European Journal of Orthodontics 24 (2002) 43–52

Accuracy of linear and angular measurements on panoramic radiographs taken at various positions *in vitro*

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SUMMARY The accuracy of measurement of tooth length and angulation on dental panoramic tomograms (DPTs) is thought to be highly dependent on head positioning technique. A model representing the dentition and the functional occlusal plane was designed using an acrylic framework and stainless steel wires. The aim was to investigate whether varying the position of the model affects the linear and angular measurements on DPTs. Four different positions were investigated: initial position representing natural head posture (NHP) (T1); lateral right cant of the occlusal plane (T2); lateral left cant of the occlusal plane (T3); and tilting the occlusal plane up anteriorly (T4). On each DPT, four sets of measurements were recorded: (1) Vertical linear measurements of the stainless steel pins and ratio calculations of the 'crown' and 'root' segments (represented by the wire above and below the occlusal plane, respectively); (2) angular measurements of the pins relative to the occlusal plane; (3) angular measurements of the pins relative to a constructed reference line; and (4) angular measurements of pins relative to each other in the same segment.

The results showed a significant error ($P < 0.05$) in all measurements when the occlusal plane was tilted up anteriorly by 8 degrees. A lateral cant of the occlusal plane by less than 10 degrees without an upward anterior rotation showed no significant effect on the measurements. This would suggest that there is some tolerance of variation in head position.

Introduction

Dental panoramic tomography conveniently provides the clinician with a comprehensive view of the entire maxillo-mandibular region, producing an image of both dental arches on a single film, and significantly reducing radiation exposure to the patient in comparison with intra-oral radiography (Frykolm *et al*., 1977). Panoramic films are useful for evaluating skeletal and dental pathology, making dimensional assessments and determining relative angulations of teeth with other structures (Langland *et al*., 1989).

Image magnification and distortion ultimately limit dimensional accuracy in panoramic radiography. If the degree of magnification was the same both horizontally and vertically in the central plane of the focal trough, then all structures, including maxillary and mandibular teeth, would be in focus on the final radiograph (Whaites, 1992). However, magnification does change from the anterior to the posterior region of the dentition and with object depth (Tronje *et al*., 1985). Horizontal dimensions on a dental pantomograph (DPT) are unreliable, especially in the anterior region, due to large variations in magnification with minor changes in position of the object relative to the focal trough (Rejebian, 1979). That author determined the percentage of distortion by comparing the vertical and horizontal dimensions of extracted teeth with the same teeth on a panoramic radiograph, and found that in the horizontal dimension, the average magnification varied from 19 per cent for the permanent maxillary central incisor to 55 per cent for the permanent second molars. In the vertical dimension, the variation has been found to be less than 23 per cent in the lower premolar region and 30 per cent in the upper premolar region (Graber, 1967). Tronje *et al.* (1981a) reported that vertical magnification did not exceed 10 per cent provided the inclination of the object was between –20 and 30 degrees to the vertical plane in the lower arch, and between –15 and 45 degrees in the upper arch.

Angular measurements are useful in determining the inclination of impacted teeth, root alignment, and crown angulation in clinical dentistry, and to assess edentulous areas for implant location (Graber, 1967). Hauck (1970) found that reproducible positioning of the patient made it possible to follow movement of teeth, loss of molar anchorage, and subsequent changes in root inclination on DPTs. He concluded that angular distortion on DPTs resulted from the combined distortion in the vertical and horizontal dimensions at different positions and depths within the focal trough. Tronje *et al.* (1981b), using theoretical models, showed that if an object is positioned within the focal trough, the mesio-distal inclination can be measured within a moderate error range of approximately 5 degrees. Samfors and Welander (1974) also examined reliability of angular measurements on DPTs and concluded that panoramic images might be reliable for angular measurements in clinical practice with an acceptable accuracy of 5 degrees.

Langland *et al.* (1989) also agreed that an error of approximately 5 degrees could be tolerated and may be considered to be insignificant for most practical clinical purposes. They stated that this also applied to measurements recorded in the anterior region so long as they were derived from adequately exposed panoramic radiographs. Welander *et al.* (1985) applied the above principles to non-cylindrical focal troughs and found that an object with a bucco-lingual inclination of between 30 and 160 degrees could have a clinically insignificant angle distortion of approximately 5 degrees. Both groups concluded that angular measurements were clinically reliable if the radiographs were taken according to the required protocol for the panoramic machine used.

Phillippe and Hurst (1978) studied the relationship between the orientation of the occlusal plane and distortion on DPTs and found that a varying amount of distortion existed with variation in the cant of the occlusal plane. They reported that correct head positioning was critical in taking DPTs and observed that when the occlusal plane was located at 6 degrees to the horizontal, there was a minimal amount of distortion, provided the magnification factor remained constant.

It is evident, therefore, that patient head positioning is important in panoramic radiography because poor positioning techniques may result in structures lying outside the focal trough, causing images to be blurred and distorted with lack of definition (Rohlin and Akerblom, 1992). The distortion can create images that are either too wide or too narrow, depending on whether the structures are on the film or source side of the focal trough (McDavid *et al.*, 1995).

Schiff *et al.* (1986) reported that positioning errors occurred with greater frequency than technical errors and that the percentage of errors appeared to be far less for the films exposed by a single trained technician. This emphasizes the importance of having adequate training in the use of panoramic radiographic equipment, a quality assurance regimen and the ability to correct any errors that may occur. According to Philippe and Hurst (1978), the clinical significance of distortion with panoramic radiography is not important provided the clinician understands that there is a small amount of distortion and that it varies with the cant of the occlusal plane.

The aim of this study was to evaluate the *in vitro* accuracy of ratio calculations between ‘crown’ and ‘root’ segments, and linear and angular measurements on four different panoramic radiographs taken at different angles on a model simulating the dental arches and the functional occlusal plane.

Materials and methods

A model was designed and constructed consisting of a clear arch-form acrylic sheet

(2 mm thick and 15 mm wide; Planmeca OY, Helsinki, Finland) with a 0.9-mm stainless steel wire (Dentaurum, Pforzheim, Germany) bonded to its periphery determining the maxillo-mandibular occlusal plane. Ten stainless steel round pins (2.0 × 20.0 mm) were bonded into holes (2 mm in diameter) drilled equidistantly through the acrylic (4 mm apart). The pin segments above the occlusal plane represented the 'crown' portion and those below the 'root' portion of the pins (Figure 1).

The model was mounted on a panoramic machine to simulate the ideal patient head position. The Siemens Orthophos Plus panoramic imaging system (Siemens AG, Bensheim, Germany) was used to generate the images of the model in four different positions. All exposures were taken on Program 11, a panoramic exposure with a constant 25 per cent vertical magnification, recommended by the manufacturer for implant measurements. The magnification factor was 1.25 with exposure settings of 60 kVp and 9 mA. The film screen was a Kodak Lanex medium screen (Eastman Kodak, Rochester, NY, USA) and the film used was T-Mat G panoramic PAN/TMG15 (Eastman Kodak).

The model was fixed to the standard 'bite-piece' of the panoramic machine. To represent the vertical or *Y*-axis (Figure 2) on the radiographic images, a stainless steel wire (0.9 mm in diameter × 40 mm in length) was bonded to the internal surface of the hollow vertical tube (5 mm in diameter × 60 mm in length). This tube is a standard component of the bite piece on the panoramic device. On radiograph T1, the occlusal plane was positioned perpendicular to the vertical reference line anteriorly.

The model was constructed using 10 stainless steel pins bonded in the incisor, canine, premolar, and molar regions on the acrylic model at angulations selected using computer generated random numbers confined to a range of approximately 15 degrees (bucco-lingually and mesio-distally) relative to the vertical plane. The angle of each pin was measured relative to the 90-degree line of the protractor, which was placed to correspond with the shaft of the pin as it emerged from the acrylic. In Figure 2, the *X*-axis represented the horizontal transverse axis around which the model was rotated in a counter-clockwise direction (T4) viewed from the right of the model (anterior part of the model tilted upwards). The *Y*-axis represented the vertical reference axis in the midline to which the lateral left and right cants of the occlusal plane were measured, respectively, and the

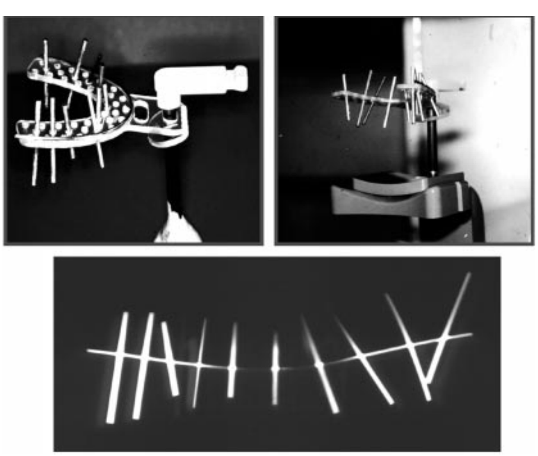

Figure 1 Photographs showing the final acrylic model and its radiographic view used in the study.

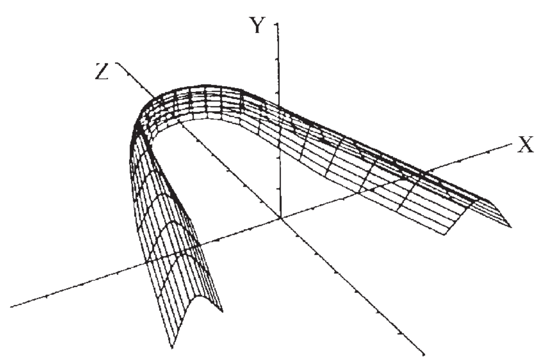

Figure 2 A three-dimensional display of the focal trough demonstrating the *X*, *Y*, and *Z* axes. The *X*-axis represents the horizontal transverse axis around which the model was rotated in a counter-clockwise direction (radiograph T4), viewed from the right of the patient. The *Y*-axis represents the vertical reference axis in the midline and the *Z*-axis represents the antero-posterior (sagittal) axis around which the model was canted to the left and right (radiographs T2 and T3). The posterior part of the focal trough is larger in all dimensions (taken from Langland *et al.*, 1989).

Z-axis the sagittal axis around which the model was canted to the left and right (T2 and T3).

The model was positioned in the panoramic unit using the focal trough guides. A total of eight exposures were taken with four different positions repeated once (Figure 2):

1. The *Y*-axis (true vertical) perpendicular to the *X*-axis (true horizontal) and the occlusal plane tilted 8 degrees anteriorly downwards, simulating the NHP (T1).
2. The right side of the model tilted down 10 degrees around the *Z*-axis (T2).
3 The left side of the model tilted down 10 degrees around the *Z*-axis (T3).
4. The *Y*-axis perpendicular to the *X*-axis, but the occlusal plane tilted up 8 degrees anteriorly, parallel to the horizontal plane (T4).

The second radiograph for each position (T1–T4) was taken after the model had been removed and repositioned, confirming the reliability of the positioning technique. All linear and angular parameters were measured on each of the eight radiographs. Each linear pin segment and all angles were measured on three separate occasions on each radiograph, and the mean of the three measurements was recorded. The two radiographs in T1, T2, T3, and T4 were also superimposed to assess for any obvious visual distortion. Of the eight DPTs, four were chosen at random to represent T1–T4.

Six different parameters were measured:

1. The lengths of the segments above and below the occlusal plane representing ‘crown’ and ‘root’ segments, respectively.
2. The total length of the pins.
3. The ‘crown–root’ ratio.
4. Angular measurement of the pins relative to the occlusal plane.
5. Angular measurement of pins relative to a reference plane taken from a line perpendicular to the most distal pin bisecting the long axis of each of the remaining pins.
6. Angular measurements of the pins relative to each other and measured in the same segment.

Tracings were carried out in a dark room and the data were transferred to a computer spreadsheet for analysis. All measurements were made on acetate sheets (3M Unitek, Monrovia, CA, USA) overlayed on fiducial lines. All linear measurements were made with a manual measuring calliper (Dentaurum) to the nearest 0.1 mm, ratios were calculated using a Casio scientific calculator and angles were measured with a cephalometric protractor (Ormco Corp. Glendora, CA, USA) to the nearest 0.5 degree.

Statistical analysis

The SPSS package 8.0 (Statistical Package for the Social Sciences, CA, USA) was used to analyse the results. The effects of tilting the occlusal plane on vertical linear dimensions, ratio calculations, and angular measurements were examined by means of an analysis of variance (ANOVA). A statistical significance level of $P = 0.05$ was selected. The extent of variation on all radiological measurements was shown using the coefficient of variation. The measurements were made from the DPTs by a single observer (SS). The mean differences and standard deviations arising from repeated measurement of the radiographs and repositioning of the model were calculated, and the statistical significance of the differences was assessed using one-factor ANOVA with repeated measures and two tailed *t*-test, respectively. Mean data were used in each case, as the degree of measurement error was very small (2 per cent).

Results

Linear measurements

Crown, root, and total length. The crown, root, and total lengths of the individual pins were compared on radiographs T1, T2, T3, and T4. ANOVA showed significant differences between the four radiographs for the crown lengths ($P = 0.000$) and a marginally significant difference between the root lengths ($P = 0.042$; Table 1). A multiple comparison test using the crowns and roots as dependent variables showed

Table 1 Crown, root, and total lengths of the left stainless steel (ss) pins from posterior to anterior L1–L5 and right ss pins from anterior to posterior R6–R10 measured from DPTs T1 to T4.

Pins	Crown and root lengths (mm)											
	T1			T2			T3			T4		
	Crown	Root	Total	Crown	Root	Total	Crown	Root	Total	Crown	Root	Total
L1	11.9	20.5	32.4	11.8	21.4	33.2	12.1	19.8	31.9	11.5	21.4	32.9
L2	13.9	17.4	31.3	12.9	18.9	31.8	14.0	17.0	31.0	13.3	18.1	31.4
L3	11.4	10.2	21.6	10.8	11.1	21.9	11.8	9.3	21.1	10.7	10.8	21.5
L4	14.1	12.5	26.7	13.7	12.3	26.0	14.0	12.5	26.5	13.2	12.6	25.8
L5	13.7	9.1	22.8	13.6	9.0	22.6	13.8	8.7	22.5	12.8	9.7	22.5
R6	11.1	10.8	21.9	11.4	10.5	21.9	11.3	10.5	21.8	10.2	11.6	21.8
R7	15.8	15.2	31.0	16.7	14.4	31.1	15.5	15.6	31.1	14.8	16.4	31.2
R8	15.2	16.4	31.6	15.8	15.7	31.5	15.1	17.0	32.1	15.0	17.1	32.1
R9	17.8	17.9	35.7	18.0	14.0	32.0	18.0	18.5	36.5	17.4	18.3	36.2
R10	12.0	15.4	27.4	12.4	14.2	26.6	11.8	16.6	28.4	11.6	16.1	27.7

*In none of the measurements was the standard deviation more than 2 per cent of the mean.

that radiograph T4 was significantly different to T1, T2, and T3. Radiographs T1, T2, and T3 showed no significant difference in crown and root lengths. Radiograph T4, however, showed a marginally significant difference to T1–T3 with a mean of 0.7 mm less crown length and 0.7 mm more root length. After correction of the T4 values by adding 0.7 mm to the crown lengths and subtracting 0.7 mm from the root lengths, there were no significant differences between radiographs T1–T4 ($P = 0.877$).

However, in the posterior segments of the model, even without the adjustment, when the occlusal plane was tilted up anteriorly by 8 degrees, the pins in this region did not vary in length because they remained well within the confines of the focal trough. The ends of the pins in the anterior regions, however, did fall outside the confines of the focal trough and thus were elongated. Due to the tilting up of the anterior part of the model (T4), the anterior pins showed foreshortening of the ‘crown’ and of elongation of the ‘root’ segments. This had an insignificant effect on the total lengths, but significantly affected the linear measurement of the crown and root portions. The difference, however, remained within 1 mm with a mean difference of 0.6 mm.

Crown–root ratio calculations. Prior to correction of the linear values in T4, the crown–root ratios were significantly different when all four radiographs were compared ($P = 0.004$), however T1–T3 showed no significant differences (Table 2). A multiple comparison test revealed that the T4 values were significantly different to those in T1–T3. Once

Table 2 Crown/root (C/R) length ratio of the left stainless steel (ss) pins from posterior to anterior L1–L5 and right ss pins from anterior to posterior R6–R10 measured from DPTs T1 to T4.

Pins	C/R length ratio of the mean values			
	T1	T2	T3	T4
L1	0.60	0.60	0.60	0.50
L2	0.80	0.70	0.80	0.90
L3	1.00	1.00	1.25	1.00
L4	1.10	1.10	1.10	1.00
L5	1.50	1.50	1.60	1.30
R6	1.00	1.10	1.10	0.90
R7	1.10	1.15	1.00	0.90
R8	0.95	1.00	0.90	0.90
R9	1.00	1.00	1.00	1.00
R10	0.80	0.85	0.70	0.70

the values in T4 had been adjusted, no significant differences existed between T1–T4 ($P = 0.930$).

Angular measurements

Angular measurements relative to the occlusal plane. The ANOVA showed significant differences between the four radiographs ($P = 0.021$). A multiple comparison test revealed that the angles measured on radiograph T4 were significantly different from those on T1–T2–T3. T1, T2, and T3 showed no significant differences between the angulation of the pins relative to the occlusal plane ($P = 0.440$). Further investigation, however, revealed that the differences in angulation of the pins to the occlusal plane between T4 and the other radiographs were all less than 5 degrees (Table 3).

Angular measurements relative to a reference plane. The ANOVA showed significant differences between the four radiographs ($P = 0.001$). A multiple comparison test indicated that the angulations on radiograph T4 were significantly increased from those in T1–T3 (Table 4), again, when the values in T4 were excluded. T1, T2, and T3 showed no significant differences between the angulation of the pins relative to the reference plane ($P = 0.476$). The differences in angulation of the pins between T4 and the other radiographs were again all less than 5 degrees.

Table 3 Angulation changes of left stainless steel (ss) pins from posterior to anterior L1–L5 and right ss pins from anterior to posterior R6–R10 measured to the occlusal table on DPTs T1 to T4.

Pins	Angulation changes of pins to occlusal plane (°)				
	T1	T2	T3	T4	Actual
L1	92.0	92.0	93.0	89.0	90.0
L2	92.0	91.5	93.0	89.0	92.0
L3	108.0	108.0	108.0	106.0	105.0
L4	90.0	89.0	90.0	86.0	100.0
L5	89.5	89.5	89.5	89.0	90.0
R6	89.0	89.0	89.0	89.0	88.0
R7	83.0	83.0	84.0	81.0	81.0
R8	72.0	71.5	71.5	71.0	70.0
R9	82.0	82.0	81.5	79.5	77.0
R10	100.0	101.0	100.0	97.0	95.0

Table 4 Stainless steel (ss) pin angulation relative to a reference line taken perpendicular to a ss pin on DPTs T1 to T4.

Pins	Pins relative to reference plane (°)			
	T1	T2	T3	T4
L1	85.0	86.0	84.0	87.0
L2	85.0	85.0	85.0	87.0
L3	100.0	102.0	99.5	103.0
L4	84.0	83.0	84.0	84.0
L5	87.0	86.0	88.0	89.0
R6	90.0	89.0	91.5	91.0
R7	72.0	72.0	69.5	72.0
R8	59.0	59.0	57.5	61.0
R9	69.5	69.0	67.5	71.0
R10	90.0	90.0	90.0	90.0

Angulation of the stainless steel pins relative to each other. Angular measurements of the stainless steel pins in the same sextant were measured relative to each other at the level of the occlusal plane. Once again, there was no statistically significant difference between DPTs T1–T3 when T4 was excluded ($P = 0.970$) and only a marginally significant difference was seen between angulations when all four DPTs were compared ($P = 0.041$). The angles in T4 appeared to be marginally smaller than those in T1–T3 and marginally larger than in reality. The largest difference in angulation was, however, less than 3 degrees.

Discussion

A DPT is an easy, rapid, and convenient method of radiographing the maxillo-mandibular region for both practitioner and patient (Mayoral, 1982; Langland *et al.*, 1989), and produces a lower radiation dose equivalent to that received from four bitewing exposures measured at the bone marrow level (White and Rose, 1979). With the use of rare earth film-screen systems (Kodak

Lanex screens) in combination with a Kodak T-Mat G film, the radiation dose is reduced by an additional 47 per cent (D'Ambrosio *et al.*, 1986).

The aim of this study was to record and test the accuracy of linear and angular measurements, and vertical ratio calculations from DPTs using an *in vitro* model exposed at different positions on the same panoramic machine.

According to Tronje *et al.* (1981b), alteration in bucco-lingual inclination of teeth (within certain limits) does not contribute significantly to linear errors on the panoramic image. In this study, however, the error did not exceed 10 per cent of the length only if the length of the object did not exceed 10 mm. This was because compensation in the relative magnification and diminution of various parts of the image occurred. Those authors suggested that placing an inclined object uniformly across the focal trough results in differential magnification due to its inclination. This, however, is only true for distances that are vertical and positioned at the centre of the focal trough. Other studies (Philippe and Hurst, 1978; Luchessi *et al.*, 1988; Taguchi *et al.*, 1997) contradict this statement, claiming that greater errors occur with increased bucco-lingual inclination of the teeth within the focal trough and such errors may be caused by the use of different panoramic machines.

Dental panoramic tomography has been considered to be inadequate for accurate measurement of structures and has been shown to be inaccurate in recording root angulations and root parallelism in posterior segments (Philippe and Hurst, 1978; Luchessi *et al.*, 1988). This has been attributed to incorrect head positioning (Schiff *et al.*, 1986) and errors associated with patient movement during exposure (Browne, 1984). According to Sanderink *et al.* (1991), unreliable DPTs could be explained by considering the position of the jaws in relation to the rotation centres and the path of the X-ray beam. They showed that inaccuracy was mainly due to backward rotation of the head and that lateral cants around the sagittal axis (*Y*-axis) of up to 10 degrees had a negligible effect.

Table 5 Angulation changes of the left stainless steel (ss) pins from posterior to anterior (molar, canine, and incisal) regions L1–L5 and right ss pins from anterior to posterior R6–R10 measured in the same segments on DPTs T1–T4.

Pins	Angulation differences between pins (°)				
	OPG T1	OPG T2	OPG T3	OPG T4	Actual
L1 and L3	16.0	15.0	16.0	16.0	15.0
L1 and L5	1.0	–1.0	1.0	–1.0	1.0
R9 and R10	20.0	21.0	21.5	19.0	18.0
R7 and R10	30.0	30.0	32.0	29.0	28.0

The constructed reference line (Table 4) is practically parallel to the occlusal plane, and measuring the pins relative to this plane served to confirm the angulations of the pins relative to the occlusal plane, as well as to check the error produced by constructing the reference lines. The results obtained from measuring the pins relative to the reference lines appear to be similar to those measured relative to the occlusal plane with no significant differences occurring in angulations in radiographs T1–T3. T4, however, shows significant differences in pin angulations relative to both the occlusal plane and reference plane, respectively.

A common finding on both DPTs and intraoral radiographs is that they are less accurate in subjects with excessively bucco-lingually inclined teeth (Luchessi *et al.*, 1988). The present study found that even though the stainless steel pins were randomly inclined up to 10 degrees in the anterior and posterior regions, the linear or angular measurements between T1, T2, and T3 did not seem to be significantly affected. However, future investigation may reveal different results for teeth that are tilted in excess of 10 degrees.

Linear measurement of the 'crown' and 'root' pin segments above and below the occlusal plane were measured three times on separate occasions. The measurements showed a significant error in identifying individual 'crown–root' segments when an upward tilt of the anterior part of the occlusal plane occurred. However, the lateral inclination of the occlusal plane up to 10 degrees did not significantly affect the accuracy of point identification. The inaccuracy appeared to be related to the antero-posterior location of the pins with regard to their position relative to the direction of the beam.

When a correction factor was applied to radiograph T4 (occlusal plane tilted upward anteriorly by 8 degrees), it seemed to compensate for the error in linear measurements occurring at the junction of the pin 'crown' and 'root' segment. The multiple comparison test confirmed that there was a significant difference between crown and root lengths measured on T4 and T1–T2–T3. A mean error of 0.7 mm was recorded in both crown and root segments of the pins in T4. This value was calculated as the difference between the mean crown and root values of the T4 radiograph, and these values were compared to those in T1–T3. The result was that the crown segments were on average 0.7 mm too short and the root segments 0.7 mm too long. The error occurred at the crown–root junction, which is the common point for measuring crown and root lengths, or calculating the crown–root ratios. The junction of the vertically orientated steel pins with the horizontally placed occlusal plane wire represented this point. Once the mean difference had been calculated, a correction factor was applied to the means of the crown and root segments and this adjustment corrected any difference that existed previously between T4 and T1–T2–T3. Therefore, vertical linear measurements and ratio calculations showed no significant difference in crown lengths ($P = 0.95$) and root lengths ($P = 0.97$) between radiographs T1–T4. Measurement error and error in accurately locating the junction between the crown and root segments may result in some individual variation.

Angular measurements also showed significant differences between T1–T4, but no significant differences were seen when the T4 measurements were excluded from the experiment. The angular differences measured between T4 and the rest of the radiographs, however, were all less than 5 degrees, a clinically insignificant amount.

If the results in Tables 1 and 2 are individually examined, there appear to be large variations in the linear and ratio measurements between T4 and T1–T3. However, in some cases differences greater than 2–3 mm also exist between pin segments in T1, T2, and T3, e.g. root segments on pin no. 9 and crown segments on pin no. 10 (Table 1). Variation in some of the pin segment lengths was noted, but the general tendency was for the pins in radiograph T4 to be slightly foreshortened in the crown segment and slightly elongated in the root segment due to the upward rotation of the anterior segment of the occlusal plane.

Measurements on DPTs taken in a clinical setting would be unreliable if insufficient attention was paid to accurately positioning the head using the focal trough guides. Further research designs in the future may determine a more precise method of determining the cemento-enamel junction (CEJ). In reality, however, the location of the CEJ may be different around the necks of teeth because of changes in the position of tooth or orientation of the X-ray beam, leading to incorrect ratio assessment. Unfortunately, all types of radiographs identify the CEJ as a two-dimensional structure and minimal changes in angulation applied to the tooth may result in a significant vertical change in its location. This change may, however, not be clinically significant. In this study, cylindrical stainless steel pins were used; therefore, any rotation would not have affected the 'crown–root' junction landmark. However, the upward rotation of the anterior part of the occlusal plane (T4) seemed to somewhat distort the junction.

Turner (1968) noted that weaknesses in radiological interpretations of linear measurements in the anterior regions of the jaw, and other recent studies (Frykolm *et al.*, 1977; Tronje *et al.*, 1981a; Luchessi *et al.*, 1988) have confirmed that deviations from normality are greater in the anterior regions of the jaw. Sanderink *et al.* (1991) found that incorrect positioning of the patient's head allowed the X-ray beam to pass outside the jaws when the anterior region was radiographed, resulting in distortion of this region. Blurring and gross distortion of the image were introduced when the head was sagittally moved as little as 1 cm in front or behind, and 3 cm laterally to the ideal position.

It may be possible to assume that using the occlusal plane as a reference plane may introduce a bias into the study. In this investigation, the occlusal plane was used as a reference line to record angular measurements. The advantage of this is that it is directly associated with the stainless steel pins and it moves constantly with the pins when the model is canted in any particular direction. Thus, the angulations would not necessarily deviate dramatically with a slight inclination of 10 degrees or less. However, any deviation beyond this value may show actual distortion between structures.

The significance of limiting the tilting of the model by 10 degrees in all directions in this study was recommended by an expert radiographer in the field of tomograms and, secondly, tilting the head more than 10 degrees was clinically obvious, even to the untrained eye. A further study undertaken using a similar model or an actual patient, and tilting the model or head by more than 10 degrees may only prove the obvious, that the amount of distortion present will be increased.

The human model is preferable to measure dental structures relative to accurate and constant reference lines, which are independent of the structures being measured. These may be, for the mandible, a horizontal line tangent to the most superior part of the condylar head bilaterally, and for the maxilla, a line tangent to the articular eminence bilaterally. The advantage of such reference lines is that not only have they been shown to be constant and reproducible (Hauck, 1970), but they are not directly related to the dentition, which eliminates any bias that may exist when making linear or angular measurements. However, orthopaedic change of any kind related to growth, surgery, or temporomandibular joint disturbances, must be taken into consideration. In the model used in this study, although constructed to represent the human skull and its dentition, it should be noted that the planes of reference differ somewhat from the human model. A model such as this may be clinically useful to calibrate a particular panoramic machine and if needed to evaluate or determine linear, ratio, or angular measurements on radiographs taken in a clinical situation.

Conclusions

This study indicates that comparing linear and angular measurements on DPTs taken at different times is sufficiently accurate for measuring changes in root length and root parallelism, to assess sites for implant location, and to measure angulation of developing third molars. This seems to be true, provided that the occlusal plane is kept at a similar angulation and the occlusal plane is not tilted more than 10 degrees.

All too often valuable information that can be obtained from DPTs is lost or ignored on the assumption that DPTs are always distorted and, therefore, of no value. It is essential that, for this radiograph to be of maximum value to the practitioner and patient, greater emphasis be placed on correct patient positioning.

These results suggest that accurate measurement of structures on DPTs is possible, provided sufficient care is taken with head positioning. If the structures are to be re-measured on subsequent radiographs, some tolerance of variation in head position is possible provided the occlusal plane is not tilted up or down anteriorly.

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Acknowledgements

This study was partially sponsored by the Australian Society of Orthodontics for Research and Education. We wish to thank Dr Fritz Byloff (University of Geneva, Switzerland), Dr Jeff Berger (University of Detriot Mercy, USA), and Mr David Baxter (Department of Radiology, United Dental Hospital, Sydney, Australia), for their valuable assistance in this study.

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