ORIGINAL ARTICLE

Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images

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Introduction: The purpose of this article was to evaluate the accuracy of measurements made on 9- and 12-in cone-beam computed tomography (CBCT) images compared with measurements made on a coordinate measuring machine (CMM), which is the gold standard. **Methods:** Ten markers were placed on a synthetic mandible, and landmark coordinates and linear and angular measurements were determined with the CMM. Three-dimensional CBCT images, measuring 9 and 12 in, were taken of the mandible with a CBCT machine (NewTom 3G, Aperio Services, Verona, Italy), and landmark coordinates and linear and angular measurements were obtained with AMIRA (Mercury Computer Systems, Berlin, Germany) software. **Results:** The coordinate intrareliability correlation coefficient was almost perfect between the 3-dimensional CBCT images and the CMM measurements. With the Student t test, we found no significant statistical difference between linear and angular measurements from the CMM and the NewTom 3G images, which differed less than 1 mm and 1°, respectively. **Conclusions:** The NewTom 3G produces a 1-to-1 image-to-reality ratio. (Am J Orthod Dentofacial Orthop 2008;134:112-16)

Human craniofacial patterns were first analyzed by anthropologists and anatomists who recorded various dimensions of ancient dry skulls. The first measurements obtained for craniofacial patterns were based on osteologic landmarks (craniometry). With time, measurements were made directly on living subjects by using palpation or pressing the supra-adjacent tissue, and, with the invention of the x-ray machine, measurements were made on cephalometric radiographs (cephalometry).[1,2]

Nevertheless, a cephalometric analysis is a 2-dimensional (2D) diagnostic rendering from a 3-dimensional (3D) structure, with measurements subject to projection, landmark identification, and measurement errors.[2,3]

Concerning radiographic projection errors, magnification and distortion of skeletal and dental structures play important roles. Magnification occurs because x-ray beams originate from a source that is not parallel to all points of the object being examined. Distortion occurs because of different magnifications between various planes. Even though many landmarks used in cephalometric analysis are located in the midsagittal plane, some landmarks and many structures that are useful for craniofacial description are affected by distortion because of their locations at different depth fields.[2,3]

Cone-beam computed tomography (CBCT) is another technique used with machines such as NewTom, iCAT, Hitachi, and Accuitomo.[4] CBCT produces a smaller radiation dose than spiral CT and is comparable to a dental periapical full-mouth series.[5] It also allows secondary reconstructions, such as sagittal, coronal, and para-axial cuts and 3D reconstructions of craniofacial structures from an acquired volumetric data set.[6]

Contrary to traditional cephalometric radiographs, it has been stated that the NewTom produces images that are anatomically true (1 to 1 in size) 3D representations.[7] The purpose of this study was to verify the accuracy of landmark coordinates and linear and angular measurements of standard 9- and 12-in images obtained from the NewTom 3G (Aperio Services, Verona, Italy) compared with a coordinate measuring machine (CMM) (MicroVal, Brown and Sharpe, North Kingston, RI), the gold standard.

MATERIAL AND METHODS

Ten titanium markers (6 mm diameter × 3 mm height) with a hollow cone for which the deepest point

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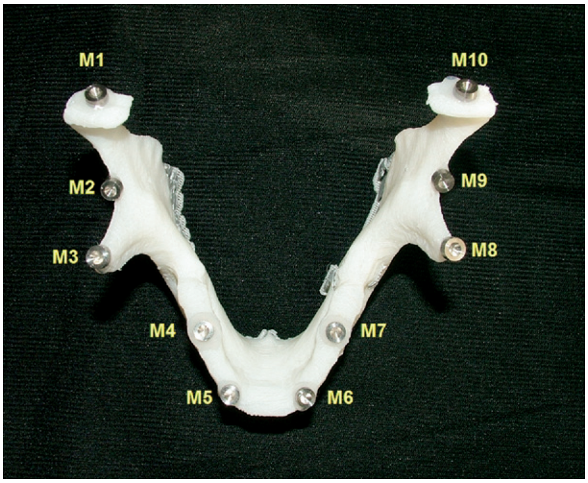

Fig 1. Mandible rapid prototype model with markers.

Fig 2. Mandible rapid prototype model with markers in CMM.

Fig 3. Mandible rapid prototype model in acrylic plastic box in NewTom 3G.

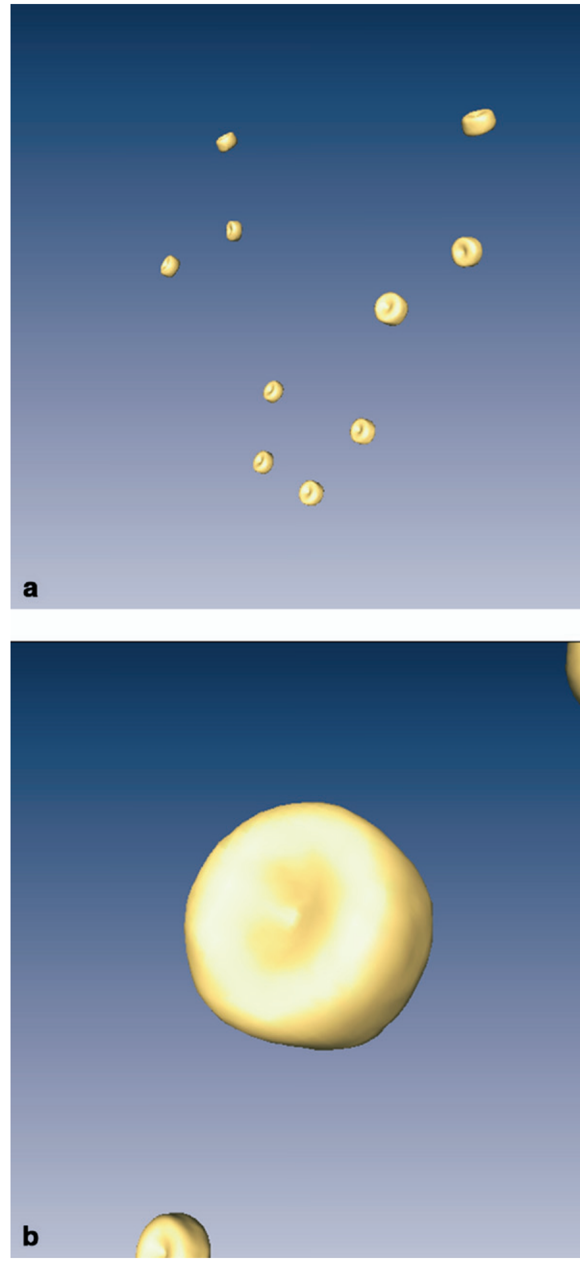

Fig 4 (a, b). NewTom 3G DICOM images of markers.

marks the center of gravity were placed on a rapid prototype mandible (Fig 1).[8] The CMM with a point stylus tip was used as the gold standard to obtain the 3D coordinates of 10 ten markers (Fig 2). All markers faced upward because the CMM could only access marks vertically. Three arbitrary markers were used to standardize the mandible in the coordinate axial system. M1 was assigned as x = 0, y = 0, and z = 0; M10 was assigned as y = 0 and z = 0; and M3 was assigned

Table I. Mean measurement error of coordinates and linear and angular measurements

	X (mm)	*Y (mm)*	*Z (mm)*	*Linear (mm)*	*Angular (°)*
CMM	–0.01	–0.04	0.04	0.05	0
9-in image	–0.7	–0.51	0.54	–0.16	0
12-in image	–0.53	–0.75	0.54	–0.05	0

as z = 0. The CMM coordinates were obtained 3 times with a week between each acquisition.

A CBCT scan was then taken of this model with the NewTom 3G at 110 kV, 6.19 mA and 8 mm aluminum filtration. Since the model did not have a soft-tissue component, the image obtained from the CBCT machine would be too dark to be analyzed. Thus, the model was placed in a phantom acrylic plastic box (26 × 24.6 × 22 cm) filled with water to simulate soft tissue. The box had divisions at the base (5.1 cm wide) and sides (2.5 cm each wide). This design gave an artificial attenuation value of soft tissue without modifying the setting of the CBCT machine (Fig 3). The mandible was placed in the box in the center of rotation of the CBCT (by using a laser light system) with the markers showing vertically (perpendicular to the horizontal plane) and then placed with the markers parallel to the horizontal plane. Because there was no difference in the numbers obtained, positioning of the mandible in the CBCT did not have a great influence. Since the origin of the coordinate system was assigned to 1 marker (M1), this should have negated any machine-related error.

The mandible was scanned 4 times (twice as a 9-in and twice as a 12-in image), and these images of the model in raw study data were converted into DICOM format. By using AMIRA software (AMIRA, Mercury Computer Systems, Berlin, Germany), the DICOM format images were rendered into volumetric images. Sagittal, axial, and coronal slices as well as the 3D reconstruction of the image were used for landmark positioning (Fig 4).

The same markers (M1, M3, and M10) were used in the CMM to standardize the coordinate axial system as were used to standardize the DICOM images with the AMIRA software. Three-dimensional coordinates of the midpoint of the markers were obtained 3 times 1 week apart. Analysis was done by the principal investigator (M.O.L.). Intrareliability correlation coefficients (ICC), measurements errors, and Student *t* tests were used to analyze the coordinates and the linear and angular measurements obtained.

RESULTS

Coordinates of the 10 markers obtained from the CMM were registered in a data sheet as the x, y, and z dimensions. The ICC for each of the 3 axes (x, y, and z) was obtained. The intrareliability value was 1.000 for each axis.

Coordinates of the 10 markers were also obtained from the DICOM 9- and 12-in images and placed in a data sheet as the x, y, and z dimensions. The ICC for each of the 3 axes was determined for both images separately. For the 9-in image, the intrareliability values were 1.000 for x and y and 0.998 for z. For the 12-in image, similar intrareliability values were obtained: 1.000 for the x and y axes, and 0.977 for the z axis.

Measurement errors of the coordinates and linear and angular measurements obtained from the CMM and the NewTom 9- and 12-in images are shown in Table I. After comparing the coordinates of each of the 3 axes from the CMM, 9- and 12-in images, we found that the intrareliability values were 1.000 for the x and y axes and 0.999 for the z axis. For the mean linear and angular measurements from the CMM compared with the 9- and 12-in images by using the Student *t* test, no significant statistical difference was found ($P > 0.05$).

Table II. Linear distances (mm) of markers with respect to reference M1

	CMM		*9-in image*		*12-in image*	
Lines	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
M1	0	0	0	0	0	0
M2	28.27	0.16	28.9	0.67	28.19	0.1
M3	43.21	0.21	43.74	0.43	43.39	0.08
M4	79.26	0.14	79.88	0.58	79.2	0.21
M5	99.08	0.06	99.67	0.65	99	0.14
M6	109.78	0.17	110.47	0.66	109.54	0.03
M7	100.48	0.03	100.61	0.46	99.86	0.16
M8	103.48	0.06	103.42	0.08	102.57	0.24
M9	98.38	0.09	98.64	0.23	97.76	0.16
M10	98.53	0.08	98.37	0.19	97.64	0.25

Table III. Angular (°) measurements

	CMM					
	A		*B*		*C*	
Triangles	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
M2(B)-M1(A)-M3(C)	32.47	0.31	37.96	0.43	109.57	0.25
M3(B)-M1(A)-M4(C)	33.99	0.25	28.99	0.34	117.02	0.58
M3(B)-M1(A)-M9(C)	76.21	0.34	25.32	0.10	78.47	0.44
M5(B)-M1(A)-M10(C)	70.91	0.11	54.62	0.07	54.48	0.04
M4(B)-M1(A)-M5(C)	5.44	0.08	20.39	0.16	154.17	0.25
M6(B)-M1(A)-M7(C)	11.10	0.16	108.95	0.06	59.95	0.10
M6(B)-M1(A)-M8(C)	37.84	0.13	75.71	0.09	66.46	0.22
M3(B)-M1(A)-M8(C)	65.58	0.17	24.52	0.14	89.90	0.30
M9(B)-M1(A)-M10(C)	16.39	0.24	81.50	0.27	82.11	0.09
M2(B)-M1(A)-M9(C)	72.22	0.33	16.55	0.11	91.23	0.44

Letters in parenthesis indicate angle opposite landmark, not beside it.

For the linear measurements, the Euclidean distance formula[9] was applied because both use similar Cartesian coordinate systems. For the linear distances of the markers with respect to the reference M1, the variation between images was a maximum of 0.6 mm (Table II).

Angular measurements were obtained by forming 10 random triangles with different orientations in space. Since each triangle has 3 angles, 30 angles were measured per method of analysis (CMM, 9- and 12-in images). Angles obtained from the NewTom images varied less than a degree with the same measurements from the CMM (Table III).

DISCUSSION

In orthodontics, cephalometric analysis has been an important tool in the diagnosis and treatment planning of patients as well as for the assessment of changes over time. Many types of measurements or norms have been made to analyze oral relationships of teeth, jaws, and cranial base.[10] A major problem associated with cephalometry is projection errors. Projection errors that have an effect on linear and angular measurements are caused by magnification and distortion and are compounded by incorrect patient positioning.[11,12]

For these reasons, a trend from traditional 2D analog films to 3D digital imaging systems is underway. It is expected that accurate patient information will allow the construction of patient-specific models that can be used for therapeutics, research, and education.[13]

In this study, we demonstrated that obtaining a 3D image with the NewTom 3G and AMIRA software is accurate within tolerable clinical limits.[14] Compared with the gold standard, 9- and 12-in images from the NewTom 3G have accurate coordinate values with some variation up to 0.6 mm in linear measurements; this can be considered clinically insignificant when the smallest distance measured was 28 mm. For the angular measurements, these varied less than a degree.

Data collection and analysis were completed by the principal investigator (M.L.). Blinding during data collection was not possible. However, measurements were acquired digitally, and the risk of investigator bias was minimal.

Some studies reported on the accuracy of traditional computed tomography (CT).[15-17] Although this technology is beneficial in dentistry, authors stated that newer and more reliable equipment and software are needed to obtain and analyze images.[15,16] Nevertheless, Matteson et al[18] found that 3D CT was accurate to 0.28% when compared with manual measurements on skulls. Waitzman et al[17] reported minimal discrepancy between direct and indirect craniofacial linear measurements on skulls and concluded that CT produced an accurate image of the object scanned.

Another study reported the accuracy of a CBCT machine. Using dry skulls with 2-mm diameter metal markers on various sites, Lascala et al[19] determined the accuracy of linear measurements of the NewTom QR-DVT 9000. They reported variations of 2 to 3 mm for distances at the maxillofacial region and 4 to 6 mm at the skull base area. These differ from our findings, with variations in linear measurements less than 1 mm from CMM measurements. Discrepancies in the findings with the study of Lascala et al could be due to the markers being used; the ones we used were designed for better location of the center point. Also, the study of Lascala et al used axial, coronal, and sagittal cuts of the 3D image to obtain the linear measurements; we used 3D reconstruction to determine distances.

Three-dimensional imaging is emerging as a display modality with potential applications in orthodon-

Table III. Continued

9-in image						12-in image					
A		B		C		A		B		C	
Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
32.00	0.27	38.52	0.95	109.47	1.17	31.72	0.12	37.36	0.23	110.92	0.22
33.61	0.30	29.13	0.23	117.26	0.46	33.47	0.07	29.10	0.19	117.43	0.26
76.20	0.21	25.71	0.25	78.08	0.38	75.99	0.37	25.76	0.08	78.25	0.31
70.59	0.72	55.23	0.53	54.17	0.37	71.54	0.17	54.78	0.07	53.68	0.14
5.46	0.17	20.67	0.57	153.87	0.74	5.38	0.16	20.25	0.42	154.37	0.58
10.93	0.12	110.55	0.65	58.52	0.53	10.94	0.12	110.29	0.49	58.77	0.44
37.89	0.35	76.55	0.67	65.56	0.33	37.96	0.06	76.48	0.16	65.56	0.2
65.32	0.11	25.02	0.25	89.66	0.24	65.15	0.34	25.03	0.10	89.82	0.43
15.93	0.48	82.59	0.41	81.48	0.17	16.67	0.14	81.91	0.56	81.42	0.56
71.69	0.60	17.03	0.40	91.28	0.55	71.95	0.33	16.75	0.09	91.29	0.3

tics. Although 3D volumetric imaging provides images that can be compared with reality with a 1-to-1 ratio, clinicians tend to analyze them by visually identifying the structures, without using exact measures or other quantitative analysis. The verification of this 1-to-1 ratio to reality has greater opportunities for qualitative analysis of craniofacial structures. The verification of the accuracy of 3D image analysis methods provides opportunities for the development of new methods of volumetric assessment and the establishment of normative parameters. This technology will give clinicians entirely new possibilities in determining changes produced by various orthodontic interventions.

CONCLUSIONS

NewTom 9- and 12-in 3D images have a 1-to-1 ratio with real coordinates and with the linear and angular distances obtained by the CMM.

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