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Radiation Dose and Accuracy Analysis of Newly Developed Cone-Beam CT for Dental and Maxillofacial Imaging

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Abstract— **Cone-beam computed tomography (CBCT) has become increasingly popular in dental and maxillofacial imaging due to its accurate 3D information, minimal radiation dose, and low machine cost. In this paper, we have proposed the newly developed CBCT scanner, called DentiiScan. Our gantry system consisting of a cone-beam X-ray source and an amorphous silicon flat panel detector is rotated around a patient's head. With the large area detector, only a single rotation is needed to reconstruct the field-of-view area from chin to eyes and our reconstructed algorithm based on GPU calculation is about 30 times faster than the CPU-based algorithm. The radiation dose was measured and compared to other dental and medical CT machines. The absorbed radiation dose from our proposed CBCT machine is significantly low. In addition, geometric accuracy was analyzed when the test object was scanned at the normal position as well as the inclined position. The results from three observers repeated for five times confirm that the machine can produce reconstructed images with high accuracy.**

I. INTRODUCTION

Conventionally, dental and maxillofacial imaging is mainly relied on panoramic and intraoral radiography; however, these 2D modalities provide insufficient information and cause superimposition of anatomic structures which can deteriorate visualization of complex anatomy during diagnosis and treatment planning. Computed tomography (CT), which produces 3D data, has been used widely for diagnosis and treatment planning in medical applications. Although all medical CT scanners can be used for dental applications, theirs radiation doses to the patient are quite high [1], [2]. Due to low radiation dose and accurate 3D imaging, a dental CT scanner based on cone-beam technology has become increasingly popular in diagnosis and treatment planning for dental applications [3]-[6], especially dental implant placement and maxillofacial surgery. Not only the machine cost seems to be less expensive than typical medical CT machines, but the machine size is also smaller.

Similar to typical CT and X-ray units, radiation safety is the first concern for cone-beam computed tomography (CBCT); therefore, radiation dose calculation needs to be considered. Many publications have compared radiation doses of different CBCT units [4]-[6]. In addition to radiation dose safety, geometric accuracy is necessary to be evaluated before clinical use. Several articles have investigated accuracy of CBCT scanners using different test objects, such as dry human skulls, and own design measuring objects with known dimensions [7]-[9].

In this paper, we propose a recently developed CBCT machine for dental and maxillofacial applications called DentiiScan. A gantry system consisting of a cone-beam X-ray source and a flat panel detector is rotated around a patient's head. With the large area detector, 3D volumetric cross-sections can be reconstructed in a large field of view (FOV) using only a single rotation. Based on the 3D filtered backprojection algorithm proposed by Feldkamp, Davis and Kress (FDK) [10], our reconstruction algorithm was modified to integrate with cupping artifact reduction and noise suppression through the acceleration of GPU (Graphics Processing Unit). The reconstructed images consisting of a series of images in the axial planes are reformatted to other 2D orthogonal planes, oblique planes, and simulated panoramic views along the dental arch. 3D surface and volume rendering of a patient's jawbones can be reconstructed from the volumetric data also. Apart from the introduction of the new machine, another aim of this work is to analyze its geometric accuracy and radiation dose assessment. Since it is not ethically appropriated to evaluate linear measurements directly on real patients, a test phantom was used for this verification purpose. The radiation dose on our machine will be can be measured in terms of Computed Tomography Dose Index (CTDI) using a tissue equivalent acrylic phantom [11] and compared with other dental and medical CT machines.

II. MATERIALS AND METHODS

A. *The Machine*

The proposed dental CT machine (Fig. 1) uses a cone-shaped X-ray beam projecting toward an X-ray flat panel

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detector through a gantry arm. This gantry system performs a complete 360-deg rotation around a patient's head to collect raw projection data for each angle (Fig. 2). Modified 3D cone-beam reconstruction based on the FDK algorithm [10] is employed to reconstruct cross-section images with a cylindrical FOV of 16 cm in diameter and 13 cm in height in just a single rotation of 18-second scan time. The specification data sheet of the new machine is summarized in Table I.

Figure 1. The newly developed CBCT machine.

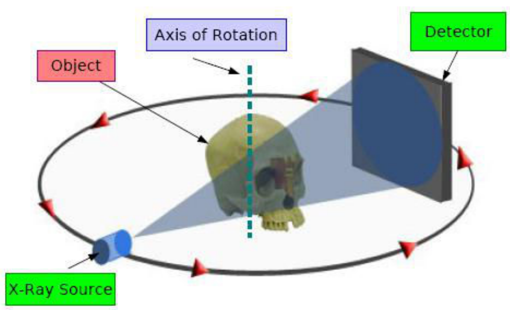


Figure 2. The cone-beam CT concept.

TABLE I. SPECIFICATIONS OF THE NEW CBCT MACHINE

X-ray tube voltage	90 kVp
X-ray tube current	6 mA
Focal spot	0.6 mm
Detector type	a-Si flat panel detector
Detector size	25 x 20 cm
Scan time	18 s
Reconstruction volume	16 cm (∅) x 13 cm (H)
Reconstruction matrix	400 x 400 x 324 voxels (0.4 mm), 800 x 800 x 168 voxels (0.2 mm)
Reconstruction time	5 s (0.4 mm), 25 s (0.2 mm)
Voxel size	0.2 mm, 0.4 mm
Patient position	Seated

For high quality image, the flat panel detector used in this system is based on amorphous-silicon thin-film-transistor (a-Si TFT) arrays coupled to a cesium-iodide (CsI) scintillator (PaxScan 2520, Varian Medical Systems, Inc., Palo Alto, CA). The total tube current-time of 108 mAs is needed to complete a 360-deg scan which is lower than traditional medical CT scanners. Once hundreds of raw projection data are collected, FDK-based image reconstruction along with cupping artifact reduction and noise suppression is calculated through GPUs to speed up the reconstruction time. For example, a volume size of 400x400x324 voxels can be reconstructed with GPU in approximately 5 seconds under a PC (Intel Core i7-950, 3.06 GHz, 4 GB of RAM, 1 TB HDD, NVIDIA GeForce GTX480 with 1.5 GB of RAM), instead of 150 seconds under CPU reconstruction. Due to a larger object size compared to beam coverage in the current cone-beam technology, only the complete data from all 360-deg projections are committed to the FOV. Although scatter radiation is expected with this large detector, low-contrast resolution is not the main purpose of the dental and maxillofacial applications. Fig. 3 shows an example of skull images acquired from our CBCT machine.

The primary 3D reconstructed images normally contain only 2D stacks of axial slices (a top-to-bottom direction), thus to display along other 2D planes, viewer software is needed. Our developed viewer software not only automatically displays multiplanar reformatting (MPR) in real-time including axial, coronal (an anterior-to-posterior direction), and sagittal (a left-to-right direction) views, but can also tilt the volumetric data to yield oblique MPR views. Moreover, in dental applications, other 2D views along a dental arch corresponding to 'panoramic' views (Fig. 3(d)) and perpendicular to the dental arch corresponding to 'cross-sectional' views can be generated in the software. 3D surface and volume rendering of the volumetric data can be employed to enhance visualization of the 3D data (Fig. 3(e)). Basic features to perform some tasks on the images include distance, angle and density measurement; zooming; panning; and window/level adjustment, etc. In addition, nerve canal and implant simulation allow one to attain treatment planning on a computer before actual surgery such that the success of surgery can be increased and the risk can be minimized.

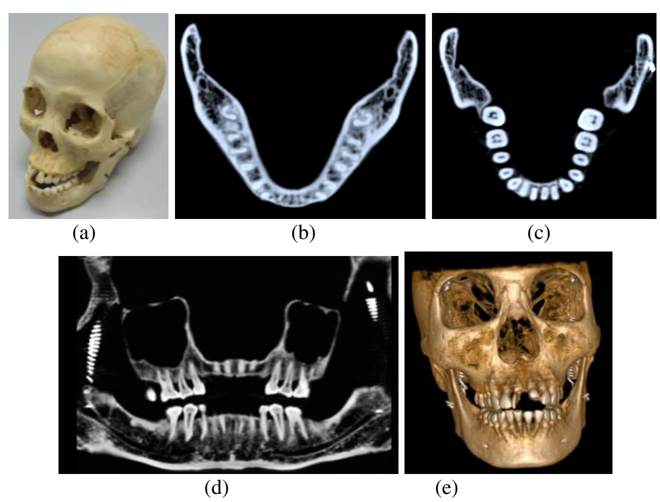


Figure 3. Example of images from the CBCT machine: (a) human skull, (b) and (c) axial images, (d) panoramic image, (e) 3D volume rendering.

B. Radiation Dose

X-ray radiation dose to patients can be measured in terms of Computed Tomography Dose Index (CTDI) using a tissue equivalent acrylic phantom consisting of 5 holes for inserting a cylindrical pencil-shaped air ionization chamber: one center hole and four peripheral holes at 0, 90, 180 and 270 degrees. The ionization chamber is inserted to each hole at a time, and repeated measurements were performed to find average absorbed doses to the phantom.

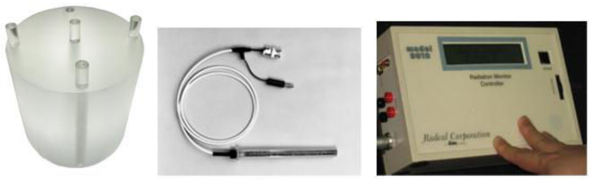


Figure 4. A CTDI acrylic phantom and an ionization chamber.

The weighted CTDI, $CTDI_w$, which represents the absorbed dose and whose unit is mGy, can be calculated from the following equation:

$$CTDI_w = 1/3\ CTDI_c + 2/3\ CTDI_p \quad (1)$$

where $CTDI_c$ is the center CTDI and $CTDI_p$ is the average peripheral CTDI. To determine the radiation risk, the effective dose, E, in mSv can be computed from the absorbed dose as follows:

$$E = DLP \times k \quad (2)$$

where k is the weighting parameter, which is equal to 0.0021 for head scan (brain) and DLP is the dose-length product (mGy-cm) which is derived from

$$DLP = CTDI_{vol} \times L \quad (3)$$

where L is the scan length (cm), $CTDI_{vol}$ is $CTDI_w$ / pitch and pitch is 1 for CBCT .

III. Results

Due to X-ray radiation and diagnosis and treatment planning purposes, the most concern of the CBCT machine is radiation dose safety and geometric accuracy of images. In this section, we measured the radiation dose from our recently developed CBCT scanner compared with other commercial CT machines. Furthermore, geometric accuracy of reconstructed images from our machine was evaluated on a known-size object using three observers with five measurements repeated on each distance.

A. Radiation Dose Comparison

The radiation dose of the developed CBCT was measured through the CTDI phantom as discussed previously and compared with two CBCT scanners: i-CAT (Imaging Sciences International, USA) and CB MercuRay (Hitachi Medical Corporation, Japan); and one medical CT scanner: LightSpeed VCT (GE Healthcare, USA), which is a 64-slice CT scanner. The settings of all systems that are close to our machine and available on their machines are shown in Table II.

TABLE II. Parameter Settings for Radiation Dose Measurement

Parameter	Dental CT			Medical CT
	DentiiScan	**i-CAT**	**CB MercuRay**	**LightSpeed VCT**
Tube Voltage (kVp)	90	120	120	120
Tube Current (mA)	6	5	15	300
Scan Time (s)	18	20	10	9
FOV in Diameter (cm)	16	16	10.2	28.5
FOV in Height (cm)	13	13	10.2	13
Pixel Spacing (mm)	0.4	0.4	0.2	0.557
Slice Thickness (mm)	0.4	0.4	0.2	5.0

TABLE III. Radiation Dose Calculations for Different Dental/Medical CT Scanners

Dental/ Medical CT	$CTDI_{vol}$ (mGy)	DLP (mGy-cm)	Effective Dose (mSv)	Factor
CB MercuRay	13.40	136.68	0.287	7.09
i-CAT	1.39	18.08	0.038	0.94
LightSpeed VCT	60.57	787.41	1.654	41.35
DentiiScan	1.48	19.28	0.040	1

The dose measurements for all CT scanners are summarized in Table III. Our developed CBCT, DentiiScan, yields quite small radiation dose, which is comparable to i-CAT, but approximately 7 times lower than CB MercuRay and 40 times lower than the 64-slice LightSpeed VCT machine. This table also proves that dental CT provides lower patient dose than medical CT, thus offering its main benefit.

B. Geometric Accuracy

A designed object we used for accuracy test consists of 9 positions for distance measurements as shown in Fig. 5. Three observers measured each position for five times. The so-called true measurement or the gold standard was obtained by the measurement of the object using the FaroArm (FARO Technologies Inc., USA), a high precision measuring machine. This test object was scanned twice: one with no inclination and another with 20 degree inclination (Fig. 6), to verify its accuracy against object alignment.

Tables IV and V show the overall mean measurements from three observers repeated for five times, the overall standard deviation and the overall absolute errors when the object was placed at no inclination and with 20 degrees of inclination, respectively. We found that the average absolute errors on both alignments are smaller than the voxel size of 0.4 mm.

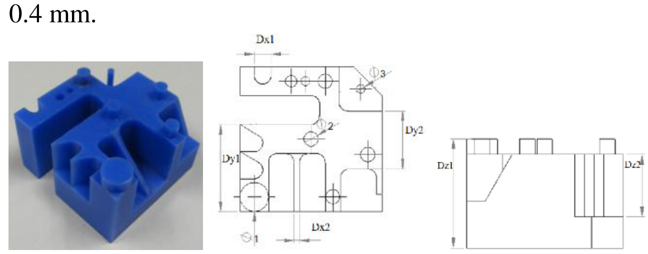
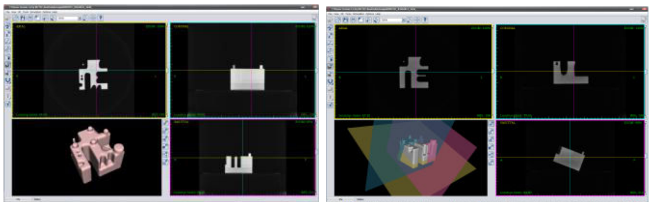


Figure 5. Our own design object for accuracy test.



(a) No inclination (b) 20-deg inclination

Figure 6. Object alignment for scanning.

TABLE IV. LINEAR MEASUREMENTS WITH NO INCLINATION

Position	True Measurement (mm)	Overall Mean (mm)	Overall SD (mm)	Overall Abs Error (mm)
Dx1	5.975	6.03	0.26	0.06
Dx2	2.028	2.11	0.22	0.08
Dy1	30.060	29.85	0.26	0.21
Dy2	20.095	19.89	0.22	0.21
Dz1	35.026	34.95	0.25	0.08
Dz2	20.075	20.03	0.13	0.04
∅1	9.856	10.06	0.15	0.20
∅2	4.787	4.98	0.07	0.20
∅3	2.709	2.43	0.21	0.28
Average Absolute Error (mm)				**0.15**

TABLE V. LINEAR MEASUREMENTS AT 20-DEG INCLINATION

Position	True Measurement (mm)	Overall Mean (mm)	Overall SD (mm)	Overall Abs Error (mm)
Dx1	5.975	6.12	0.20	0.15
Dx2	2.028	2.04	0.16	0.01
Dy1	30.060	29.8	0.31	0.26
Dy2	20.095	19.93	0.15	0.17
Dz1	35.026	34.88	0.24	0.15
Dz2	20.075	20.03	0.11	0.04
∅1	9.856	10.1	0.13	0.24
∅2	4.787	4.97	0.10	0.18
∅3	2.709	2.38	0.24	0.32
Average Absolute Error (mm)				**0.17**

IV. CONCLUSION

In this paper, we have proposed the newly developed cone-beam CT machine, DentiiScan, with fast GPU-based reconstruction for dental and maxillofacial imaging. To ensure its readiness and capability, we analyzed the radiation dose and accuracy of reconstructed images acquired from the machine. According to the UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) that reports the risk of 5% per sievert, our machine provides about 40 microsieverts, which is comparable to other dental CT and lower than medical CT, thus it tends to cause less than 0.001% for the risk of cancer. Geometric accuracy of the machine has been proven to be less than one voxel size. The low-dose and high-accuracy results confirm that our proposed CBCT machine is capable for diagnosis and treatment planning in dental and maxillofacial applications.

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