

Accuracy of reconstructed images from cone-beam computed tomography scans

Manish Lamichane,^a Nina Kay Anderson,^b Paul H. Rigali,^c Edward B. Seldin,^d and Leslie A. Will^e
Lancaster, Pa, and Boston, Mass

Introduction: The aim of this study was to determine whether 2-dimensional (2D) images produced from cone-beam computed tomography (CBCT) images taken with an iCAT scanner (Imaging Sciences International, Hatfield, Pa) can substitute for traditional cephalograms. **Methods:** Lateral and frontal cephalograms were taken of a radiographic phantom with known dimensions. Landmarks on the 2D images were traced and measured manually by 2 examiners and then digitally in Dolphin 10 (Dolphin Imaging Sciences, Chatsworth, Calif) by the same examiners. A CBCT scan was taken of the phantom, and orthogonal and perspective projections were created from the scans. Frontal and lateral cephalograms were created by using the 3-dimensional function in Dolphin 10, digitized into Dolphin, and traced by the same 2 examiners. Linear measurements were compared to assess the accuracy of the generated images from the CBCT scans. **Results:** Measurements on the orthogonal projections were not significantly different from the actual dimensions of the phantom, and measurements on the perspective projections were highly correlated with those taken on standard 2D films. **Conclusions:** By constructing a perspective lateral cephalogram from a CBCT scan, one can replicate the inherent magnification of a conventional 2D lateral cephalogram with high accuracy. (*Am J Orthod Dentofacial Orthop* 2009;136:156.e1-156.e6)

Orthodontic diagnosis and treatment planning are based on the comparison of specific craniofacial features to accepted normative data sets to assess feature relativity and to anticipate changes in growth and development of the face. Two-dimensional (2D) imaging has been the accepted cephalometric tool for the past 75 years. Technological advances in 3-dimensional (3D) imaging in the form of cone-beam volumetric or computed tomography (CBCT) appear to offer significant advantages in both quality and quantity of the data of true anatomy. The lack of an accepted 3D analysis and potentially higher ionizing radiation ex-

posure are currently barriers to the replacement of 2D radiographic records with 3D imaging in orthodontics.¹⁻⁴ By using a novel software application, 2D images can be generated from 3D CBCT scans, providing a potential bridge between older and newer technologies.

The historic basis of cephalometric analysis is the identification of important anatomic structures as landmarks traced on acetate paper followed by measurement of distances and angles between these skeletal, dental, and soft-tissue landmarks. Each analysis consists of a set of these measurements that are compared to established normative data derived from studies of "normal," homogenous populations. Measurements and tracings of the lateral cephalogram can also be compared with previous or future cephalograms of a patient to assess both treatment and growth-related effects.

Despite its usefulness, 2D cephalometry has several limitations: (1) vertical and horizontal displacement of structures on the image proportional to their distance from the film or recording plane, (2) imperfect superimposition of the right and left sides of the face because of differential magnification (3) patient positioning errors leading to further image distortion, (4) inaccuracies in landmark location and identification (5) error in manual data collection and processing during cephalometric analysis, and (6) inconsistent calibration of x-ray source-to-film distances and central x-ray beam alignment.⁵⁻⁷

Regardless, cephalometry remains a mainstay in orthodontic diagnosis because it is the only practical

^a Private practice, Lancaster, Pa.

^b Clinical instructor, Department of Developmental Biology, School of Dental Medicine, Harvard University, Boston, Mass.

^c Assistant professor, Department of Orthodontics, School of Dental Medicine, Tufts University, Boston, Mass.

^d Associate professor, Department of Oral and Maxillofacial Surgery, School of Dental Medicine, Harvard University; Massachusetts General Hospital, Boston, Mass.

^e Professor, Department of Orthodontics, School of Dental Medicine, Tufts University, Boston, Mass.

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Reprint requests to: Leslie A. Will, Department of Orthodontics, Tufts University School of Dental Medicine, One Kneeland St, Boston, MA 02111; e-mail, Leslie.Will@tufts.edu.

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quantitative tool that permits spatial evaluation of skeletal and dental structures at relatively high resolution.⁸

Before CBCT, measurement comparisons between 2D and 3D imaging modalities centered mainly on medical computed tomography devices comparing 3D reconstruction algorithms with slices.⁹ A more recent approach used a software program that created a computerized 3D image from 3 coplanar radiographs of dry skulls. The skulls were measured by several examiners using sliding calipers, and 2D landmark measurements were compared with the 3D values. The results indicated that the 3D method was 4 to 5 times more accurate than the 2D approach. Some landmark measurements could not be completed because of skull morphology and the physical limits of the calipers.¹⁰

The most recent accuracy studies involving CBCT scans have shown not only that 3D measurements are much more accurate than 2D measurements, but also that they are close to reality.^{11,12} An in-vitro study measured the size of intraosseous defects in human mandibles and similar-sized defects in acrylic blocks compared with linear and volumetric measurements from CBCT scans with an i-CAT scanner (Imaging Sciences International, Hatfield, Pa). The mean linear inaccuracy was less than 0.3 mm for both the human specimen and the acrylic.¹³ Vandenberghe et al¹⁴ compared cone-beam (CB) images of periodontal defects with those obtained from intraoral digital radiography and found that accuracy was not significantly different between the 2 imaging modalities, and that the CB images were more accurate in assessing furcation involvements and crater defects. These studies showed that CBCT measurements are accurate compared with the actual physical dimensions of various phantom shapes.

One group took this idea a step farther and compared cephalometric measurements from reconstructed CB lateral cephalograms using the NewTom 3 G (QR-NIM s.r.l., Verona, Italy) with conventional cephalograms taken on 10 dry skulls.¹⁵ By using an early version of Dolphin 3D (Dolphin Imaging and Management Systems, Chatsworth, Calif), both orthogonal and perspective projections of the midsagittal plane were constructed from the CB image. Only 1 measurement was found to be different between the imaging modalities, and the orthogonal measurements were the most accurate representation of skull measurements. The authors concluded that CBCT can be used for conventional cephalometry.

The specific aim of this study was to determine whether a constructed image from the i-CAT scanner was equivalent to a conventional cephalogram by comparing linear distances between radiographic markers on 3 images to the actual dimensions of a phantom.

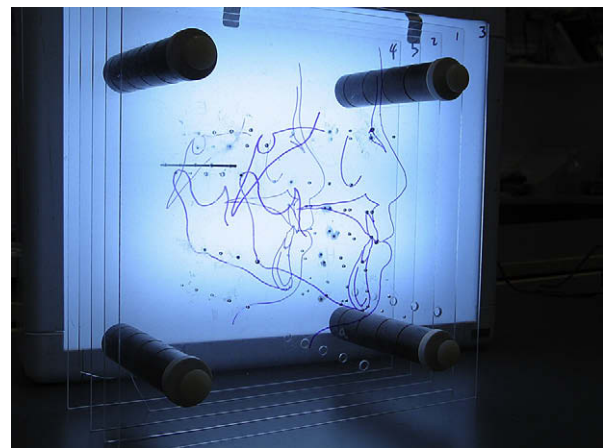


Fig. The radiographic phantom with known dimensions was constructed of 5 acrylic sheets with steel bearings at the corners and at anatomic landmarks.

MATERIAL AND METHODS

Because of the difficulty and inaccuracy inherent in measuring internal landmarks on dry human skulls, a radiographic phantom was fabricated (Elm Street Iron Works, Cambridge, Mass). The phantom consisted of 5 sheets of acrylic (2.2 mm thick) joined with spacers so that the overall width of the device was 115.0 mm. In addition, 8 steel bearings (diameter, 1.5 mm) were embedded in the sheets as radiographic markers at various depths of the phantom. The 8 bearings represented the corners of an exact 100-mm cube (Fig). Lateral and frontal cephalograms were taken of the phantom to calibrate its position and to illustrate the effects of image magnification. To accomplish this, 4 metal rods (diameter, 1.6 mm) were inserted through the assembly at approximately the locations of porion, gonion, orbitale, and A-point. In a well-calibrated cephalometer, the central beam would pass through the ear rods exactly perpendicular to the film, and the porion rod should appear as a single dot on the film. The remaining rods and radiographic markers would show a pattern of divergence from the central beam.

Once the desired image was obtained with the central beam at porion, an image was taken with the central beam passing through the geometric center of the cube as marked on its right and left lateral surfaces. The object-to-film distance was the standard 15.0 cm, and the source-to-object distance was measured at 150.0 cm to the midsagittal plane. The phantom was rotated 90°, and a frontal cephalogram was taken with the central beam passing through the geometric center of the cube as marked on its anterior and posterior surfaces. Each radiograph was scanned, and the images were saved as

Table I. Mean combined measurements

	<i>Theoretical (mm)</i>	<i>Physical/box (mm)</i>	<i>3D tool/box (mm)</i>	<i>Orthogonal (mm)</i>	<i>Theoretical (mm)</i>	<i>2D (manual) (mm)</i>	<i>2D (digital) (mm)</i>	<i>Perspective (mm)</i>
Lateral								
Horizontal								
A-B	100.00	99.88	99.78	100.18	113.80	113.46	114.21	114.76
C-D	100.00	99.91	99.70	99.93	113.80	113.55	114.38	114.70
E-F	100.00	99.80	99.75	100.18	106.46	106.11	106.73	106.73
G-H	100.00	99.88	99.85	99.93	106.46	106.19	106.78	106.86
Vertical								
A-C	100.00	100.15	100.64	100.88	113.80	113.89	115.64	115.55
B-D	100.00	100.21	100.54	100.85	113.80	113.87	115.63	115.51
E-G	100.00	100.17	100.69	100.88	106.46	106.44	108.21	107.79
F-H	100.00	100.21	100.69	100.85	106.46	106.44	108.16	107.71
Diagonal								
A-D	141.40	141.57	141.64	141.96	160.93	160.78	162.30	162.61
B-C	141.40	141.46	141.68	142.15	160.93	160.51	162.51	162.64
E-H	141.40	141.42	141.80	141.96	150.54	150.09	151.89	151.61
F-G	141.40	141.42	141.70	142.15	150.54	150.16	151.91	151.74
Posteroanterior								
Horizontal								
B-F	100.00	99.68	99.53	99.14	106.46	106.46	107.15	105.89
D-H	100.00	99.83	99.71	99.04	106.46	106.49	107.35	106.01
A-E	100.00	99.76	99.65	99.14	113.80	113.80	114.61	113.39
C-G	100.00	99.91	99.66	99.04	113.80	113.88	114.96	113.60
Vertical								
B-D	100.00		100.54	100.10	106.46	106.88	106.24	106.94
F-H	100.00		100.83	100.09	106.46	106.90	106.40	107.18
A-C	100.00		100.63	100.10	113.80	114.36	113.94	114.54
E-G	100.00		100.70	100.09	113.80	114.45	114.03	114.43
Diagonal								
B-H	141.40		141.79	141.06	150.54	150.66	151.48	150.79
D-F	141.40		141.31	141.55	150.54	150.57	151.14	150.44
A-G	141.40		141.95	141.06	160.93	161.18	161.84	161.68
C-E	141.40		141.25	140.55	160.93	161.21	161.76	160.84

A-H, the steel bearings at the 8 corners of a 100-mm cube within the radiographic phantom.

24-bit gray-scale JPEG files for digitization. A 100-mm bar was included in the scan for calibration purposes.

The phantom was then positioned in the CBCT scanner. An extended field-of-view scan was taken. From the CBCT images, 2D lateral and frontal cephalograms were constructed by using the 3D function of Dolphin 10 (Dolphin Imaging Sciences). Each image was constructed 2 ways: orthogonal with 0% magnification and perspective with approximately 10% magnification. The perspective parameters in Dolphin allowed for the central beam, or mechanical portion, to be placed at the exact center of the image and the source-to-object and object-to-film distances to be set identically to our cephalometer distances of 150.0 and 15.0 cm, respectively.

Six images were digitized for measurement: 3 lateral and 3 frontal. Each set of 3 images consisted of a 2D analog film, and orthogonal and perspective projections. The 6 images were labeled part A. One week after the images were obtained, the phantom was radio-

graphed and scanned again according to the same protocol by using the same equipment. This second set of 6 images was labeled part B.

Two examiners (M.L. and L.A.W.) independently made the following 6 sets of measurements on the parts A and B images: (1) directly measuring the distances between markers on the phantom using a sliding digital Vernier caliper (Digimatic, Mitutoyo, Aurora, Ill); (2) making the same physical measurements on the lateral and frontal analog films; (3) making the same digital measurements on the 3D image using the Dolphin 3D tool; (4) measuring the analog films in Dolphin after scanning; (5) digitally measuring the lateral and frontal orthogonal projections in Dolphin; and (6) digitally measuring the lateral and frontal perspective projections in Dolphin.

To determine intraexaminer reliability, each set of measurements was made on different days. In addition, both examiners made the same measurements in reverse

Table II. Independent *t* tests (examiners 1 vs 2) across landmarks by measurement tool

	Examiner	n	Mean (mm)	SD (mm)	P value
Calipers	1	16	110.59	18.567	0.965
	2	16	110.30	18.471	
3D tool	1	24	113.92	19.973	0.999
	2	24	113.92	19.933	
Orthogonal	1	24	113.53	19.870	0.992
	2	24	113.58	19.755	
Time 2 calipers, reverse order	1	16	110.30	18.513	0.980
	2	16	110.14	18.716	
Time 2 3D tool, reverse order	1	24	113.90	19.984	0.998
	2	24	113.88	19.915	
Time 2 orthogonal, reverse order	1	24	113.63	19.939	0.911
	2	24	114.28	20.027	
Time 3 calipers	1	16	110.29	18.571	0.995
	2	16	110.25	18.591	
Time 3 3D tool	1	24	114.05	19.991	0.992
	2	24	114.10	19.967	
Time 3 orthogonal	1	24	113.57	19.941	0.942
	2	24	113.99	20.004	
Time 4 calipers, reverse order	1	16	110.40	18.554	0.995
	2	16	110.35	18.576	
Time 4 3D tool, reverse order	1	24	114.09	19.980	0.994
	2	24	114.13	20.019	
Time 4 orthogonal, reverse order	1	24	114.01	20.024	0.997
	2	24	114.03	20.095	

Table III. Pearson correlations among measurement modalities (n = 24)

	Calipers	3D tool
3D tool	1.000*	
Orthogonal	1.000*	1.000*

*Correlation is significant at the 0.01 level.

order on the same images to determine whether there were any order or learning effects.

Horizontal, vertical, and diagonal measurements were made between each pair of points on the phantom and on each image (CBCT images and posteroanterior and lateral cephalograms) to enable comparison and to assess regional magnification and distortion in the films. The data sheets were grouped by modality, image, and dimension. The same two examiners were responsible for 4 sets of measurements as previously described: part A forward and backward, and part B forward and backward, resulting in 8 sets of measurements.

RESULTS

The data were divided into magnified and unmagnified measurements. The unmagnified modalities included physical measurements of the phantom, 3D

Table IV. ANOVA across all measurement modalities and theoretical measurements

	n	Mean (mm)	SD (mm)	95% CI for mean	
				Lower bound (mm)	Upper bound (mm)
Theoretical	24	113.80	19.936	105.38	122.22
Calipers	16	110.33	18.569	100.43	120.22
3D tool	24	114.00	19.969	105.57	122.43
Orthogonal	24	113.83	19.950	105.40	122.25

tool measurements, and orthogonal image measurements. Magnified modalities consisted of physical and digital measurements on the 2D radiographs and perspective image measurements (Table I). Theoretical values were based on the manufactured dimensions of the phantom and the calculated radiographic magnifications (Table I). All analyses were done with SPSS software (version 15.0, SPSS, Chicago, Ill).

Two columns of theoretical measurements constituted the standard against which the landmark measurements were tested. The first theoretical column contained the manufactured dimensions of the cube. Across all 24 landmarks, 6 measurement modalities, 2 time periods, and landmark order, *t* tests showed no significant differences between examiners (Table II). All measurements were also highly significantly correlated (Table III), providing a rationale for combining each examiner's 4 sets of measurements into 1 mean measurement for each modality for the remaining analyses.

One-way analysis of variance (ANOVA) was used to compare the physical measurements, the 3D tool, and the orthogonal projections against the theoretical values. No significant differences between the physical measurements and the theoretical values were found (*P* = 0.935) as shown in Table IV.

Following the same protocol used for the unmagnified data across all landmarks, measurement modalities, time periods, and landmark order, *t* tests showed no significant differences between examiners (Table V). All measurements were also highly significantly correlated (Table VI), providing additional rationale for combining the measurements into 1 mean measurement for each modality for the remaining analyses. One-way ANOVA tests across the 3 types of measurement tools and magnified theoretical values showed no significant difference (*P* = 0.999) in landmark measurements (Table VII).

DISCUSSION

The specific aim of this study was to determine whether 2D images produced from CBCT images can substitute for traditional cephalograms. Although

Table V. Independent *t* tests (examiners 1 vs 2) across magnified landmarks by measurement tool

	Examiner	n	Mean (mm)	SD (mm)	P value
2D manual	1	24	125.49	22.348	0.992
	2	24	125.43	22.334	
2D digital	1	24	126.15	22.575	0.982
	2	24	126.00	22.414	
Perspective	1	24	125.72	22.516	0.915
	2	24	126.42	22.707	
Time 2 manual, reverse order	1	24	125.42	22.304	0.995
	2	24	125.46	22.410	
Time 2 2D digital, reverse order	1	24	125.52	22.469	0.911
	2	24	126.25	22.634	
Time 2 perspective, reverse order	1	24	125.86	22.432	0.939
	2	24	126.36	22.721	
Time 3 manual	1	24	125.29	22.310	0.990
	2	24	125.22	22.314	
Time 3 2D digital	1	24	126.22	22.553	0.898
	2	24	127.06	22.727	
Time 3 perspective	1	24	125.20	22.368	0.928
	2	24	125.79	22.461	
Time 4 manual, reverse order	1	24	125.29	22.310	0.985
	2	24	125.17	22.342	
Time 4 2D digital, reverse order	1	24	126.22	22.553	0.988
	2	24	126.31	22.578	
Time 4 perspective, reverse order	1	24	125.20	22.368	0.866
	2	24	126.30	22.563	

orthogonal projections are unmagnified and therefore should be closer representations of true anatomy than magnified values, the expectation was that perspective projections with similar magnification to analog films would prove to be more accurate for comparison with serial cephalograms and cephalometric norms.

These results confirmed that orthogonal projections are more representative of anatomy than perspective projections for linear measurements. Measurements between radiographic markers on the orthogonal projections were statistically no different from the dimensions of the phantom.

Previous studies attempting to assess the geometric accuracy of analog films and CBCT measurements used various methods to establish a standard for comparison.^{9-11,13,15,16} One approach is to repeatedly measure both the object and its radiographic images to establish the comparative standard. This approach would be appropriate for an experimental design involving human skulls when exact measurements are unknown. It has been shown that, with sufficient trials of measurement and thorough statistical analysis, repeatable values can be ascertained.^{9,11} The problem is the possibility that, although the measurements are repeatable, they might still be inaccurate.¹² Others offered a stated comparative standard based on the dimensional reliability of a manu-

Table VI. Pearson correlations among magnified measurement modalities (n = 24)

	2D manual	2D digital
2D digital	.999*	
Perspective	.999*	1.000*

*Correlation is significant at the 0.01 level.

Table VII. ANOVA across all magnified measurement modalities and theoretical measurements

	n	Mean (mm)	SD (mm)	95% CI for mean	
				Lower bound (mm)	Upper bound (mm)
Magnified theoretical	24	125.33	22.384	115.880	134.784
2D manual	24	125.35	22.333	115.917	134.778
2D digital	24	126.22	22.554	116.691	135.739
Perspective	24	125.86	22.510	116.352	135.362

factured object.¹⁷ Our approach was to produce a radiographic phantom of known dimensions and to use a protocol of repeated measurements to validate the manufactured dimensions. The findings of no statistically significant differences across measurement modalities and the manufactured dimensions, in addition to highly significant correlations, allow for either data set to represent the comparative standard in this study.

With regard to the Dolphin 3D tool, the results indicate that its measurements accurately reflect the dimensions of the phantom. Statistical comparisons with both the manufactured and physically measured dimensions were not significantly different and were highly correlated. In future studies, this tool might prove to be useful when physical measurement is difficult—eg, on the human skull.

We physically measured the 2D analog films despite the results of several studies showing that digital measurements are as accurate as hand measurements in cephalometric analyses.^{16,18,19} The variability in hardware at different facilities and the rapid evolution of software applications make it necessary to calibrate each system before any study.

Although the perspective images were of good quality, minimal scatter was observed empirically at some radiographic markers. This could have been due to the variable position of the markers in the 2-mm slice of the CT scan. Alternatively, a presumed halation artifact in limited-volume CBCT might appear when a radiopaque object is located near the surface of the body—in this case, the phantom.²⁰ In future studies, this issue could be addressed by selecting titanium radiographic markers rather than steel bearings.

There are already many indications for 3D imaging. Because the 2D images can easily be generated from 3D data, we must determine whether the images are accurate and comparable. This study demonstrated that the technology is in place to avoid unnecessary additional exposure to ionizing radiation. The objective, as always, is to achieve accurate and reliable measurements of anatomic structures with minimal harm to the patient.

CONCLUSIONS

By constructing a perspective lateral image from an i-CAT CBCT scan, one can replicate the inherent magnification of a conventional 2D lateral cephalogram with high accuracy. This image can be used in place of a 2D lateral cephalogram for comparison with either normative data or serial records. This measure eliminates the need to take an additional lateral cephalogram once a CBCT scan has been taken, increasing efficiency and reducing ionizing radiation to the patient. As treatment progresses, a serial lateral cephalogram can be taken and compared with the perspective image from an earlier CBCT scan at much lower radiation than another CT scan. The eventual standardization of the CBCT as an initial record will allow clinicians to gather significantly more accurate and comprehensive information about the patient while maintaining useful diagnostic tools commonly used by orthodontists.

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