations		Caliper	Iluma 0.3 mm ³	Iluma 0.3 mm ³ 3-D	Iluma 0.2 mm ³	Iluma 0.2 mm ³ 3-D	Accutomo	Accutomo 3-D
Caliper	Pearson correlation	1	0.998 ^a	0.999 ^a	0.998 ^a	0.996 ^a	0.998 ^a	0.998 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³	Pearson correlation	0.998 ^a	1	1.000 ^a	0.999 ^a	0.999 ^a	0.999 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.3 mm ³ 3-D	Pearson correlation	0.999 ^a	1.000 ^a	1	0.998 ^a	0.998 ^a	0.999 ^a	0.999 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³	Pearson correlation	0.998 ^a	0.999 ^a	0.998 ^a	1	0.998 ^a	0.997 ^a	0.998 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Iluma 0.2 mm ³ 3-D	Pearson correlation	0.996 ^a	0.999 ^a	0.998 ^a	0.998 ^a	1	0.997 ^a	0.998 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Accutomo	Pearson correlation	0.998 ^a	0.999 ^a	0.999 ^a	0.997 ^a	0.997 ^a	1	1.000 ^a
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13
Accutomo 3-D	Pearson correlation	0.998 ^a	0.999 ^a	0.999 ^a	0.998 ^a	0.998 ^a	1.000 ^a	1
	Sig. (two-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	
	<i>N</i>	13	13	13	13	13	13	13

^a Correlation is significant at the 0.01 level (two-tailed)

measurements were only statistically significant for measurements of the skull base [18]. The differences in study findings may be related to observer performance and calibration or hardware/software capabilities of the different systems tested. It is also possible that in the previous study, the 2-mm diameter metal spheres affixed to the skull to mark the distances to be measured caused scatter and beam hardening that adversely affected observer performance.

The present study did not compare CBCT to 2-D systems; however, CBCT has already been shown to be superior to 2-D cephalometric radiography in providing linear measurements [19, 20]. Both intra-observer and inter-observer reliability in the identification of anatomical structures and landmarks have been shown to be significantly higher with CBCT when compared to 2-D measurements [21]. A study comparing linear measurement of the temporomandibular joint using CBCT and digital cephalometric radiography obtained similar results [22]. Moreover, skull orientation during CBCT scanning has not been found to affect accuracy or reliability of measurements [23–25].

Studies comparing CBCT with multi-slice CT found both 3-D methods yielded similarly accurate results in terms of measurements, but with a considerably lower effective radiation dose with CBCT when compared to CT [26, 27]. Our results are, in general, similar to the previous findings [28–30] in terms of measurement accuracy and reproducibility thereby suggesting the use of CBCT units in dentomaxillofacial diagnosis, treatment planning and follow-up.

Conclusion

All 2-D and 3-D images obtained with the Iluma and 3D Accutomo 170 CBCT units tested in the present study performed similarly in terms of accuracy and reproducibility of measurements of predetermined mandibular, maxillary, and skull-base distances, with no differences in intra-observer or inter-observer agreement. Therefore, we recommend the use of CBCT in the measurement of the dentomaxillofacial region.

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