

Measurement accuracy with a new dental panoramic radiographic technique based on tomosynthesis

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ABSTRACT

Objective: To investigate measurement errors and head positioning effects on radiographs made with new dental panoramic radiograph equipment that uses tomosynthesis.

Materials and Methods: Radiographic images of a simulated human head or phantom were made at standard head positions using the new dental panoramic radiograph equipment. Measurement errors were evaluated by comparing with the true values. The phantom was also radiographed at various alternative head positions. Significant differences between measurement values at standard and alternative head positions were evaluated. Magnification ratios of the dimensions at standard and alternative head positions were calculated.

Results: The measurement errors were small for all dimensions. On the measurements at 4-mm displacement positions, no dimension was significantly different from the standard value, and all dimensions were within $\pm 5\%$ of the standard values. At 12-mm displacement positions, the magnification ratios for tooth length and mandibular ramus height were within $\pm 5\%$ of the standard values, but those for dental arch width, mandibular width, and mandibular body length were beyond $\pm 5\%$ of the standard values.

Conclusions: Measurement errors on radiographs made using the new panoramic radiograph equipment were small in any direction. At 4-mm head displacement positions, no head positioning effect on the measurements was found. At 12-mm head displacement positions, the measurements for vertical dimensions were little affected by head positioning, while those for lateral and anteroposterior dimensions were strongly affected. (*Angle Orthod.* 2013;83:117–126.)

KEY WORDS: Panoramic radiograph; Quantitative measurement

INTRODUCTION

Panoramic radiographs, which allow visualization of overall structures of dentoalveolar anatomy at low cost and relatively low radiation exposure, have been widely applied in clinical practice and research in dentistry.¹ They have been used to qualitatively examine and evaluate dental caries,² periradicular disease,³ maxillary impacted canines,⁴ mandibular impacted third molars,⁵ alveolar bone,⁶ and developing teeth.⁷ In orthodontic practice, they can provide indispensable diagnostic information about the teeth and their surrounding structures.⁸

The disadvantages of the panoramic radiograph are no constant magnification, image distortion, and narrow image layer. There have been a few quantitative measurement studies, which evaluated gonial angle,⁹ mandibular ramus height,¹⁰ alveolar bone height,¹¹ tooth length,¹² root resorption,¹³ and mesio-distal root angulation.¹⁴ Even dimensions in the vertical direction may entail a variable amount of magnification on panoramic radiographs.¹² Panoramic radiographs

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Figure 1. The image simulated human head or phantom.

have been of limited use for quantitative studies because of their image distortion.

In recent years, computed tomography (CT) has been widely used in the health sciences fields. However, CT may be unnecessary depending on the purpose of individual examination. Tomosynthesis methodology has been considered as an alternative to CT for optimization of radiation exposure.¹⁵ Tomosynthesis (coined from a combination of the words “tomography” and “synthesis”) is a technology that reconstructs tomographic slices at any desired plane. Tomosynthesis has been applied to perioral radiography in the dental region.¹⁶ It may resolve the disadvantages of the panoramic radiograph and make otherwise blurred images clearer. However, the detectors, which can acquire data at a high speed, have not been available. As a result, panoramic radiography using tomosynthesis has not been used in daily clinical practice.¹⁷ A new semiconductor detector has been developed and is now available for panoramic radiography.¹⁸ Radiographs made using tomosynthesis technology show little or no distortion of images.¹⁹ Three-dimensional (3D) panoramic images can be obtained using an image mapping technique.²⁰ The new panoramic radiograph is suitable for quantitative measurements including 3D components. Because the equipment has a larger image layer than the conventional panoramic radiograph, it is anticipated that patient head positioning will have little influence on the measurements. In order to assess the clinical usefulness of the new technology it

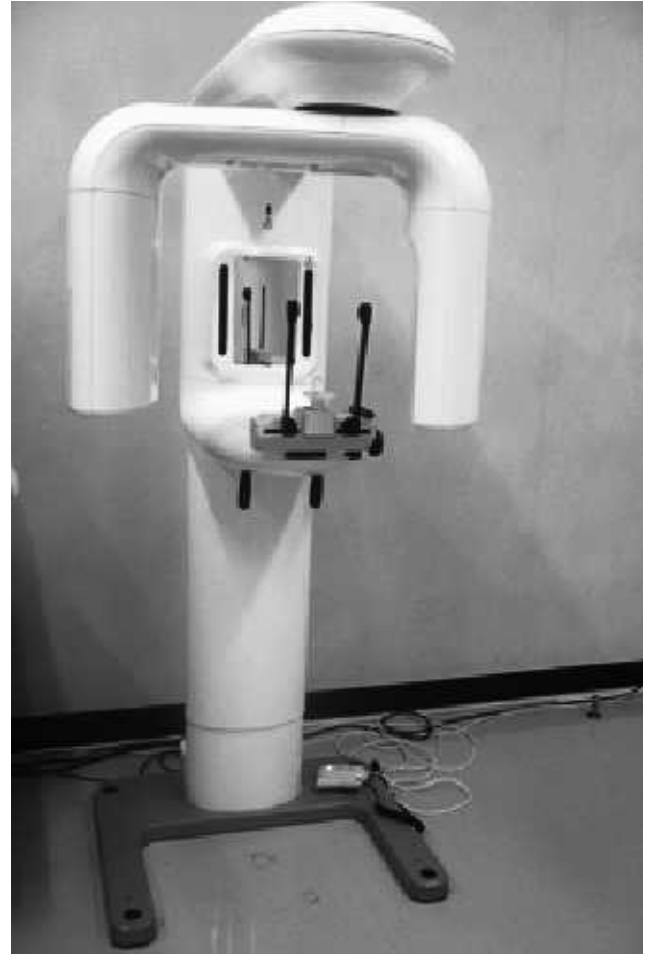


Figure 2. New dental panoramic radiographic equipment (QRmaster-P, Telesystems Co Ltd, Osaka, Japan) used in this study.

was considered necessary to determine the magnitude of measurement errors and to investigate the influence of different patient head positions.

Therefore, the purpose of the present study was to investigate measurement errors and the effects of head positioning on measurements made with new dental panoramic radiograph equipment that involves use of tomosynthesis technology.

MATERIALS AND METHODS

A simulated human head (Dental X-ray head phantom, Kyoto Kagaku Co Ltd, Kyoto, Japan) was used as the subject (Figure 1). The subject consisted of soft tissue equivalent and hard tissue equivalent media that have X-ray absorption rates equal to those of the human body.

Recording Methods

Images of the phantom were recorded using new panoramic radiograph equipment (QRmaster-P, Telesystems Co Ltd, Osaka, Japan) (Figure 2). The rolling



Figure 3. The phantom is set at the standard head position for 3D panoramic radiography. For the standard position of the head, the phantom was positioned so that its Frankfort plane was horizontal to the floor, the midsagittal plane was perpendicular to the floor, and the maxillary right canine cusp tip was aligned with the canine light guide.

radii of the X-ray source and the detector were 504 mm and 155 mm, respectively. The X-ray tube voltage and current were 80kVp and 4mA, respectively. The phantom was positioned with the Frankfort plane parallel to the floor, the midsagittal plane perpendicular to the floor, and the maxillary right canine cusp tip aligned with the canine light guide (Figure 3). This position was defined as the standard head position. Tomosynthesis and 3D mapping methods were used for data acquisition. Tomosynthesis is a digital imaging technique that allows an arbitrary number of in-focus tomographic planes to be generated retrospectively from a sequence of projection image data acquired by a single motion of the panoramic X-ray equipment. From the raw data, the layer that showed the highest frequency image was extracted with the edge analysis method, and the location of the image was determined with 3D mapping.²⁰

CT images of the phantom were also recorded using a CT scanner (SOMATOM Emotion 6, Siemens, Munich, Germany). The X-ray tube voltage and current were 130 kVp and 120 mA, respectively. Slice

Table 1. The Definitions of Measurement Points

Measurement Points	Definitions
Central incisor edge	Incisal edge midpoint of the central incisor
Lateral incisor edge	Incisal edge midpoint of the lateral incisor
Canine cusp tip	Cusp tip of the canine
Central incisor root apex	Root apex of the central incisor
Lateral incisor root apex	Root apex of the lateral incisor
Canine root apex	Root apex of the canine
Central incisor mesial point	Mesial widest contour of the central incisor
Central incisor distal point	Distal widest contour of the central incisor
Lateral incisor mesial point	Mesial widest contour of the lateral incisor
Lateral incisor distal point	Distal widest contour of the lateral incisor
Canine cusp mesial point	Mesial widest contour of the canine
Canine cusp distal point	Distal widest contour of the canine
Cd	The uppermost point of the condyle

thickness was 0.4 mm, with a one-pixel size of 0.47 mm.

Data Analyses

Experiment 1: Assessment of differences between measurements and true values. The panoramic radiograph image data were transferred to a personal computer (Endeavor MR6900, Seiko Epson Corporation, Suwa, Japan). Several anatomic landmarks were determined visually, and the dimensions were measured using the software for QRmaster-P (Telesystems, Co, Ltd, Osaka, Japan) as measurement values. In addition, the same dimensions were measured on the phantom using a pair of Vernier calipers (Mitutoyo Corporation, Kawasaki, Japan) to yield true values. Dimensions that could not be measured using the calipers were measured on the CT image and

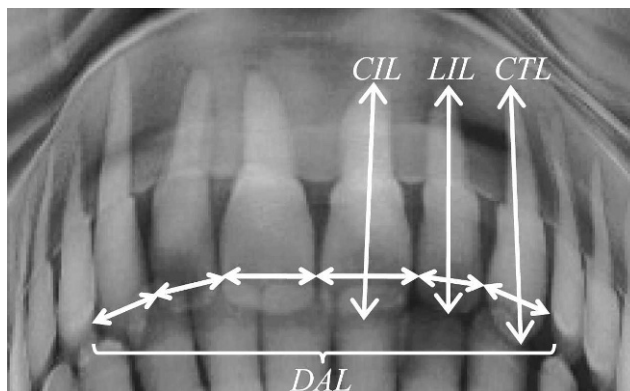


Figure 4-1. The dental dimensions. CIL indicates central incisor length, the distance between the central incisor edge and root apex; LIL, lateral incisor length, the distance between the lateral incisor edge and root apex; CTL, canine tooth length, the distance between the canine cusp tip and root apex; and DAL, dental arch length, the sum of the crown widths of the six anterior teeth (total of distances between the central incisors mesial and distal points, distances between the lateral incisors mesial and distal points, and distances between the canines mesial and distal points).

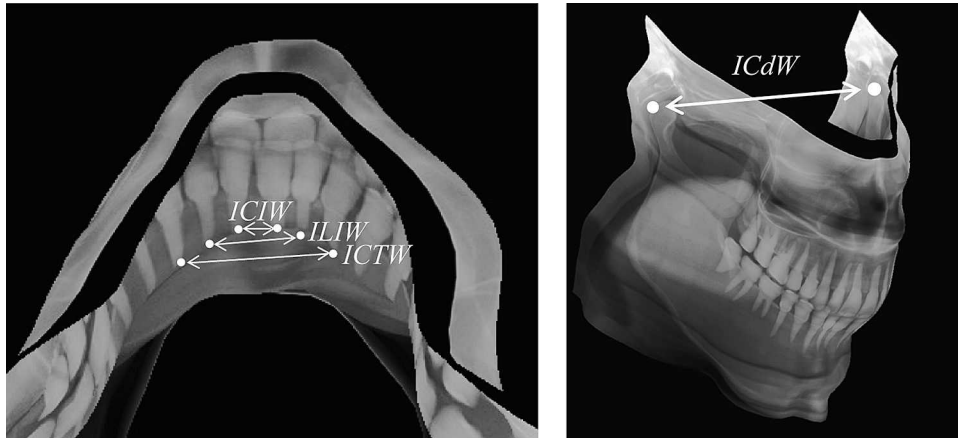


Figure 4-2. The dentomandibular dimensions. *ICIW* indicates intercentral incisor width, the distance between the right and left central incisor root apices; *ILIW*, interlateral incisor width, the distance between the right and left lateral incisor root apices; *ICTW*, intercanine tooth width, the distance between the right and left canine root apices; and *ICdW*, inter *Cd* width, the distance between the right and left *Cd*.

regarded as the true values. The CT images were transferred to a personal computer (MacPro, Apple, Cupertino, Calif) and measured using the imaging software package OsiriX (open-source DICOM viewer). All dimensions were measured five times by one of the authors with a minimum interval of 1 day between measurements. The mean of the five values was then regarded as the final measurement value. The measurement error was then defined as the measurement value minus the true value. The measurement percent value was the measurement error divided by the true value multiplied by 100.

The definitions of several points are shown in Table 1. They were determined on the right and left

sides in upper and lower jaws. The definitions of dimensions are shown in Figure 4.

Experiment 2: Measurement values according to head positioning. Image data were obtained using the phantom and 3D panoramic radiograph equipment, which were the same as those used in experiment 1. The phantom was radiographed at the standard and alternative head positions by one of the authors five times with minimum intervals of 1 day. The mean of the five values was determined to be the final measurement value. The various head positions were 4 mm, 8 mm, and 12 mm forward; 4 mm, 8 mm, and 12 mm backward; 4 mm, 8 mm, and 12 mm rightward; and 4 mm, 8 mm, and 12 mm leftward from the standard head position (Figure 5).

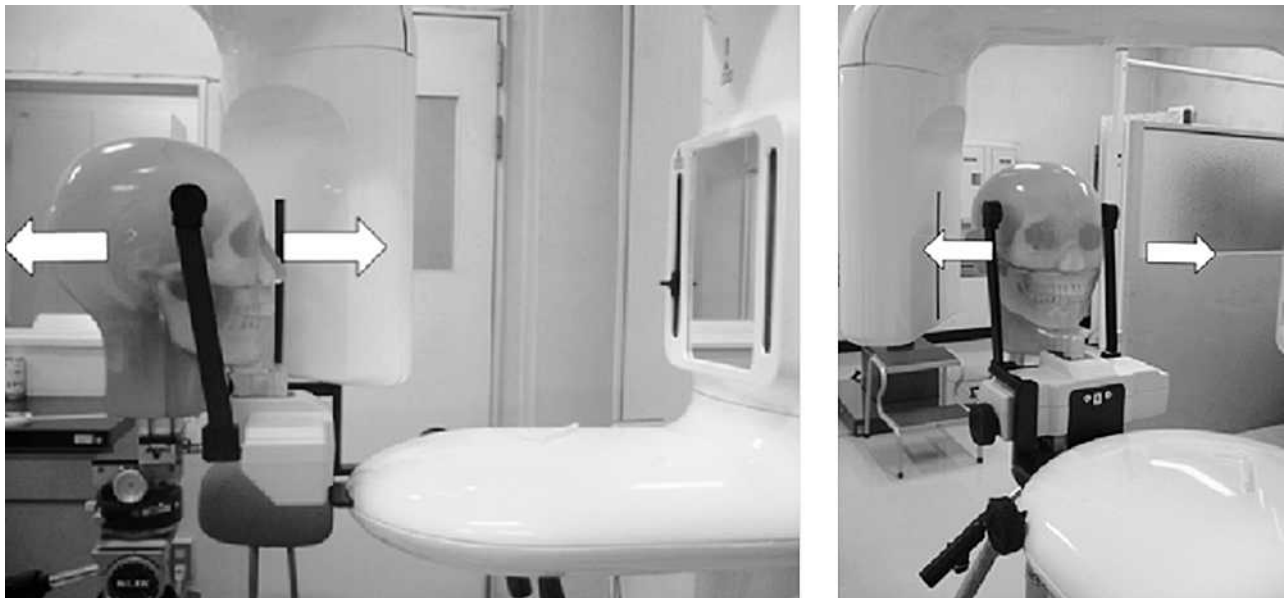


Figure 5. The phantom was radiographed five times (with a minimum interval of 1 day) by one of the authors at the standard and various head positions. The phantom was positioned 4 mm, 8 mm, or 12 mm forward from the standard head position. Similarly, the phantom was positioned 4 mm, 8 mm, or 12 mm backward; 4 mm, 8 mm, or 12 mm rightward; and 4 mm, 8 mm, or 12 mm leftward from the standard head position.

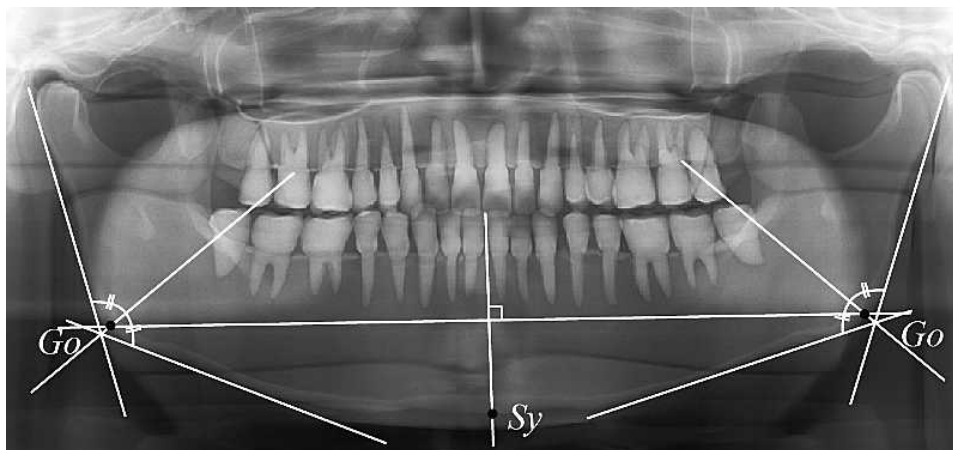


Figure 6. The mandibular landmarks. *Go* indicates a point on the bony contour of the mandibular angle (it was intersected by the bisector of an angle between a mandibular posterior tangential line and a mandibular lower tangential line); *Sy*, a point on the bony chin defined by the intersection of a vertical reference line and the lower mandibular border (the vertical reference line was perpendicular to a line between the right and left *Go*, through a midpoint between the mesioincisal angles of lower central incisors).

The dimensions in experiment 1 were measured. In addition, the following points and dimensions were defined according to the definition provided by Larheim²¹ (Figures 6 and 7).

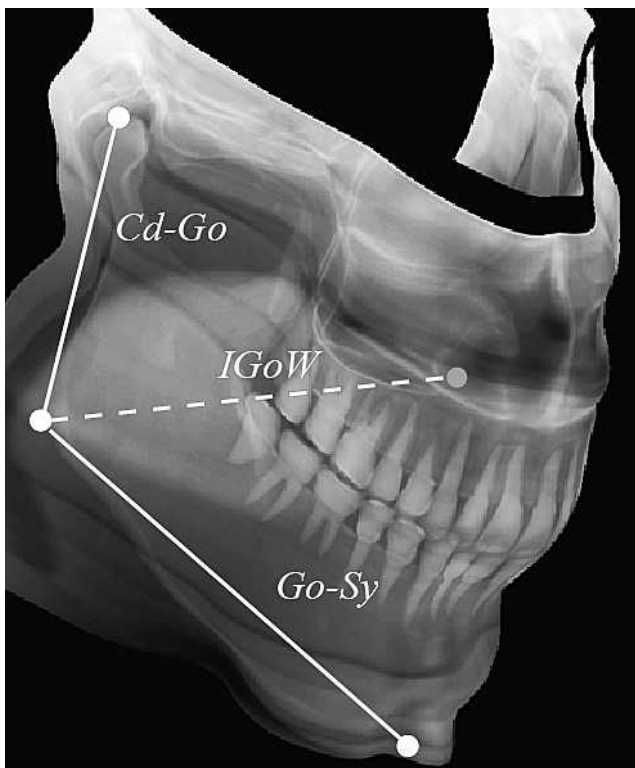


Figure 7. The mandibular dimensions. *IGoW* indicates inter *Go* width, the distance between the right and left *Go*; *Cd-Go*, *Cd-Go* distance, the distance between *Cd* and *Go*; and *Go-Sy*, *Go-Sy* distance, the distance between *Go* and *Sy*.

Statistical Analyses

The values at the standard head position were defined as standard. Tests for significant differences between the standard value and the values in the various head positions were conducted using Dunnett analysis. The level of significance $P < .01$ was chosen for all tests. Analyses were performed using statistical software (SPSS 14.0, Chicago, Ill).

Magnification ratios of the dimensions at each head position to the standard value were calculated.

RESULTS

The measurement value, true value, measurement error, and measurement percent error for each dimension are shown in Table 2. The measurement errors were small in any direction.

The measurement values at the standard head position; 4 mm, 8 mm, and 12 mm forward; 4 mm, 8 mm, and 12 mm backward; 4 mm, 8 mm, and 12 mm rightward; and 4 mm, 8 mm, and 12 mm leftward from the standard head position are shown in Tables 3 through 6. At 4-mm head displacement positions, head positioning had no effect on measurements of a variety of dimensions. At 12-mm head displacement positions, the measurements for vertical dimensions were little affected by head positioning, while those for lateral and anteroposterior dimensions were strongly affected.

DISCUSSION

Measurement errors, which were defined as the differences between the new panoramic radiographic measurements and calipers or CT measurements, were small for all dimensions in the present study. Calipers and CT are recognized as methods that can

Table 2. The Measurement Values, True Values, and Measurement Errors

Dimension ^a	Measurement Values		True Values		Measurement Errors	
	Mean, mm	SD, mm	Mean, mm	SD, mm	mm	%
Upper right <i>CIL</i>	22.7	0.0	22.8	0.1	-0.1	-0.4
Upper right <i>LIL</i>	22.2	0.1	22.8	0.1	-0.6	-2.7
Upper right <i>CTL</i>	26.9	0.1	26.6	0.2	0.3	1.1
Upper left <i>CIL</i>	22.4	0.0	22.5	0.1	-0.1	-0.4
Upper left <i>LIL</i>	21.9	0.0	22.3	0.2	-0.4	-1.8
Upper left <i>CTL</i>	24.6	0.1	24.5	0.1	0.1	0.2
Lower right <i>CIL</i>	22.5	0.0	21.9	0.1	0.6	2.5
Lower right <i>LIL</i>	23.4	0.2	22.7	0.1	0.7	3.0
Lower right <i>CTL</i>	26.2	0.1	25.7	0.2	0.5	1.6
Lower left <i>CIL</i>	22.6	0.1	22.7	0.2	-0.1	-0.5
Lower left <i>LIL</i>	21.5	0.1	21.7	0.1	-0.2	-1.0
Lower left <i>CTL</i>	23.9	0.1	23.9	0.1	0.0	0.0
Upper <i>DAL</i>	40.8	0.2	41.6	0.2	-0.8	-1.8
Lower <i>DAL</i>	37.2	0.1	37.2	0.1	0.0	0.0
Upper <i>ICIW</i>	10.1	0.1	9.4	0.1	0.7	7.4
Upper <i>ILIW</i>	19.7	0.1	18.3	0.1	1.4	7.7
Upper <i>ICTW</i>	31.0	0.1	30.5	0.0	0.5	1.6
Lower <i>ICIW</i>	6.7	0.1	6.4	0.1	0.3	4.7
Lower <i>ILIW</i>	13.9	0.1	13.1	0.0	0.8	6.1
Lower <i>ICTW</i>	22.7	0.1	22.4	0.1	0.3	1.3
<i>ICdW</i>	100.0	0.3	99.9	0.1	0.1	0.1

^a *CIL* indicates central incisor length; *LIL*, lateral incisor length; *CTL*, canine tooth length; *DAL*, dental arch length; *ICIW*, intercentral incisor width; *ILIW*, interlateral incisor width; *ICTW*, intercanine tooth width; and *ICdW*, inter *Cd* width.

be used to determine linear measurements with acceptable accuracy.^{22,23} Therefore, the results suggest that measurements using the new panoramic radiography are likely to be accurate. Moreover, tooth length is mainly composed of the vertical component, dental arch width and intercondyle distance are composed mainly of the lateral component, and dental arch length is composed of the lateral and anteroposterior components. Accordingly, measurements should be accurate in any direction. An earlier study documented the fact that 14% to 17% of the tested anterior tooth lengths could not be accurately measured because of the narrow image layer.¹² Horizontal measurements have been reported to be unreliable because of the variation in magnification factor.²¹ However, the results from the present study suggest that the new panoramic radiographic equipment is capable of providing acceptably accurate quantitative measurements in any direction. In orthodontics, root resorption has usually been evaluated using panoramic or periapical radiographs.¹³ However, anterior teeth are not really included in the tomographic layer of the panoramic radiographs. The new panoramic radiographic equipment is considered to be useful and appropriate for the evaluation of anterior tooth root resorption in orthodontic practice.

At 4-mm displacement head positions, head positioning had no effect on the measurements. It has been reported that positioning errors occur with greater

frequency than technical errors in panoramic radiographs.²⁴ Previous panoramic radiography has been quite sensitive to positioning errors because of the relatively narrow image layer, particularly in the anterior region.²⁵ In the new panoramic radiographic system described here, patient head positioning is less sensitive.

Considering tooth length, at 8-mm displacement positions, all dimensions were within $\pm 5\%$ of the standard values. At 12-mm displacement positions, almost all dimensions were within $\pm 5\%$ of the standard values. This means that even at 12-mm displacement positions, head positioning had little effect on tooth length. It has been documented that the image layer in the previous panoramic radiographic system is 5 mm in the anterior region and 10 mm in the molar region.²⁶ The high accuracy of tooth length measurements, in the present report, even at 12-mm displacement positions, suggests that the image layer is substantially wider, for the anterior teeth, than has been previously reported for other techniques.

Considering dental arch length, at 8-mm displacement positions, there was no dimension that was significantly different from the standard value or beyond $\pm 5\%$ of the standard value. At the 12-mm forward position, upper and lower dental arch lengths were significantly different from the standard values and more than 5% smaller than the standard values. The results suggest that at various displacement

Table 3. The Measurement Values at the Standard and Forward Head Positions

Dimension ^a	Standard, mm	4-mm Forward		8-mm Forward		12-mm Forward	
		mm	%	mm	%	mm	%
Tooth length							
Upper right <i>CIL</i>	22.7	22.8	100.4	22.5	99.0	22.4*	98.6
Upper right <i>LIL</i>	22.2	22.3	100.4	22.2	100.0	22.0*	99.0
Upper right <i>CTL</i>	26.9	27.1	100.9	26.9	100.0	26.7	99.4
Upper left <i>CIL</i>	22.4	22.2	99.0	22.3	99.5	22.0*	98.1
Upper left <i>LIL</i>	21.9	22.1	100.9	22.0	100.5	21.8*	99.5
Upper left <i>CTL</i>	24.6	24.6	100.0	24.6	100.0	24.2*	98.5
Lower right <i>CIL</i>	22.5	22.8	101.4	22.1	98.3	21.2*	94.3
Lower right <i>LIL</i>	23.4	24.0	102.5	23.0	98.2	22.7*	96.9
Lower right <i>CTL</i>	26.2	26.7	102.1	25.6	97.9	25.4*	97.1
Lower left <i>CIL</i>	22.6	23.0	101.8	22.5	99.6	22.0*	97.3
Lower left <i>LIL</i>	21.5	21.6	100.4	20.9*	97.1	20.2*	93.9
Lower left <i>CTL</i>	23.9	24.0	100.5	23.5	98.4	23.0*	96.3
Dental arch length							
Upper <i>DAL</i>	40.4	40.6	100.5	39.3	97.3	35.1*	86.9
Lower <i>DAL</i>	36.6	36.9	100.8	34.6	94.5	31.1*	85.0
Dental arch width							
Upper <i>ICIW</i>	9.5	9.8	103.2	8.1*	85.6	7.8*	82.9
Upper <i>ILIW</i>	18.9	19.4	102.5	17.1*	90.8	16.4*	86.7
Upper <i>ICTW</i>	31.0	31.0	100.0	28.1*	90.8	26.5*	85.6
Lower <i>ICIW</i>	6.5	6.5	100.0	6.2	95.1	6.1*	93.8
Lower <i>ILIW</i>	13.9	13.6	98.1	13.4	97.0	13.1*	94.7
Lower <i>ICTW</i>	23.0	22.8	99.2	22.4	97.7	21.1*	92.0
Mandibular length							
<i>ICdW</i>	99.9	99.3	99.4	96.1*	96.2	95.9*	96.0
<i>IGoW</i>	97.9	98.4	100.5	87.9*	89.7	86.7*	88.5
Right <i>Cd-Go</i>	61.9	62.0	100.2	62.1	100.4	61.5	99.4
Left <i>Cd-Go</i>	61.4	61.9	100.9	59.8	97.5	61.0	99.4
Right <i>Go-Sy</i>	87.4	87.1	99.7	82.8*	94.7	76.9*	88.0
Left <i>Go-Sy</i>	88.6	85.0	96.0	77.7*	87.7	73.1*	82.5

^a *CIL* indicates central incisor length; *LIL*, lateral incisor length; *CTL*, canine tooth length; *DAL*, dental arch length; *ICIW*, intercentral incisor width; *ILIW*, interlateral incisor width; *ICTW*, intercanine tooth width; *ICdW*, inter *Cd* width; *IGoW*, inter *Go* width; *Cd-Go*, *Cd-Go* distance; and *Go-Sy*, *Go-Sy* distance.

* $P < .01$. The values in bold font are beyond $\pm 5\%$ of the standard value.

positions, except at the 12-mm forward position, head positioning had little effect on dental arch length measurements.

Considering dental arch width, upper dimensions were significantly different at the 8-mm forward position from the standard values and more than 5% smaller than the standard values. At the 8-mm backward position, lower dimensions as well as upper dimensions were significantly different from the standard values and more than 5% larger than the standard values. Objects situated between the central plane of the image layer and the X-ray beam are magnified, while objects located between the central plane and the film are minified.²⁷ In the present study, the effect of the head position on measurements was larger in the lower jaw than in the upper jaw. The findings may be explained by the fact that the lower anterior tooth root apices are positioned beyond the image layer of the new panoramic radiographic equipment at the 8-mm backward position. This is

explained by the fact that at the 12-mm backward position, the lower anterior tooth lengths were minified, although the teeth should be magnified because of their location closer to the X-ray source. At the 12-mm displacement positions, almost all dimensions were significantly different from the standard values and beyond $\pm 5\%$ of the standard values. The results indicate that the measurements for dental arch width are affected by head positioning displacements of 8 mm and 12 mm.

Considering the mandibular ramus height, no dimension was significantly different from the standard value at any head position. All dimensions were within $\pm 5\%$ of the standard values. This means that head positioning had no effect on the measurements for the mandibular vertical dimensions.

Considering mandibular width and body length, at the 8-mm and 12-mm forward positions, the mandibular widths and bilateral mandibular body lengths were more than 5% smaller than the standard values. At the

Table 4. The Measurement Values at the Backward Head Position

Dimension ^a	4-mm Backward		8-mm Backward		12-mm Backward	
	mm	%	mm	%	mm	%
Tooth length						
Upper right <i>CIL</i>	22.5	100.4	22.1*	98.6	22.6*	100.8
Upper right <i>LIL</i>	22.2	101.4	22.1	100.9	22.2*	101.4
Upper right <i>CTL</i>	24.9	101.4	24.7	100.6	24.6	100.0
Upper left <i>CIL</i>	22.5	99.0	22.7	100.0	23.8*	104.8
Upper left <i>LIL</i>	22.2	100.0	22.3	100.4	22.9*	103.1
Upper left <i>CTL</i>	26.9	100.0	27.2	101.3	27.8*	103.5
Lower right <i>CIL</i>	22.9	101.3	22.3	98.7	22.3*	98.7
Lower right <i>LIL</i>	21.7	100.8	21.7*	100.8	20.4*	94.8
Lower right <i>CTL</i>	24.1	100.9	24.3*	101.8	23.7	99.2
Lower left <i>CIL</i>	22.6	100.5	21.9*	97.4	21.9*	97.4
Lower left <i>LIL</i>	23.2	99.1	22.4*	95.6	21.0*	89.7
Lower left <i>CTL</i>	25.9	99.0	25.3*	96.7	24.9*	95.2
Dental arch length						
Upper <i>DAL</i>	41.0	101.5	41.0	101.5	40.4	100.0
Lower <i>DAL</i>	37.5	102.5	37.5	102.5	37.7	103.0
Dental arch width						
Upper <i>ICIW</i>	9.9	104.2	12.0*	126.6	14.6*	154.1
Upper <i>ILIW</i>	19.5	103.1	21.1*	112.0	24.5*	130.0
Upper <i>ICTW</i>	30.4	98.1	30.9*	99.7	34.6*	111.8
Lower <i>ICIW</i>	6.8	104.6	9.7*	148.9	12.8*	196.6
Lower <i>ILIW</i>	14.4	104.2	19.4*	140.2	23.7*	170.7
Lower <i>ICTW</i>	23.8	103.7	25.4	110.4	28.1*	122.5
Mandibular length						
<i>ICdW</i>	99.8	99.9	99.5	99.6	106.6*	106.7
<i>IGoW</i>	95.3	97.3	95.3	97.3	103.9*	106.1
Right <i>Cd-Go</i>	63.0	101.8	63.8	103.1	64.0	103.4
Left <i>Cd-Go</i>	61.4	100.0	61.6	100.4	61.8*	100.7
Right <i>Go-Sy</i>	91.7	104.9	93.1	106.5	101.5*	116.1
Left <i>Go-Sy</i>	88.0	99.3	84.7	95.6	96.6*	109.1

^a *CIL* indicates central incisor length; *LIL*, lateral incisor length; *CTL*, canine tooth length; *DAL*, dental arch length; *ICIW*, intercentral incisor width; *ILIW*, interlateral incisor width; *ICTW*, intercanine tooth width; *ICdW*, inter *Cd* width; *IGoW*, inter *Go* width; *Cd-Go*, *Cd-Go* distance; and *Go-Sy*, *Go-Sy* distance.

* $P < .01$. The values in bold font are beyond $\pm 5\%$ of the standard value.

12-mm backward position, the mandibular widths and bilateral mandibular body lengths were more than 5% larger than the standard values. These results mean that the measurements for lateral and anteroposterior dimensions were affected by the anteroposterior positioning of the phantom.

At the 12-mm rightward position, right mandibular body length was more than 5% smaller than the standard value, while at the 12-mm leftward position the left mandibular body length was more than 5% smaller than the standard value. The results could be explained by the following reason. When the object is displaced rightward (or leftward), the distance between the X-ray beam and the right (or left) mandible tends to appear larger than that at the standard head position. The measurements, particularly on the same side were affected by head positioning. These findings may be caused the fact that high-frequency structures overlapped to the mandible interrupt the edge analysis. The mandibular

measurements for lateral and anteroposterior dimensions were affected by head positioning.

CONCLUSIONS

- Measurement errors on radiographs made using the new dental panoramic radiographic equipment were small in any direction.
- At 4-mm head displacement positions, head positioning had no effect on measurements of a variety of dimensions.
- At 12-mm head displacement positions, the measurements for vertical dimensions were little affected by head positioning, while those for lateral and anteroposterior dimensions were strongly affected.

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Table 5. The Measurement Values at the Rightward Head Position

Dimension ^a	4-mm Rightward		8-mm Rightward		12-mm Rightward	
	mm	%	mm	%	mm	%
Tooth length						
Upper right <i>CIL</i>	22.4	100.0	22.3	99.5	22.5	100.4
Upper right <i>LIL</i>	21.9	100.0	22.0	100.5	22.6*	103.2
Upper right <i>CTL</i>	24.6	100.0	24.6	100.0	25.2*	102.6
Upper left <i>CIL</i>	22.6	99.5	22.8	100.4	23.0	101.2
Upper left <i>LIL</i>	22.6	101.7	22.3	100.4	22.5	101.3
Upper left <i>CTL</i>	27.2	101.3	27.1	100.9	26.9	100.0
Lower right <i>CIL</i>	22.6	100.0	22.6	100.0	22.6	100.0
Lower right <i>LIL</i>	21.0	97.6	21.0	97.6	21.0*	97.6
Lower right <i>CTL</i>	23.7	99.2	23.7	99.2	23.6*	98.7
Lower left <i>CIL</i>	22.5	100.0	22.4	99.6	22.1*	98.3
Lower left <i>LIL</i>	23.7	101.2	23.6	100.8	23.2	99.1
Lower left <i>CTL</i>	26.0	99.4	25.4	99.4	25.4*	97.1
Dental arch length						
Upper <i>DAL</i>	40.4	100.0	40.4	100.0	40.0	99.0
Lower <i>DAL</i>	36.5	99.7	36.5	99.7	36.7	100.3
Dental arch width						
Upper <i>ICIW</i>	9.5	100.0	9.8	104.0	8.5*	90.3
Upper <i>LIW</i>	18.6	98.6	20.0	104.0	17.5*	93.0
Upper <i>ICTW</i>	30.3	97.7	31.0	100.0	28.9*	93.5
Lower <i>ICIW</i>	6.5	99.7	6.4	97.8	5.9*	90.8
Lower <i>LIW</i>	13.4	97.0	13.7	99.0	13.0*	93.9
Lower <i>ICTW</i>	22.9	99.5	23.0	100.0	22.1	96.2
Mandibular length						
<i>ICdW</i>	98.2	98.3	98.7	98.8	93.8*	93.9
<i>IGoW</i>	98.0	100.1	99.3	101.4	97.1	99.1
Right <i>Cd-Go</i>	62.3	100.7	61.8	99.9	59.7*	96.5
Left <i>Cd-Go</i>	61.6	100.4	62.0	101.0	63.8*	104.0
Right <i>Go-Sy</i>	86.0	98.4	85.6	97.9	82.1*	93.9
Left <i>Go-Sy</i>	86.9	98.1	92.1	104.0	92.0*	103.9

^a *CIL* indicates central incisor length; *LIL*, lateral incisor length; *CTL*, canine tooth length; *DAL*, dental arch length; *ICIW*, intercentral incisor width; *LIW*, interlateral incisor width; *ICTW*, intercanine tooth width; *ICdW*, inter *Cd* width; *IGoW*, inter *Go* width; *Cd-Go*, *Cd-Go* distance; and *Go-Sy*, *Go-Sy* distance.

* $P < .01$. The values in bold font are beyond $\pm 5\%$ of the standard value.

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Table 6. The Measurement Values at the Leftward Head Position

	4-mm Leftward		8-mm Leftward		12-mm Leftward	
	mm	%	mm	%	mm	%
Tooth length						
Upper right <i>CIL</i>	22.3	99.5	22.8	101.7	22.4	100.0
Upper right <i>LIL</i>	22.0	100.5	22.5*	102.7	22.3*	101.8
Upper right <i>CTL</i>	24.5	99.8	24.8	101.0	24.5	99.8
Upper left <i>CIL</i>	22.6	99.5	22.8	100.4	22.4*	98.6
Upper left <i>LIL</i>	22.3	100.4	22.4	100.8	22.5*	101.3
Upper left <i>CTL</i>	27.2	101.3	27.7*	103.1	27.1	100.9
Lower right <i>CIL</i>	23.0	101.8	23.0	101.8	23.1	102.2
Lower right <i>LIL</i>	21.9	101.8	22.0	102.2	21.3	99.0
Lower right <i>CTL</i>	24.2	101.3	24.2*	101.3	23.2*	97.2
Lower left <i>CIL</i>	22.5	100.1	22.7	101.0	22.4	99.6
Lower left <i>LIL</i>	23.1	98.6	23.4	100.0	23.3	99.5
Lower left <i>CTL</i>	25.7	98.2	26.3	100.5	25.7*	98.2
Dental arch length						
Upper <i>DAL</i>	40.6	100.5	39.4*	97.5	38.9*	96.3
Lower <i>DAL</i>	36.9	100.8	36.6	100.0	36.2	98.9
Dental arch width						
Upper <i>ICIW</i>	9.6	101.5	8.4*	88.8	8.5*	89.9
Upper <i>ILIW</i>	18.6	98.6	16.9*	89.3	16.0*	84.7
Upper <i>ICTW</i>	30.8	99.6	30.0	97.0	26.7*	86.2
Lower <i>ICIW</i>	6.6	101.5	6.6	101.5	6.6*	101.5
Lower <i>ILIW</i>	13.5	97.3	13.5	97.1	13.2*	94.9
Lower <i>ICTW</i>	22.7	98.9	22.0	95.6	21.6	93.8
Mandibular Length						
<i>ICdW</i>	99.9	100.0	98.4	98.5	83.1*	83.1
<i>IGoW</i>	94.3	96.3	94.0	96.0	95.1	97.1
Right <i>Cd-Go</i>	63.2	102.1	63.1	102.0	63.3	102.3
Left <i>Cd-Go</i>	59.8	97.5	60.5	98.6	58.8	95.8
Right <i>Go-Sy</i>	86.7	99.2	89.4	102.3	91.7*	104.9
Left <i>Go-Sy</i>	84.5	95.4	78.7*	88.8	78.0*	88.1

* *CIL* indicates central incisor length; *LIL*, lateral incisor length; *CTL*, canine tooth length; *DAL*, dental arch length; *ICIW*, intercentral incisor width; *ILIW*, interlateral incisor width; *ICTW*, intercanine tooth width; *ICdW*, inter *Cd* width; *IGoW*, inter *Go* width; *Cd-Go*, *Cd-Go* distance; and *Go-Sy*, *Go-Sy* distance.

* $P < .01$. The values in bold font are beyond $\pm 5\%$ of the standard value.

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