

Comparison of the Accuracy of Cone Beam Computed Tomography and Medical Computed Tomography: Implications for Clinical Diagnostics with Guided Surgery

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Purpose: This study compared the accuracy of cone beam computed tomography (CBCT) and medical-grade CT in the context of evaluating the diagnostic value and accuracy of fiducial marker localization for reference marker-based guided surgery systems. **Materials and Methods:** Cadaver mandibles with attached radiopaque gutta-percha markers, as well as glass balls and composite cylinders of known dimensions, were measured manually with a highly accurate digital caliper. The objects were then scanned using a medical-grade CT scanner (Philips Brilliance 64) and five different CBCT scanners (Sirona Galileos, Morita 3D Accuitomo 80, Vatech PaX-Reve3D, 3M Imtech Iluma, and Planmeca ProMax 3D). The data were then imported into commercially available software, and measurements were made of the scanned markers and objects. CT and CBCT measurements were compared to each other and to the caliper measurements. **Results:** The difference between the CBCT measurements and the caliper measurements was larger than the difference between the CT measurements and the caliper measurements. Measurements of the cadaver mandible and the geometric reference markers were highly accurate with CT. The average absolute errors of the human mandible measurements were 0.03 mm for CT and 0.23 mm for CBCT. The measurement errors of the geometric objects based on CT ranged between 0.00 and 0.12 mm, compared to an error range between 0.00 and 2.17 mm with the CBCT scanners. **Conclusions:** CT provided the most accurate images in this study, closely followed by one CBCT of the five tested. Although there were differences in the distance measurements of the hard tissue of the human mandible between CT and CBCT, these differences may not be of clinical significance for most diagnostic purposes. The fiducial marker localization error caused by some CBCT scanners may be a problem for guided surgery systems. *INT J ORAL MAXILLOFAC IMPLANTS* 2013; 28:536–542. doi: 10.11607/jomi.2403

Key words: accuracy, cone beam computed tomography, diagnostics, guided surgery, reference marker

Multislice computed tomography (CT) provides three-dimensional (3D) data, offering information

on craniofacial anatomy for diagnosis and treatment planning as well as an objective method for the classification of bone.¹ In the last 10 years, cone beam CT (CBCT) has become more available as an alternative to CT for imaging in the head and neck region. The principal advantages of CBCT are the reduced radiation exposure as compared to CT² and the affordability of CBCT devices compared to conventional CT equipment. CBCT scanners have a smaller field of view than CT because the x-ray source creates a cone-shaped beam, which revolves around the patient's head as 2D image sensor intensifier plates pick up the images. CBCT images have been shown to be successful for various clinical uses, including repair of cleft lip and palate,³ orthodontic therapy,⁴ and treatment of mandibular osteomyelitis.⁵ Articles about the use of CBCT for surgery often report its use in implant placement.^{6,7} Recent articles have discussed the use of CBCT/CT in conjunction with third-party proprietary implant software programs for

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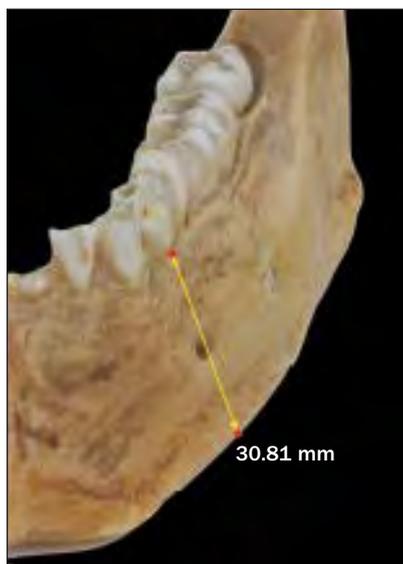


Fig 1 (Left) Human mandible used as scan object.

Fig 2 (Below) Digital caliper (series 500, Mitutoyo).



diagnosis and planning in nonimplant applications and cases.⁸⁻¹⁰ Newer technologies are available for the use of CBCT image data as the basis for image-guided craniofacial and orthognathic surgery.¹¹⁻¹³

A prerequisite for accurate 3D reconstructions and guided surgery systems is high geometric accuracy of the image data.¹⁴ However, studies of the geometric accuracy of CBCT devices report considerable differences between devices.¹⁵ The geometric accuracy of a CBCT scanner is reported to be lower than that of a multislice CT scanner because of the inherent nature of the technology.¹⁶

The goal of the present study, therefore, was to assess the efficacy of CBCT for selected clinical applications in head and neck surgery and to evaluate the limitations of this technology based on its clinical accuracy. An additional objective was to determine whether the image data from different CBCT devices allowed accurate fiducial marker localization, a key element for the accurate registration of reference marker-based guided surgery systems.

MATERIALS AND METHODS

Study Design

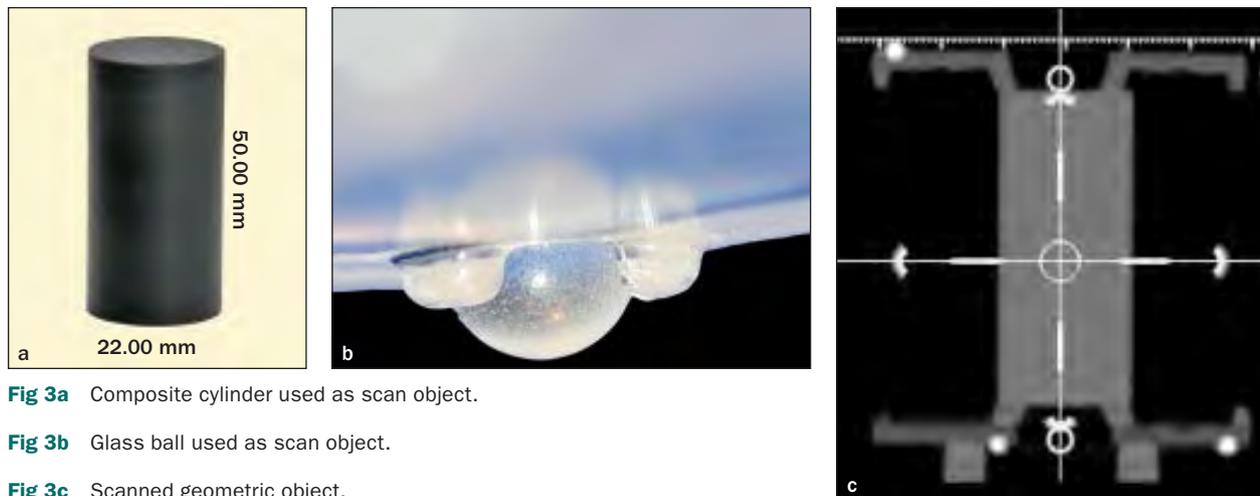
One human cadaver mandible (Fig 1) was used to examine the accuracy of measurements made on CT and CBCT images. Two uniform gutta-percha reference points were placed in the cadaver mandible, one in the right premolar region and one in the left molar region. These points were used to make caudal-cranial measurements. The mandible was then scanned with one

CT device and five CBCT machines. A digital caliper (series 500, Mitutoyo) with an accuracy of ± 0.02 mm was used as the “gold standard” for measurements (Fig 2). The distances between the two uniform reference points were measured with the caliper, and the values were compared with those measured on the CT/CBCT images.

Additionally, uniform fiducial markers consisting of a radiopaque ball with a known diameter of 3 mm (Sirona) and a highly precise composite resin cylinder with a diameter of 22 mm and a length of 50 mm were first measured with the digital caliper. The objects were then scanned with CT/CBCT and the images were measured; these measurements were compared with the caliper measurements (Fig 3). All measurements were performed by one examiner.

The CT machine used was a Philips Brilliance 64-slice scanner (Philips Healthcare) set to 120 kV, 200 mA, a tilt of 0.0 degrees, and a 0.6-mm slice thickness. Helical scans were reformatted to obtain 3D views by volume rendering using a personal computer. The CBCT machines used were the Sirona Galileos (Sirona Dental Systems), the Morita 3D Accuitomo 80 (J. Morita Mfg Corp), the Vatech PaX-Reve3D (Vatech), the 3M Imtech Iluma (3M Imtech), and the Planmeca ProMax 3D (Planmeca Oy).

Images were reconstructed in any plane from the projection data. The same computer and graphics software was used for all CT and CBCT scans. The maximum resolution mode (voxel size) for implant treatment was used for all scanners: Sirona Galileos: 0.15 mm; Morita 3D Accuitomo 80: 0.08 mm; Vatech PaX-Reve3D: 0.25 mm; 3M Imtech Iluma: 0.09 mm; and Planmeca ProMax 3D: 0.10 mm.

Fig 3 Uniform geometric objects.**Fig 3a** Composite cylinder used as scan object.**Fig 3b** Glass ball used as scan object.**Fig 3c** Scanned geometric object.**Table 1** Measurement Deviations (in Millimeters) of the Tested CT/CBCT Scanners

Machine	Type of detector	Mandible (average)	Ball		Cylinder		Radiation dose (μ Sv)
			Range	Average	Range	Average	
Philips Brilliance 64 CT	CT	0.03	0.12	0.08	0.11	0.07	250–480
Sirona Galileos	Image intensifier	0.22	0.26	0.15	2.17	1.14	29–68
Planmeca ProMax 3D	Flat panel	0.11	0.42	0.22	0.77	0.47	8–250
Vatech Pax-Reve 3D	Flat panel	0.20	0.65	0.36	0.71	0.38	12.16–60.64
3M Imtech Iluma	Flat panel	0.10	0.12	0.05	0.09	0.04	5–160
Morita Accuitomo 80	Flat panel	0.51	1.23	0.65	0.88	0.36	13

Measurement of Distance

During CT scanning, the mandible with gutta-percha points attached and the uniform geometric objects were positioned in the same way to ensure that comparable images of the region of interest were obtained. Using cross-sectional views, axial views, and reformations of the data, the ends of the radiopaque markers were easily identified. The measurement tool of a commercially available proprietary implant software program (Simplant, Materialise) was used to make measurements on the CT slices by using a computer mouse to position the measurement tool cursor on the markers of interest. All the measurements were performed with the same software settings. The linear caudal-cranial distance between the ends of the markers was calculated, displayed, and recorded.

To evaluate the accuracy of the CT/CBCT devices, the caliper measurements of the gutta-percha reference markers were compared to the measurements made on the CT/CBCT images. Using these markers as indices, the same planes could be measured on the CT/CBCT images and directly on the cadaver mandibles.

The values obtained by direct anatomic and radiographic measurements were compared. All measure-

ments were performed twice by the same investigator. Measurement error was calculated by subtracting the value obtained on the images of the CT/CBCT (f_i) from the value obtained by direct measurement of the cadaver (y_i) and then expressed as the absolute error $e_i = f_i - y_i$, where f_i is the prediction and y_i the true value. The CT and CBCT values for measurement error were compared.

Statistical Analysis

Differences between the actual (caliper) bone measurements and the various radiographic measurements were determined. All values were expressed as means \pm standard deviations. The paired t test was used for statistical analysis. Results were considered to be statistically significant at $P < .05$.

RESULTS

Measurement deviations for all tested devices are shown in Table 1. The differences between the CBCT measurements and the caliper measurements were larger than the differences between the spiral CT measurements and the caliper measurements. Linear

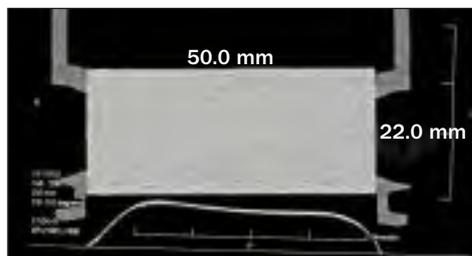
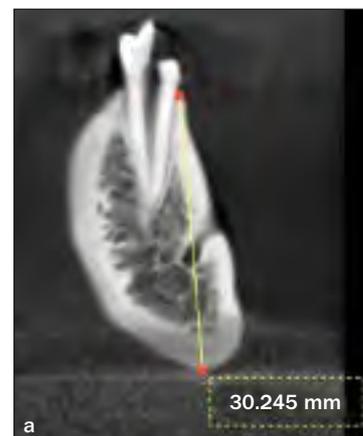
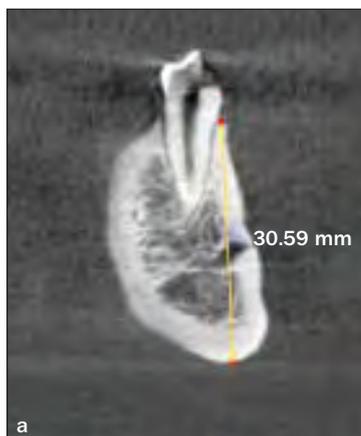


Fig 4 Measurement of composite cylinder with the Philips CT.



Figs 5a and 5b Measurement of the human mandible using (a) the Sirona CBCT and (b) the Morita CBCT.

Figs 6a to 6f Measurement of the glass ball with the different CT/CBCT machines.

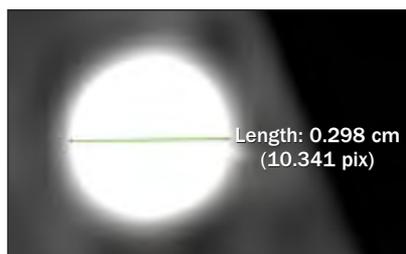


Fig 6a Measurement of the glass ball with the 3M Imtec CBCT.

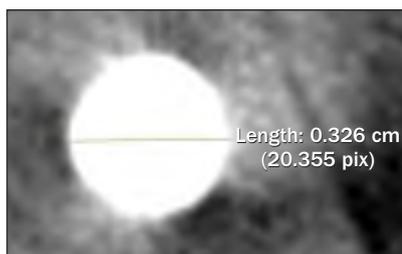


Fig 6b Measurement of the glass ball with the Planmeca CBCT.



Fig 6c Measurement of the glass ball with the Morita CBCT.

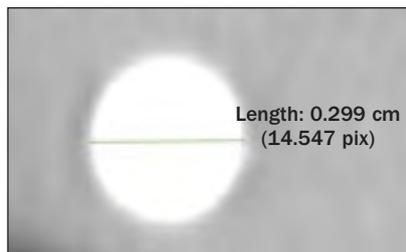


Fig 6d Measurement of the glass ball with the Philips CT.

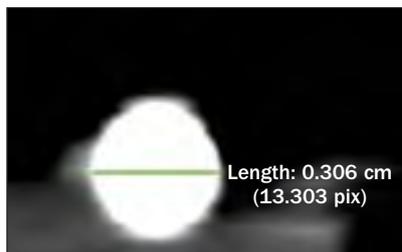


Fig 6e Measurement of the glass ball with the Vatech CBCT.

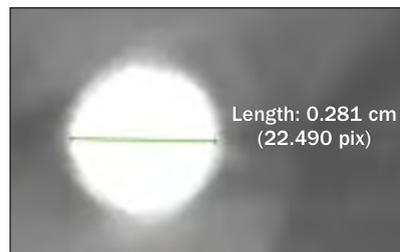


Fig 6f Measurement of the glass ball with the Sirona CBCT.

distance measurements on the human mandible revealed an average error of 0.03 mm for the CT scanner. The distance measurements on the uniform known geometric objects showed similarly precise measurements, with an average absolute error of 0.08 mm. No statistically significant difference was observed between the accuracy of the CT and caliper measurements. Measurement error was found to range from 0 to 0.1 mm on the images produced by CT. CT measurements of the cadaver mandible and the geometric objects were, therefore, highly accurate (Fig 4).

In comparison, the CBCT devices showed differences in the absolute error of the linear measurements

from 0.1 to 0.6 mm on the human mandible, with an average error of 0.23 mm (Fig 5). Differences of 0 to 2.3 mm were detected by the linear measurements on the uniform known geometric objects. The differences in the linear measurements of the glass ball ranged from 0.01 to 1.27 mm, with an average error of 0.29 mm (Fig 6). Measurements of the cylinder showed differences between 0.00 and 2.27 mm, with an average error of 0.48 mm. The measurements of the uniform geometric objects were statistically significantly different from the gold standard (digital caliper) measurements.

Additionally, a statistically significant difference ($P = .041$) was recognized between the two scanning

methods. The average absolute error on the human mandible was 0.03 mm with CT and 0.22 mm with CBCT. The CBCT data presented higher "image noise" compared to medical CT. Additionally, the contrast of the CBCT images was lower than contrast in the CT images.

DISCUSSION

Therapeutic options in head and neck surgery are dependent on precise diagnostic imaging. Three-dimensional diagnostics are most important in oral surgery and implant dentistry. Additional imaging is frequently necessary to determine the proximity of vital structures in the areas of planned implants, the amount of available bone in an area, and the potential need for bone augmentation and grafting procedures.¹⁷ Imaging of difficult anatomical situations does not always warrant the increased expense and higher radiation of a medical CT. With CBCT, a smaller field of interest is scanned with reduced radiation. In 2007, the recommendations of the International Commission on Radiological Protection (ICRP) emphasized the contribution of the head and neck region to the effective dose. The ICRP included salivary glands, the extrathoracic region, and the oral mucosa in the calculation of effective dose, which resulted in an upward reassessment of the fatal cancer risk from oral and maxillofacial radiographic examinations.¹⁸ CBCT can be recommended as a dose-sparing technique in comparison to alternative medical CT scans for common oral and maxillofacial radiographic imaging.¹⁹ In addition, the affordability of CBCT equipment compared to conventional CT encourages its widespread use in dental practice.^{20,21}

The 3D images provided by CBCT appear to be a reliable tool for preoperative evaluation before oral surgery. CBCT images can be obtained in any plane by primary reconstruction of the Digital Imaging and Communication in Medicine (DICOM) images. In CBCT images, the spatial resolution is nearly the same in all directions, whereas in CT images there is a loss of resolution in the direction of cross-sectional reformatting. When the slice thickness of CT is decreased to obtain more accurate data, higher doses of radiation are needed for similar visualization quality.²² CBCT therefore has an advantage in this regard.

The present comparison of CBCT and CT revealed reliable measurements for anatomic objects for both imaging modalities. Several reports have presented very accurate measurements for CT scanners.²³⁻²⁸ Kobayashi et al reported that errors associated with measurements on CT scans can range from 0 to 1.1 mm, with an average measurement error of 0.36 ± 0.24 mm.²⁵ Wang et al evaluated the precision and accu-

racy of human cortical bone reconstruction using 3D CT scans. The model dimensional error in the coronal, sagittal, and axial directions displayed a mean of 0.21 mm, with a standard deviation of 0.12 mm and a maximum error of 0.47 mm.²⁹ However, the results were most accurate when the slice thickness was set to 0.5 mm.

The data presented here indicate that most CBCT machines cannot measure the distance between two points in mandibular bone as accurately as CT, although CBCT, on average, provided satisfactory information about 3D distances. The CBCT and CT scanners both presented underestimations of the uniform known measured object. With CBCT, only one geometric object was overestimated.

In this study, the geometric accuracy of most CBCT units was not comparable to that of the medical CT. This might be a problem for implant planning systems that use geometric reference markers, because the CBCT data that are used to plan implant positions are ultimately incorporated into a surgical drilling guide, which is fabricated from that data and plan. The results of the anatomic scans within this study reveal that the accuracy of CBCT scanners in general is fine, but depending on the material scanned, specific CBCT units have issues with the accurate detection of the scanned object. Therefore it is crucial for clinicians using guided surgery systems to ensure that fiducial markers are picked up accurately by the specific CBCT scanner used. The CBCT scanner and the guided surgery system must work together seamlessly to avoid large errors in fiducial marker localization.

There are various reasons for the greater errors in fiducial marker localization caused by CBCT scanners. Tests revealed the lack of cone beam correction algorithms that rectify geometric errors closer to the circumference of the imaging field in units with large apertures. The contrast of CBCT scanners is lower than that of CT. This is another reason why the linear measurements for the geometric objects may show a higher error. Furthermore, CBCT units can rotate with a slight wobble, providing an additional potential source of image distortion. A correction algorithm is used to remove that distortion prior to the image reconstruction. Errors in the algorithm or changes in the wobble pattern over time may result in additional residual distortion. Sharpe et al reported that the mechanical accuracy and reproducibility of CBCT were about 1 mm.³⁰ Studies discussing rotational displacement, such as the investigation of Oh et al, are unusual, because corrections in rotational displacement are not made in most cases; the hardware is not capable of adjusting rotation.³¹ Furthermore, the reconstruction time of a CBCT, which rotates around the patient's head, is longer than that of a typical medical CT. Patient motion may cause

the target to migrate from the position it occupied at the time that the CBCT projection data were acquired, adding another potential source of distortion.

In this study, the accuracy of the image intensifier system (Sirona Galileos) appeared to be sufficient for linear measurements of the human mandible. Nevertheless, the measurements of the geometric objects showed large deviations. One study that used the DICOM dataset of a Sirona Galileos CBCT did not achieve adequate accuracy to fabricate surgical templates for CT-guided implant placement.³² According to this study, the DICOM dataset obtained from low-dose Sirona Galileos appears to show a high deviation, making this specific device inadvisable for accurate transfer of surgical information in applications such as dental implant surgery. Furthermore, a characteristic artifact caused by halation may reduce image quality.^{24,33}

There were some limitations and potential sources of measurement error in this study. The distances that could be measured were small; therefore, only a limited number of measurements was possible. The experimental study was conducted entirely *in vitro*, and reproducibility *in vivo* was not assessed. The study was performed under idealized conditions by one trained practitioner. The true clinical results will likely differ in practice, where conditions are not ideal, and variations in imaging technique, technical expertise, and assessment of the results will also influence the effectiveness of the imaging modality.

All scanners were used in the maximum resolution mode, which was different for every machine. Considering the differences, it is clear that a true comparison of machines is not possible. The scanners were used as in everyday clinical situations. The results show the diagnostic potential in a typical clinical setting. Some scanners, such as the Vatech PaX-Reve3D, are able to use a higher resolution (0.08-mm voxel size) than those used in this study, but the field of view must be reduced to 5 × 5 cm. Since most guided surgery systems based on fiducial markers require at least three different markers within an array of 8 × 8 cm, this study used machine settings that could obtain images following the clinically relevant parameters for implant evaluation. The potential of the higher-resolution CBCT scanners for other applications, such as endodontics, might be significant.

CONCLUSION

Computed tomography (CT) provided the most accurate images in this study, closely followed by only one cone beam CT (CBCT) device of the five tested. Although there were differences in the distance mea-

surements of the hard tissue of the human mandible with CT and CBCT, these differences may not be of clinical significance for most diagnostic purposes. The accuracy of the tested CBCT scanners in this study is high enough for selected clinical applications in head and neck surgery. However, the fiducial marker localization error caused by some CBCT scanners for the geometric objects used in this study might be a problem for guided surgery systems, as most guided surgery systems rely on accurate fiducial marker localization. Further investigation is needed to truly evaluate which fiducial marker object is ideal for accurate detection by most CBCT scanners.

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