THE RELIABILITY OF CROWN-ROOT RATIO, LINEAR AND ANGULAR MEASUREMENTS WHEN TAKEN ON PANORAMIC RADIOGRAPHS

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A thesis submitted in partial requirement for the degree of Master of Dental Science (Orthodontics)

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Australia

1999
DEDICATION

This dissertation is dedicated to my wonderful wife Alexia and daughters Angelique and Melanie in appreciation of their love, support and encouragement during the preparation of my thesis and throughout the Masters program.
ABSTRACT

In dentistry, panoramic radiographs or orthopantomographs (OPG’s) are widely used. Panoramic radiography has overcome many limitations of extra-oral radiography. It is however uncertain whether the quality of the images produced is sufficient for accurate measurement of the size and orientation of dental structures to be carried out.

The aim of this study is to evaluate the reliability of crown and root length, crown-root ratio and angular measurements of teeth relative to constructed reference lines and to other teeth in the same region on consecutively taken OPG’s of the same patient.

In this retrospective study 20 cases were selected, 10 with 5 implants in each jaw (age range between 20 and 60 years old) and 10 with a full permanent dentition (age range between 12 and 16 years old). The cases were selected according to certain inclusion and exclusion criteria. Vertical linear measurements and ratio calculations on teeth and implants as well as angular measurements were compared on two OPG’s taken on separate occasions.

Four measurements recorded and compared were:
1. The crown or coronal segment lengths and the root or apical segment lengths of 10 teeth (T) and 10 implants (I).
2. The crown-root ratio on 10 teeth and 10 implants on each panoramic radiograph.
3. The angulations of 10 teeth and 10 implants relative to specific reference lines in each jaw.
4. The angles between teeth and implants in the same sextant.

The findings of the study showed that there were no statistically significant differences between vertical linear measurements. The crown-root ratios and coronal-apical segment ratios between radiographs T1 and T2 also showed no significant differences (p > 0.05). The ratios, however, appeared to be were less reliable than the linear measurements as they were totally dependent on the precise location of the cemento-enamel junction (CEJ). Angulations of tooth or implant axes relative to respective reference lines showed marginally significant differences (p=0.001) for some of the teeth, however, the differences were less than 5°, a
range variation considered to be clinically acceptable. Angles measured between teeth or implants in the same sextant showed no significant differences between OPG’s T1 and T2.

The results therefore seem to support the hypothesis that the linear vertical measurements, ratio calculations and angular measurements can be used to compare crown and root lengths, crown-root ratios and tooth angulations on panoramic radiographs taken of the same patient at different times with consistent accuracy.
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the following people:

To Professor M A Darendeliler, Professor and Chair and Dr JP Geenty, Honorary Associate Lecturer, Discipline of Orthodontics, University of Sydney, for their invaluable guidance and support.

To Drs Fritz Byloff and Jeff Berger and Atul Mehta for their assistance in the organisation of this research report.

To Mr David Baxter for his assistance with the radiography in this study.

To Mr Peter Petocz, statistician and Senior Lecturer, School of Mathematical Sciences, UTS, for his guidance in the study design and analysis of the data.

To my friends and future colleagues Yvonne Poon, Michèle Fong and Gareth Ho for their friendship and ongoing support throughout the program.

My sincere thanks and appreciation to my wife Alexia and two daughters, Angelique and Melanie, for their patience, encouragement and support.
DECLARATION

This is to certify that the work presented in this thesis was carried out by the candidate in the Discipline of Orthodontics, Faculty of Dentistry, University of Sydney, and has not been submitted to any other university or institution for a higher degree. I agree that the library shall make it freely available for inspection.

[Signature]

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1. LITERATURE REVIEW

Intra-oral radiographs are widely used in dentistry and their importance and accuracy are well documented (Majoral, 1982). They are, however, limited in their coverage of the maxillo-mandibular structures and multiple films are needed for a comprehensive examination. Conventional extra-oral radiographs such as the lateral cephalogram can achieve better coverage, but anatomical structures of the facial skeleton that are not in the midline cannot be measured accurately because of distortion. Bilateral structures produce two images and it is difficult to differentiate between right and left sides (Baumrind and Franz, 1971).

Another commonly used radiograph is the panoramic radiograph, also commonly known as the orthopantomogram (OPG). This is an extra-oral radiograph that has over the years overcome many limitations of extra-oral radiography including controlled magnification in the vertical dimension, decreased overlapping of tooth contact areas and single point contact of the rotating beam onto the object to allow for a sharper, well defined image (Langland, 1989). X-ray developers and developing chemicals have also been improved over the years.

Panoramic radiography also has the added advantage of displaying the entire maxillo-mandibular region on a single film. Other advantages of this type of radiograph include the increased coverage of the dental arches and associated structures, relatively undistorted anatomic images, reduced radiation dosage for the patient and simplicity of operation (Frykholm, 1977, Whaites 1992). However, whether the quality of the images produced is sufficient to obtain precise measurement of peri-dental structures for clinical assessment, as well as undertaking research involving the measurement of the size and orientation of dental structures to be carried out, remains to be determined.

1.1 History of panoramic radiography

Over the past four decades there have generally been two techniques of taking panoramic radiographs (Langland et al., 1989). The first, outdated technique used a
static intra-oral source of radiation with multiple films placed extra-orally (Berger, 1943). The second technique, commonly known as rotational panoramic radiography, involved the use of an extra-oral source of radiation and a single film (Husden et al, 1957). The latter technique, although modified somewhat from its original design, is still in use today.

In 1943 Horst Berger invented an intra-oral source tube panoramic technique (Van Aken, 1973). This technique employed an intra-oral source of radiation without the use of screen or slow-speed screen films. A small x-ray tube was inserted into the patient’s mouth and the radiation directed from inside the mouth through the jaws onto an extra-oral film moulded to the outside of the patient’s face (Fig. 1). The x-ray source, patient and film were all stationary during the exposure and separate exposures were made of the maxilla and the mandible. A current of approximately 0.1 mA and a kilovoltage (kV) ranging between 40 and 80 kV was used with this particular panoramic unit.

Dr H Numata (1934) of Japan was the first to propose and experiment with an extra-oral rotational panoramic radiographic technique using an intra-oral film. In 1949,

**Figure 1**: Intra-oral x-ray source tube invented by Dr H Berger (1943) showing the curved extra-oral film holder (A) and the intra-oral source of the x-ray beam (B) (from Langland et al, 1989).
Dr Robert Nelson, became the first person to achieve practical application of the panoramic radiograph in the United States, where he initially used his prototype apparatus for x-raying dry skulls only (Nelson and Kumpala, 1952).

In 1950, applying the work done by Nelson and Kumpala, Paatero constructed a prototype of his pantomograph and using this technique he radiographed live patients. At this stage a long film was inserted into the patient’s mouth lingual to the teeth in each jaw. Intensifying screens were used as the film speed was slow and a separate film was taken of each jaw. The intra-oral film method was short-lived, however, due to the limited space within the oral cavity, making it impossible to accommodate the size of the film needed to reveal all the necessary dental structures in each arch. Scientists were also looking for a panoramic method that required only a single exposure (Nelson and Kumpala, 1952)

![Diagram](image)

**Figure 2:** The Concentric-single axis method of Pantomography where a single jaw could only be exposed at one time. The beam came from a stationary tube and the patient and film rotated at the same speed in opposite directions (from Paatero, 1954)
In 1949 Paatero also made the observation that radiographs could be taken by placing the film extra-orally (Paatero, 1949). This technique made it possible to radiograph the curved surfaces of the jaw and display them onto one plane in a panoramic view. This method was known as the concentric-single axis method where a stationary narrow x-ray beam was aimed through the axis of the object and the film (bent in a film cassette). The film and the object were also rotated in opposite directions at the same angular speed (see Fig. 2).

He called his technique pantomography. This is a shortened version of the words **panoramic**, meaning “an unobstructed or complete view of a region in every direction” and **tomography** meaning “an x-ray technique for making radiographs of layers of tissue in depth, without interference of the tissues above and below that level” (Paatero, 1954).

*Figure 3: The axis of rotation is constantly moving in an adjustable semi-elliptical path (dotted line) conferring to the patient’s dental arch. This is a diagramatic representation of three positions of the x-ray tube and film cassette during their continuous movement around the patient. The cassette also moves simultaneously on its own axis during the exposed cycle. (from Langland et al, 1989)*
In 1954, Paatero found a way of using three rotational axes, two eccentric and one concentric. By using two eccentric rotational axes on the sides of the jaw and a single concentric axis on the anterior region of the jaws, he attained a projection in which the x-rays penetrate the teeth perpendicularly, thereby eliminating the problem of overlapping.

In 1954, Sairenji of Japan, patented the orthopantomographic system where the patient sits or stands immobile while the x-ray tube rotates around the neck and the film cassette moves around the face, rotating about its own axis. Hudsen and Kumpala later modified this technique into a double eccentric panoramic unit with an interruption midway to re-orientate the patient. This method became known as the Panorex x-ray machine (Hudsen and Kumpala, 1957).

In 1962, the practice of repositioning the patient was completely eliminated. An interrupted x-ray generation was incorporating into the system while the chair shifted and automatically repositioned the patient. In the 1970’s, Drs Morris and Hudson of the United States developed panoramic x-ray machines whereby the x-ray rotational centre changed half way through the exposure by the automatic movement of the tubehead-film cassette assembly, instead of by shifting of the chair. The more modern panoramic x-ray machines all operate in this fashion and the methods and techniques of panoramic radiography are continuously improving providing images that are sharper and far more accurate on which to measure linear and angular dimensions.

1.2 Scientific Background of Panoramic Radiography

1.2.1 Frequency of use

According to the United Nations report to the General Assembly in 1988, dental radiography represents the most frequent diagnostic X-ray examination undertaken in the developed countries of the world. Of all the dental radiographic examinations carried out, the use of panoramic radiology has shown a marked increase of 20-30% of all radiographs taken by practitioners in the western world (Rushton and Horner,
1996). In Great Britain (UK) up until 1993, the total number of panoramic radiographs exceeded 1.5 million within the general dental services of England and Wales, representing approximately 10% of all dental radiographic examinations. This excluded those taken in private practice, in hospitals and within the community dental services (Rushton and Horner, 1996). In the USA, the proportion of practitioners using panoramic radiography ranged from 26% to 60% (Nakfoor and Brookes, 1992) where as France the number of films taken exceeded that of the UK, carried out mostly by radiologists (46%). In Australia, it was estimated that in 1988, 6% of practitioners used panoramic radiography (Monsour et al., 1988).

In the USA, panoramic views and lateral cephalograms comprise the basic films considered necessary for orthodontic diagnosis and treatment planning (Atchinson et al., 1991). Atchinson et al., showed that in an American orthodontic practice 70% of children in the primary and mixed dentition and 90% of children in the permanent dentition phase were assessed using a panoramic film. Panoramic views are also recommended by more than two-thirds of orthodontic departments within dental schools in the UK (Osman et al, 1985).

1.2.2 Diagnostic applications

Specific applications of panoramic radiography to the dentition do not only include the detection of caries and an assessment of the alveolar bone, but also dimensional assessments and determination of the relative angulations of the teeth. (Kane, 1967). The assessment of the dimension and orientation of structures from panoramic radiographs can be used in clinical dentistry to determine inclination of impacted teeth, the overall shape, length and relative position of roots and for implant site assessment (Wyatt et al., 1995). Panoramic radiographs are commonly used diagnostic tools in orthodontics for diagnosis and treatment planning and also to evaluate the effects of treatment, for example, crown angulation, root alignment and root resorption (Graber, 1967, Reitan, 1974). They are also useful for making linear dimensional and angular measurements and can be used in conjunction with other radiographic views when greater clinical accuracy is required (Thanyakarn et al., 1992).
Panoramic radiography is a widely used procedure for examination of the skeletal and dental bases and also the dentition (Larheim and Svanaes, 1986). Few reports, however, are available dealing with the accuracy and reproducibility of the method. Past studies have shown the panoramic radiograph to be inferior to intra-oral periapical and bitewing radiographs in many respects, such as the diagnosis of caries, periodontal bone heights and periapical pathology (Muhammed and Manson-Hing, 1982). However, the design of the above study and many others comparing intra to extra-oral films may be criticized in their materials and methods for having a small sample size, differing diagnostic thresholds, the failure to derive figures for sensitivity and specificity and the absence of a “gold standard” for specific measurements (Rushton and Horner, 1996).

1.2.3 Analysis of errors in measurement

According to Houston (1983) it is important to define the sources of error in radiographic measurement and to distinguish between bias and random errors. Bias or systematic errors occur when comparing radiographs that are geometrically distorted or actual lengths taken from a model to that of the image without taking into account the magnification factors involved. Random errors may arise as a result of variation in the positioning of the patient on the panoramic unit or variations in film density or sharpness leading to difficulty in identifying a particular landmark. There are also two terms, namely, validity and reproducibility, that need to be adequately defined and understood as they are relevant to the analysis of errors in radiographic measurements. Validity or accuracy of measurement is the extent to which, in the absence of measurement error, the value obtained represents the object of interest. Reproducibility or reliability is the closeness of successive measurement of the same object (Houston, 1983).

The randomization of record measurement is shown to be one of the most important methods of avoiding bias, but according to Baumrind and Franz (1971) it appears to be rarely done in most radiographic studies. Random errors also need to be taken into consideration when evaluating individual radiographs. Measurements showing a
high error in relation to total variability are of little value in clinical assessment. Therefore, if any study using measurements is to be of value, it is imperative that an error analysis be done to test the validity and reliability of landmarks and measurements in order to minimise the errors occurring in a particular analysis.

It is important to consider which points are to be measured and the method of measurement. Changes in bony anatomy due to growth and remodelling ultimately may affect the landmarks used if two radiographs being compared are taken at different time periods. The radiographic image is also enlarged and may be distorted. Adjustments of linear measurements are needed if radiographs taken on different systems are to be compared. The reproducibility of measurements also vary according to the quality of the records, the conditions under which they are measured and the care and skill of the measurer (Houston, 1982). Random errors may also arise as a result of variations in positioning of the patient. Variations in film density and sharpness also lead to random errors. One of the greatest sources of random errors is difficulty in identifying a particular landmark.

1.2.4 Accuracy of panoramic radiographs

Panoramic radiology is a modified form of tomography (McDavid et al., 1985) and all tomographic techniques blur the images of structures above and below the "in focus" layer commonly known as the focal trough. Due to the relatively narrow image layer of focal trough, especially in the anterior region, it renders the technique sensitive to positioning errors (Welander, 1974). The focal trough ranges from 4.5mm to 12mm in the anterior regions and is two to three times greater in the molar or posterior regions (Fig 4 A).

Panoramic images are further degraded, to a variable extent by shadows of the soft tissues and surrounding air. Ghost images of the spine and mandible further reduces the diagnostic quality (Langland et al., 1992). According to Langland et al., there are also variations in the horizontal angle of the slit X-ray beam and the line of the dental arches, resulting in variable amounts of overlap of the contact points of teeth, especially in the premolar region.
The diagnostic quality of panoramic radiographs is heavily dependent upon careful attention to technique and processing. Schiff et al (1986) evaluated a variety of films taken by dental students, faculty members and technicians in a hospital environment. They found that 80% radiographs showed some degree of error, the ratio being reduced to 53% when using only one technician to position all the patients. In another study, Smith et al., (1993) examined the quality of 387 radiographs submitted to the Dental Practice Board of England and Wales and found that 26% were of no diagnostic value.

Figure 4: A. Two-dimensional view of the focal trough for the Siemens Orthophos Plus panoramic machine. The solid line represents the sharpest plane within the focal trough and the dotted line represents the area where motion blur is minimal. The Z axis represents the sagittal axis and the X axis the transverse axis. The focal trough is narrow in the anterior region and wider in the posterior region bilaterally. B. Diagram representing a three dimensional view of the focal trough showing the depth, height and width dimensions. The posterior part of the focal trough is larger in all three dimensions. (from Langland et al, 1989).
Brezden and Brookes (1987) examined 500 films in the USA and found that 18% of films were inadequate. In each of these studies, low density or low contrast and incorrect positioning of the patient were cited as frequent causes of inadequacy.

Many of the modern panoramic machines have ways of assisting the radiographer in precisely positioning the patient, such as digital displays and adequately designed bite forks. These guides help to minimize distortion effects and to maximize the sharpness and accuracy of the image. Larheim and Svanaes (1986) found that the highest reliability in comparing radiographs was obtained when the same radiographer positioned the patient and recorded all the exposures.

![Diagram](image)

**Figure 5:** A three dimensional display of the focal trough demonstrating the X, Y and Z axes. The X-axis represents the horizontal transverse axis. The Y-axis represents the vertical reference axis in the midline and the Z-axis represents the antero-posterior (sagittal) axis (from Langland et al, 1989).

Studies have shown periapical radiographs to have a higher degree of accuracy and reproducibility (Demaut and Munck, 1986; Levander and Malmgren, 1988).
Panoramic radiographs may not always have pinpoint accuracy in measuring vertical and angular measurements, but they do have the advantage of giving a higher diagnostic yield i.e. more diagnostic information on a single film, when compared to other radiographic views such as periapical or lateral cephalogram radiographs. They show increased coverage of the dental arches and the associated structures as well as reduction in radiation dose to the patient. (Stentstrom et al., 1987),

1.2.5 Accuracy of linear and angular measurements

In the past many studies were carried out to test and compare panoramic radiographs for accuracy of measurement in the horizontal and vertical dimensions. Kane, as early as 1967, made a comparison between consecutive radiographs (T1 and T2) of thirty randomly selected patients. The patients were removed and subsequently repositioned for the second exposure. This eliminated any discrepancies in measurement due to growth. He measured the vertical distance between the lower border of the right mandibular canal and the lower border of the right mandible on radiographs T1 and T2. He found a significant difference of 0.5mm in only seven of the thirty sets of radiographs. Horizontal measurements were not evaluated in this study as they showed large variation in magnification.

Richardson (1969) examined a sample of thirty-six patients and he investigated the reliability of a repositioning technique using panoramic radiography. Two panoramic radiographs were taken, the patient again being removed and subsequently repositioned for the second exposure. Reference points and lines were inscribed on the paired radiographs. He measured six horizontal and two vertical measurements between bony and tooth structures in the midline. He found differences in midline vertical measurements between paired radiographs to be significantly less than those found for horizontal measurements. Of the vertical midline measurements only 12% had differences of greater than 0.5mm. The range of variation between paired panoramic radiographs at the midline was zero to 0.8mm and only one difference in measurement was greater than 1.0mm.

Wyatt et al (1994) found that assessment of vertical dimensions were consistently
more accurate on lateral cephalometric radiographs than on panoramic radiographs and that no significant differences in the accuracy of angular measurements were found between any of the lateral cephalometric and panoramic projections.

Image magnification and distortion ultimately determine dimensional accuracy in panoramic radiography. Tronje et al (1985) found a variation in magnification factors both horizontally and vertically. The horizontal magnification varied markedly throughout the rotation of the x-ray beam but it would increase in regions where the average jaw fell outside the focal trough. He found no marked variation in vertical magnification within the focal trough, however, it did increase when the average jaw fell outside the central plane of the image layer. He also concluded that if a discrepancy existed due to a combination of both horizontal and vertical magnification, significant distortion of the image resulted.

Richardson (1969) found horizontal measurement in the molar regions to be more reliable than those taken in the premolar and anterior regions. Rejeban (1979), showed that horizontal dimensions in panoramic radiographs are unreliable, especially in the anterior region, because they show large variations in magnification with small change in the position of the object relative to the image layer. In contrast, he found the magnification factor variation in the vertical dimension to be insignificant.

In panoramic radiography, the focus of projection in the horizontal dimension differs from that of the vertical dimension. In the horizontal dimension the rotation centre serves as the functional focus, whereas in the vertical dimension, the x-ray source serves as the focus (McDavid, et al., 1985). It has been shown that horizontal measurements on panoramic x-rays are longer and more distorted than vertical measurements (Larheim and Svanaes, 1986).

Shape and size distortion of the radiographic images in the vertical plane is a function of projection factors. These include factors such as alignment of film, object and x-ray source, object to x-ray source and film to x-ray source distances. Because the x-ray source serves as the functional focus, the vertical dimension is
unaffected by the rotation of the beam in the horizontal plane. Tronje et al (1981) demonstrated that a projected length of a vertically orientated 10mm object, located at the central plane within the image layer, does not exceed 10%. This is provided the inclination of the object is between $-20^0$ and $30^0$ to the vertical plane in the lower jaw and between $-15^0$ and $45^0$ in the upper jaw.

In the horizontal dimension, however, both projection and motion factors influence size and shape distortion. Two motion factors play an important role in horizontal dimensional change of radiographic images. These are the speed between the film as it rotates on its own axis and the projection of object points onto the film. If the motion cycle of the panoramic machine varies at all during successive exposures, it will follow that the horizontal dimension of the radiographic images of the patient's teeth and jaws will vary accordingly (Langland, 1989). Zach et al (1969) stated that due to the patient being static while the x-ray source and film cassette circulate around the head, this may be a major contributing factor to the significant variation found between measurements on paired panoramic radiographs in the horizontal plane.

Magnification is defined as the ratio of source to film and source to object distances i.e. image size to object size. In the vertical dimension the magnification would be calculated by dividing the distance from the x-ray source to the film by the distance from the x-ray source to the object. In the horizontal dimension, however, since the focus is different it would be necessary to divide the distance from the intra-oral rotation centre to the film by the distance from the rotation centre to the object. This makes the magnification factor much greater in the horizontal than in the vertical dimension (McDavid et al., 1985).

In panoramic radiography, the film is attached to a rotating system and moves in the same direction as the beam (Fig. 3). The film is given the correct speed by opposing the movement of the beam and it moves in a direction opposite to that of the beam. Although this does not effect the central projection of the object, it does affect the length of the image recorded on the film, so that the registered image may become foreshortened in the direction of the movement. Selecting the correct film speed is vital in reducing and equalizing the horizontal and vertical magnification (Tronje et
al., 1981). He showed that the speed of the film relative to the movement of the beam in order to maintain minimal and equal vertical and horizontal magnification factors on a curved plane in the focal trough, is directly proportional to the distance between the centre of rotation and the film.

Thanyakarn et al. (1992) in their study looked at how the observer performed measuring tooth length on teeth distributed between the canine and molar regions in both the mandible and the maxilla. They concluded that true linear radiographic measurements of real objects like teeth were difficult and that radiographic tooth-length measurements are highly influenced by the observer performance. Larheim et al. (1984) and Thanyakarn et al. (1992) both found that the mean difference in tooth length between repeated exposures was close to zero, and that variability that did occur was mainly due to error from repeated measurements on the same film. They also suggested that inter- and intra-observer variation be considered when evaluating the effects of orthodontic treatment radiographically.

Angular measurements between images of the teeth depend on the combined effects of vertical and horizontal magnification. Despite the fact that horizontal measurements are unreliable, angular measurements may be performed reliably on panoramic radiographs (Langland et al., 1989). Angular measurements are useful in determining the inclination of impacted teeth, implant site assessment, crown angulation and root alignment in orthodontics (Venta, 1993). It has been shown that if an object is positioned within the focal trough, its mesio-distal inclination can be measured within a moderate error range of +/- 5° (Frykholm et al., 1977). Welander et al. (1985) confirmed this concept by applying it to non cylindrical-image layers. They found that an object with a bucco-lingual inclination of between 30° and 160° could have a clinically insignificant angle distortion of 5°. Both these authors supported the conclusion that angular measurements were clinically reliable on technically correct panoramic radiographs (Nelson and Artun, 1997).

Angular distortion on panoramic radiographs may, however, occur as a result of combined distortion of the vertical and horizontal dimensions at different positions and depths within the image layer. If distortion is clearly evident in the image, an angular measurement will not be reliable. Furthermore, angular measurements
should only be performed between object details portrayed in the same region of the radiographs (Tronje et al., 1981). The effect of adding an inclination in the third dimension i.e. the buccolingual direction has been shown by Tronje et al. to have only a limited effect on angle distortion. Only severe buccolingual inclinations may significantly affect angular measurements.

In an in vitro study Wyatt et al. (1994), compared the accuracy of angular and dimensional measurements between panoramic and standardized lateral oblique radiography. They concluded that panoramic radiography is still the most convenient form of radiograph for dimensional and angular assessments, but when greater clinical accuracy is required, it may be necessary to supplement the panoramic radiograph with lateral cephalometric or periapical radiographs.

Thanyakarn et al.(1992) compared actual and radiographic tooth lengths of the maxillary first molar and second premolar and mandibular premolars. They found the mean difference between repeated measurements of actual and radiographic tooth lengths were small and insignificant. They also found that the vertical magnification in panoramic radiography was lower for mandibular premolars (13-15%) than for maxillary second premolars and first molars (17-28%). The palatal root of the maxillary first molar had the highest vertical magnification (28%) and all the other roots could be measured with a high degree of reproducibility.

In conventional panoramic radiography, there is a path of single beam radiation directed so that a bilaterally symmetrical image is produced. Although the ideal rotational path directs the slit beam perpendicular to the dental arches, the limitations of using single beam projection geometry often results in varying amounts of overlap of proximal dental surfaces. The superimposed blurred image of the spinal cord in the anterior and an enlarged ghost of the contro-lateral mandible may also occur (McDavid et al., 1983). By introducing a panoramic machine with a wide focal trough, one can reduce the amount of interproximal overlap and blurring of malpositioned structures of diagnostic interest.

Leite et al.(1994) introduced a multiple-beam panoramic system to yield three
dimensional data limited to regions of diagnostic interest. This reduces the number of proximal overlaps in a significant manner and displaces the image of the spinal cord from the anterior segments and midline. This is acquired by using multiple off-axis projection angles rather than conventional single beam projection. The introduction of multiple projections into the panoramic process augments the already existing more simplistic bilaterally symmetrical technique of the panoramic process.

There is wide agreement (Christen and Segreto (1968), Larheim et al.(1984), Tronje et al. (1985) and Thanyakarn et al.(1992)) that when using panoramic radiography for assessment of orthodontic treatment effects, such as root resorption, the reproducibility of measuring tooth lengths is reproducible provided the patient is correctly positioned in the machine at the time of exposure. The exception is the palatal root of the maxillary first molar as shown by Thanyakarn in his study. These roots appear to have the highest vertical magnification factor ranging from 6-41% when compared with an average of 5% for all the other roots. There seems to be agreement among these studies that vertical measurements and calculations using the roots of all the teeth, other than the palatal root of the maxillary first molar, are reproducible.

Larheim and Svanaes (1986) investigated the reproducibility of reference points on the bony contour of the mandible and the lower central incisors to make horizontal, vertical and angular measurements on repeated panoramic exposures. They found that for most of their variables, there were no repeated errors and no errors that occurred systematically due to error of measurement. The unreliability of the horizontal variables despite the use of head positioners and using the same radiographer, was however apparent. Although the patient’s head may be accurately positioned, the inclination of the incisor teeth, or the underlying skeletal pattern may make it impossible to position both the mandibular and maxillary teeth ideally inside the focal trough (Fig. 7) (Whaites 1992).
Figure 6: Diagrams showing the vertical walls of the focal trough in the incisor region and the relative positions of the teeth with different underlying dental or skeletal abnormalities. A. Class I; B. Severe Angle Class II division I malocclusion; C. Skeletal Class II with normal angulation of the dentition to their respective bases; D. Angle Class III skeletal base. The shaded areas outside the focal trough will be blurred and out of focus. (from Whaites, 1992).

According to Langland et al. (1989), this was due to distortion influenced by two effects, namely; the “projection” factor and the “motion” factor. Larheim and Svanaes (1986) also showed that there were no statistically significant differences for both vertical and angular measurements on the right and left sides.

1.2.6 Motion blur or “unsharpness”.

In panoramic radiography, the unsharpness or motion blur in the plane of rotation is commonly defined as “absolute unsharpness”. This is the total length of the projection at the film plane of an “infinitesimally” narrow line positioned
perpendicular to the rotational plane (Welander, 1974). An additional definition, “relative unsharpness” was introduced by Welander and Wickman (1977) and is defined as the absolute unsharpness divided by the magnification factor for the object depth where the line is situated. Both absolute and relative unsharpness will express motion blur, which is commonly associated with rotational panoramic radiography (McDavid et al., 1984).

Motion blur in panoramic radiography may result from failure of the focal spot to perform as a point source when the beam fails to strike the film sharply at a single point. Secondly, there may be diffusion of light from the intensifying screens and thirdly there may also be a mismatch between the speed of the film and the radiographic shadows of points outside the central plane of the focal trough (Fig. 8).

![Figure 7: Diagrams A-D showing the anterior and posterior regions of the mandible relative to the focal trough when the patient is not positioned correctly i.e. too close to the machine (A), too far away from the machine (B) or asymmetrically positioned within the machine (C and D).](image-url)
Film or image sharpness is vital when assessing panoramic images. It allows the resultant image to be sharper and more clearly defined. Due to the fact that the x-ray source and the film move in the same direction, the successive rays do not project a given object point, in a sharply depicted plane within the focal trough, at the same point along the film path. The object point will thus be recorded as a single point on the film, thus enhancing its sharpness on the x-ray image.

![Diagram showing the relative movements of the tube-head, cassette carrier and film during an exposure cycle of a continuous-mode panoramic unit.](image)

**Figure 8:** Diagram showing the relative movements of the tube-head, cassette carrier and film during an exposure cycle of a continuous-mode panoramic unit. Here the patient faces the panoramic machine and away from the operator. Note the different part of the film is exposed at different stages in the cycle (from Whaites, 1992).

The cassette speed required to achieve image sharpness is the same speed needed to equalize horizontal and vertical magnification factors (Welander *et al.*, 1984). Unsharpness not only depends on motion blurring as discussed previously, but also on the size of the focal spot and the screen-film combination which is chosen for a particular system (Tronje *et al.*, 1982). Another factor affecting both motion blur as
well as the image layer thickness of panoramic radiographs, is the displacement of
the patient toward the rotation centre of the beam or source of the x-ray. This results
in broadening of the image of the teeth. Displacement of the patient away from the
film will result in narrowing of the image of the teeth (Fig. 7). Both absolute and
relative unsharpness can be used to calculate layer thickness. It is however thought
that relative unsharpness is the more meaningful of the two because it reflects more
accurately the effect of the motion blur when the image is viewed (Welander and
Wickman, 1974). Unsharpness due to the focal spot, the recording system and the
motion blurring is also taken into account in defining layer thickness.

It is important in clinical practice, to know the layer thickness that results from the
exposure of a panoramic radiograph in a certain unit (McDavid et al.,1984). Taking
this into account, along with the size of the focal spot and the screen-film
combination that is employed, the data obtained may prove to be more accurate and
can be applied clinically without any doubt.

The human facial morphology is highly variable and an extremely complex one.
Any vertical distances as well as angles may be distorted due to variations in the
normal anatomy and this will lead to certain errors in measurement. It is therefore
necessary to assess the use of ratio calculations to measure and compare changes in
proportion as well as stable reference lines in each respective jaw for measuring the
long axis of teeth against. This study will compare the above in addition to
comparing actual lengths of teeth and angles in the same segment on two radiographs
taken on separate occasions. None of the in vivo studies mentioned in the literature
review have compared two radiographs taken consecutively prior to any treatment
changes and assessed linear, ratio or angular changes.
2. **INTRODUCTION**

2.1 **Research components**

The present study is divided into two parts. In the first part an *in vitro* investigation was carried out to determine the validity of comparing the dimensions of structures from two OPG's taken on the same patient at different times. The second part was an *in vivo* study to determine whether the findings in part one are clinically valid.

2.2 **Research Objectives**

Panoramic radiography has overcome many limitations of extra-oral radiography (Whaites 1992). However, as mentioned above it is unknown whether the quality of the images produced is adequate to allow research involving the measurement of the size and orientation of dental structures to be carried out.

The objectives of this study are to evaluate:

1. The reliability of the measurement of tooth crown and root length individually and as a calculated ratio of the crown to root length.
2. The reliability of measuring angles between teeth and certain reference planes constructed from stable reference lines in each jaw.
3. The reliability of measuring angles between teeth in the same segment on two panoramic radiographs of the same patient.

The null hypothesis states :-

The distortion of images in the horizontal and vertical dimensions, lack of definition and superimposition of anatomic structures on panoramic radiographs are such that it is not possible to make any linear or angular measurements with sufficient accuracy to be useful in oral diagnosis and treatment planning.
3. PART ONE

TITLE: The accuracy of linear, ratio and angular measurements on panoramic radiographs taken at various positions in vitro.

Part one of the study was designed to evaluate the *in-vitro* accuracy of linear, ratio and angular measurements on four different panoramic radiographs taken at different angles on a model simulating the dental arches and the functional occlusal plane.

3.1 Part one – Methods and materials

A model was designed consisting of a clear arch-form acrylic sheet (2mm thick and 15mm wide) (Planmeca OY, Helsinki, Finland) with a 0.9mm stainless steel wire (Dentaurum, Pforzheim, West Germany) bonded to its periphery determining the maxillo-mandibular occlusal plane. 10 stainless steel round pins (2.0 x 20.0mm) were bonded into holes (2mm in diameter) drilled through the acrylic equidistantly, approximately 4mm apart. The pins were bonded to the model at various angulations to the occlusal plane. The portion of the pin above the occlusal plane represented the "crown" segment and that below the occlusal plane the "root" segment (Fig. 9).

*Figure 9: Photo representing the acrylic model represented in the study*
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, West Germany) was used to generate the images of the model in four different positions. All exposures were taken by a single operator on Program 11, a panoramic exposure with a constant 25% vertical magnification, recommended by the manufacturer for implant measurements. The overall magnification factor was 1.25 with exposure settings of 60kVp and 9mA.

Figure 10: A three dimensional display of the focal trough demonstrating the X, Y and Z axes.

The entire model assembly (occlusal plane and dental units) was fixed to the standard "piece" of the panoramic machine. It was positioned in the unit using the focal trough guides and eight total exposures in 4 different positions (repeated once) were taken:

1. The Y-axis (true vertical) perpendicular to the X-axis (true horizontal) and the occlusal plane tilted 8° down anteriorly, simulating the ideal or Natural Head Position (NHP) (T1).
2. The X-axis lowered 10° on the right (T2).
3. The X-axis lowered 10° on the left (T3).
4. The Y-axis perpendicular to the X-axis, but the occlusal plane tilted up 8° anteriorly, parallel to the horizontal plane (T4).
This would give a variation in head position of approximately 10° to the right and left and the head tilted 8° up anteriorly with the occlusal plane lying parallel with the horizontal.

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 line taken from a line drawn perpendicular to the most distal pin (Pin no. 10). This line bisects the long axis of each of the remaining nine pins.
6. Angular measurements of the pins relative to each other and measured in the same segment.

3.2 Part One - Results

The SPSS 8.1 (Statistical Package for the Social Sciences, California, USA) statistical package was used to analyze 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.

3.2.1 Linear measurements

3.2.1.1 Crown and root segment lengths

When the crown and root lengths on the individual pins were compared, the ANOVA showed significant differences between the four radiographs for the crown lengths (p = 0.00) and a marginally significant difference between the root lengths (p = 0.04). The multiple comparison test using the crowns and roots as dependent
variables showed radiograph T4 as significantly different to T1, T2 and T3. The radiographs T1, T2, and T3 showed no significant differences of the crown and root lengths. Radiograph T4, however, showed a marginally significant difference to T1-T3 with a mean of 0.7mm less crown length and 0.7mm more root length. This indicates that an error in measurement occurred at the junction between the crown and root segments.

*Figure 11: Graphical representation of measurements showing “crown” and “root” lengths in T1, T2, T3 and T4.*

### 3.2.1.2 Total length

Comparison of the total length of the pins, after accounting for distortion and adjusting the data, there were no significant differences between radiographs T1-T4 (p = 0.877). However, without the adjustment of the values in T4 as mentioned above, when the occlusal plane was tilted up anteriorly by 8°, the pins in the posterior segments of the model did not vary in length as they remained well within the confines of the focal trough. The superior and inferior ends of the pins in the anterior region, however, fell outside the confines of the focal trough and were elongated.
Figure 12: Diagram representing the model in the T1 position (A), the T4 position (B), the narrow slit X-ray beam (C), the panoramic film (D) and the hollow vertical tube (E), a standard component of the panoramic device connecting to the model via an anterior extension. A represents the occlusal plane at 8° to the horizontal in the sagittal plane and B the occlusal plane parallel to the horizontal. In the anterior region with an upward tilt of the anterior region of the model (B), the terminal ends of the pin segments above and below the occlusal plane in the anterior region become positioned outside the confines of the focal trough. Their angulation to the beam also changes creating distortion of the image (L and L'). This results in a foreshortening of the pin segment above and lengthening of the segment below the occlusal plane. The linear dimensions of the posterior pins in both A and B are not significantly affected by the upward rotation of the anterior region as they continue to be situated within the confines of the focal trough. More importantly, the pin axis remains perpendicular to the x-ray beam with no distortion in the height of the pins between T1 and T4 (l and l').
Although this had an insignificant effect on the total lengths of the pins, it did affect the linear measurement of the crown and root portions. The difference, however, remained within 1mm range with a mean difference of 0.6mm and this has been shown to be clinically insignificant.

3.2.1.3 Crown-root ratio calculations.

Prior to correction of the linear values in T4, the crown root ratios were significantly different when all four of the panoramic radiographs were compared (p=0.004), although T1-T3 showed no significant differences in crown-root ratios (Table II). A multiple comparison test indicated that the T4 values were significantly different to those in T1-T3. Once the values in T4 had been adjusted, no significant differences existed between T1-T4 (p = 0.930).

![Graphical representation comparing “crown-root” ratio calculations in T1, T2, T3 and T4.](image)

**Figure 13:** Graphical representation comparing “crown-root” ratio calculations in T1, T2, T3 and T4.
3.2.2 Angular measurements

3.2.2.1 Angular measurements relative to the occlusal plane.

The ANOVA showed significant differences between the four radiographs (p=0.021). A multiple comparison test found T4 to be significantly different to those in T1, T2 and T3. The differences in angulation of the pins to the occlusal plane between T4 and the other radiographs were, however, all less than 5°, a clinically insignificant amount. Further analysis also revealed that radiographs T1, T2, and T3 showed no significant differences \( (p = 0.440) \).

![Occlusal Plane Angle](image)

**Figure 14:** Graphical representation comparing angular changes of the pins relative to the occlusal plane in T1, T2, T3 and T4.

3.2.2.2 Angular measurements relative to a reference line.

The ANOVA showed significant differences between the four radiographs (p = 0.001). A multiple comparison test again indicated that angular measurements in T4 were significantly different to those in T1, T2 and T3. When T4 was excluded, the T1, T2 and T3 showed no significant differences between the angulation of the pins.
relative to the reference line (p = 0.476). The differences in angulation of the pins between T4 and the other radiographs, however, were all less than 5°.

3.2.2.3 Angulation of the stainless steel pins relative to each other.

Angular measurements of 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 panoramic radiographs T1-T3 when T4 was excluded (p = 0.970) and only a marginally significant difference was seen between angulations when all four panoramic radiographs were compared (p = 0.041). Again, the largest difference in angulation was less than 3°, which is considered to be clinically insignificant.

3.3 Part one - Discussion

In the past, panoramic radiography 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 the posterior segments (Luchessi et al., 1988). This has been attributed to incorrect head positioning and positioning errors appear due to patient movement during the exposure (Brown, 1984). According to Sanderink et al. (1991) unreliable panoramic radiography could be explained by considering the position of the jaws in relation to the rotation centre and the path of the x-ray beam. This study showed that inaccuracy was mainly due to antero-posterior rotational movement and that lateral tilting of the head up to 10° is negligible. This was confirmed by Xie et al. (1994) using panoramic radiographs on dried skulls.

An in vitro model was used in this study to ensure that the positioning technique was accurate, reproducible and in three-dimensions. It served as a calibrated reference that may be used in future investigations of linear and angular measurements. A common finding of both panoramic and intra-oral radiographs is that they are less accurate in cases with excessively inclined (bucco-lingual) teeth (Luchessi et al., 1988). The present study found that even though the stainless steel pins were
randomly inclined up to $10^0$ in the anterior and posterior regions, the linear or angular measurements between T1, T2 and T3 did not seem to be significantly affected. This, however, may be different for teeth that are tilted in excess of $10^0$.

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 that significant error in identifying individual “crown” and “root” segments existed when an upward rotation of the anterior segment of the occlusal plane occurred. The lateral inclination of the occlusal plane up to $10^0$ did, however, not significantly affect the accuracy of point identification. The inaccuracy appeared to be related to the anterior - posterior location of the pins and their position relative the direction of the beam (Fig. 11).

Examination of the results shows large variations in the linear and ratio measurements between T4 and T1-T3. In some cases differences of greater than 2-3mm 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 (Fig 11). There was a general tendency for the pins in radiograph T4 to be slightly foreshortened in the crown segment and elongated in the root segment due to an upward rotation of the anterior part of the occlusal plane.

Some bias does exist when using the occlusal plane as a reference line. In this study the occlusal plane was used as a reference line to measure angular measurements. 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 significantly with a slight inclination of $10^0$ or less. However, any deviation beyond this value may show actual distortion between structures.

3.4 Part one - Conclusion

This study indicates that comparing linear and angular measurements on panoramic radiographs 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 the occlusal plane is kept at a similar angulation and the occlusal plane is not tilted more than 10°.

Our results suggest that accurate measurement of structures on panoramic radiographs is possible provided sufficient care is taken with head positioning technique. 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.
PART TWO

4. MATERIALS AND METHODS

4.1 Study Design

In this retrospective study 20 cases were selected, 10 with 5 implants in each jaw from the Prosthodontic Department (age range between 20 and 60 years) and 10 with a full permanent dentition (age range between 12 and 16 years) from the Orthodontic Department at the United Dental Hospital. Each selected case had two panoramic radiographs (OPG’s) taken on two separate occasions, T1 and T2. The period between T1 and T2 on all the radiographs ranged from one month to less than three years, and no treatment was performed during this period.

All the OPG’s were taken on the same panoramic unit (Siemens Orthopos Plus). The radiographs of the dentate cases were exposed on Program 9 and those of the implant cases on Program 11, both standard settings prescribed by the manufacturer. A single operator exposed the radiographs using a standard technique.

The measurements performed in this study were vertical linear and angular. The linear measurements were divided into crown and root lengths or coronal and apical implant segment lengths as well as crown-root or implant-segment ratios. The crown length extended from the cusp tip to the cemento-enamel junction (CEJ) and the root length from the CEJ point to the apex of a single rooted tooth and apices of either the mesial or distal buccal root of the molars. The implants were divided into a coronal-segment length extending from the mesial or distal corner of the implant to the implant segment junction (ISJ). The apical-segment length extended from the ISJ point to the most apical mesial or distal corner of the implant (as outlined in detail in section 4.5.1). Randomly selected teeth or implants in the incisor, bicuspid and molar region were measured to assess the crown and root lengths as well as the implant segment lengths and to calculate the ratios.
The angular measurements were recorded by measuring the long axis of the teeth and implants relative to specific reference lines and also relative to each other in the same sextant. The results were tabled and statistical analyses using the student $t$ test were performed to compare the final results.
Materials and methods summary

Retrospective Study
(20 cases)

Two OPG’s taken consecutively
(≤3 years apart)

10 cases with at least 5 implants in each jaw. Taken from the Prosthodontic Department at the United Dental Hospital (UDH)

10 cases with a full permanent dentition (excluding third molars). Taken from the Orthodontic Department at UDH

All panoramic radiographs were taken on the same OPG machine (Siemens Orthophos Plus).

Program 11 Implant cases

Program 9 Dentate cases

Single operator

Single positioning technique
Measurements used in this study

Angular measurements

Reference lines:
- Maxilla: Articular eminence, Maxillary tuberosity
- Mandible: Constructed gonion, Sigmoid notch

1. Measuring the long axis of teeth and implants in the incisor, bicuspid and molar region relative to stable reference lines in the maxilla and mandible respectively
2. Measuring the angulation of the long axis of the teeth or implants relative to each other in the same sextant

Long axis of the teeth or implants

Linear measurements

Crown-root or implant-segment lengths

1. Randomly selected teeth or implants in the incisor, bicuspid and molar region were used to:
   a) Measure the crown-root or implant-segment lengths.
   b) Calculate the crown-root or implant-segment ratio

2. Reference landmarks were the cusp tip, the cemento-enamel junction (CEJ) and the root apex

Crown-root or implant-segment ratios

All results were tabulated

Statistical analysis: Students’ t test

FINAL RESULTS
4.2. Sample size and selection criteria

Sixty patient files were randomly selected from the Orthodontic and Prosthodontic Departments at the United Dental Hospital.

Twenty cases were then selected from each group, each with two OPG’s taken within three years of each other. From the twenty cases in each group, 10 OPG’s were picked based on certain inclusion and exclusion criteria required on both the initial (T1) and the subsequent (T2) radiographs. The selection criteria was as follows:

Table 4.1 Inclusion criteria used for the study

<table>
<thead>
<tr>
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<th>Inclusion Criteria</th>
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<tbody>
<tr>
<td></td>
<td>Dentate</td>
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<tr>
<td>Age range</td>
<td>12 - 16 years</td>
</tr>
<tr>
<td>OPG</td>
<td>Two OPG’s &lt; 3yrs apart (range: 1 month to 3 years)</td>
</tr>
<tr>
<td>Panoramic Unit</td>
<td>Siemens Orthophos Plus (Program 9)</td>
</tr>
<tr>
<td>Developer</td>
<td>Kodak M35 Auto developer</td>
</tr>
<tr>
<td>Operator</td>
<td>Single</td>
</tr>
<tr>
<td>Patient positioning</td>
<td>Standardised technique</td>
</tr>
<tr>
<td>Growth Status</td>
<td>&lt; 10% adolescent growth</td>
</tr>
<tr>
<td>Image sharpness</td>
<td>Crown/root outlines and CEJ points clearly visible</td>
</tr>
<tr>
<td>Dentition present</td>
<td>Full Dentition (with/without early developing third molars)</td>
</tr>
<tr>
<td>Root apex</td>
<td>Closed</td>
</tr>
</tbody>
</table>
Exclusion Criteria

1. OPG’s with positioning errors resulting in asymmetries or gross distortions of the entire image or parts thereof.
2. Films that were of inferior quality and processing faults leading to poor contrast and ill-defined images.
3. OPG’s with teeth displaying severe rotations (defined relative to the lack of clarity and sharpness).
4. OPG’s displaying teeth or implants with severe angulations (defined relative to the lack of clarity and sharpness).
5. Radiographs displaying teeth with poor definition and implant images with poorly defined threads and outline.

*Table 4.2 Summary of common positioning errors and the resulting faults on the film leading to the elimination of panoramic radiographs in this study.*

<table>
<thead>
<tr>
<th>Positioning error</th>
<th>Film fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient too far from the film</td>
<td>Anterior teeth magnified in width and out of focus</td>
</tr>
<tr>
<td>Patient too close to the film</td>
<td>Anterior teeth narrowed and out of focus</td>
</tr>
<tr>
<td>Patient positioned asymmetrically (head turned to the right or left)</td>
<td>Posterior teeth enlarged on one side and reduced on the other</td>
</tr>
<tr>
<td>Patient's chin positioned too high or too low</td>
<td>Distortion in the shape of the mandible and the anterior teeth out of focus</td>
</tr>
<tr>
<td>Patient wearing earrings, jewelry, dentures or orthodontic appliances</td>
<td>Artefactual shadows of the offending object</td>
</tr>
<tr>
<td>Failure to instruct the patient to keep still throughout the cycle</td>
<td>Vertical or horizontal distortion of the part of the image being produced at the time of the movement</td>
</tr>
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</table>
Figure 15: Photographs illustrating the panoramic radiographs of a dentate patient with a full permanent dentition and agenesis of the third molars (A) and a patient from the implant group with at least five implants in both jaws (B).

4.3 Panoramic device used for exposures

The Siemens Orthophos Plus panoramic imaging system (Siemens AG, Bensheim, West Germany) was used to generate the images on all the radiographs in this study. This is the same unit that was utilized for part one of this study (section 3.0). Radiographs in the dentate cases were exposed on the Program 9 setting of the Siemens unit giving a constant magnification factor of 1.25 and acceptable sharpness and clarity in dentate cases. The implant group of OPG’s were exposed on Program 11, a setting with a constant 25% vertical magnification recommended by the manufacturer for use in implant assessment.

The magnification factor for both Programs 9 and 11 was 1.25 with exposure settings of 60kVp and 9mA. A Kodak Lanex medium screen (Eastman Kodak, Rochester, NY, USA) and T-Mat G panoramic PAN/TMG15 film (Eastman Kodak, Rochester, NY, USA) was utilized during exposures.
4.4 Technique used for patient positioning

A radiographer with more than 10 years experience on various panoramic units exposed all the radiographs used in this study utilising the panoramic unit specified above. The patients were all positioned on the panoramic machine using the standard bite-piece and focal trough guides.

This “bite-piece” is a standard component of the panoramic unit consisting of a 1.5mm thick plastic component apparatus which accommodates the upper and lower incisal third of the central incisor teeth. The bite-piece is in turn attached to a vertical horizontal tube connected to the panoramic unit. The upper and lower incisors were then positioned into grooves on the upper and lower sides of the bite-piece (Fig. 16).

The focal trough guides consist of reference optical light beams used to align the Mid-Sagittal (MSP) and the Frankfort Horizontal (FH) planes. The head was orientated so that the FH line (line joining superior aspect of the external auditory meatus to orbitale) was orientated parallel to the ground in both the sagittal and transverse planes and the midline structures were centered (Fig. 16). The patients were asked to remain as still as possible during the exposure.

The radiographs were then developed using an automatic developer (Kodak M35, Eastman Kodak, Rochester, NY, USA).

The author carried out tracings in a dark room and the data was transferred to a computer spreadsheet for analysis. All measurements were made on acetate sheets (3M Unitek, Monrovia, CA, USA), overlaid on fiducial lines. All linear measurements were made with a manual measuring caliper (Dentaurum PTY LTD, Pforzheim, Germany) to the nearest 0.1mm, ratios were calculated using a scientific calculator and angles were measured with a cephalometric protractor (Ormco Corp. Glendora, CA, USA) to the nearest 0.5 degree.
Figure 16: Photograph illustrating the Orthophos Plus panoramic unit, showing the positioning of a patient using the focal trough guides provided.

4.5 Landmark selection for linear and angular measurements

Teeth and implants utilised for linear or angular measurements were selected and an attempt was made to attain an even distribution between the incisal, bicuspid and molar regions.

4.5.1 Linear Measurements

The landmarks selected for the vertical linear measurements on teeth and implants were defined as follows:
4.5.1.1 Dentate patients

1. The cusp tip of a tooth identifiable on both radiographs (T1 and T2).
2. The mesial or distal cemento-enamel junction (CEJ) point, whichever was more clearly defined on both radiographs.
3. The apex of a single rooted tooth, the apex of the buccal root of the first bicuspid(s) or the apices of either the mesial or distal buccal root of the molars.

The crown length therefore extended from the cusp tip to the CEJ point. The root length extended from the CEJ point to the apex of a single rooted tooth and apices of either the mesial or distal buccal root of the molars

4.5.1.2 Implant patients

1. The most coronal mesial or distal corner of the implant, selected according to the clarity of the landmark on both OPG’s.
2. The junction between the standard abutment and the implant base or the tip of the implant screw, termed the implant-segment junction (ISJ), selected according to the clarity of the landmark on both OPG’s.
3. The most apical mesial or distal corner of the implant when viewed from the buccal aspect.

The coronal-segment length extended from the mesial or distal corner of the implant to the ISJ point. The apical-segment length extended from the ISJ point to the most apical mesial or distal corner of the implant.

4.5.2 Ratio calculations

The same vertical linear measurements obtained in section 4.5.1 were used to calculate the crown-root or implant-segment ratios respectively. The crown-root ratio of a tooth was defined as the crown length divided by the root length. For the implants, implant-segment ratio was defined as the coronal segment divided by the
apical segment length.

4.5.3 Angular measurements

To obtain angular measurements using teeth and implants, it was necessary to accurately determine the long axis of all the individual teeth and implants on their respective OPG’s. Secondly, in order to construct a valid and reliable reference line it was necessary to locate certain landmarks that were easily identifiable and would not change as a result of growth or due to physiological eruption of teeth, e.g. third molars. These landmarks were determined as follows:

4.5.3.1 Determining the long axis of Teeth

Loss of specific landmarks used as reference points e.g. a cusp tip or indentations on occlusal or incisal surfaces may occur due to tooth movement, either as a result of normal physiological eruption or orthodontic treatment. It was, therefore, necessary to devise a method to accurately determine the long axis of the tooth without relying on landmarks that change due to tooth movement.

A horizontal line was drawn through the CEJ points on the mesial and distal of the tooth as viewed from the buccal. This line was bisected by a vertical line passing through the apex of a single rooted tooth (Fig. 17) or through the furcation area (point B) in multi-rooted teeth (Fig. 18).
Figure 17: Diagram illustrating the image of the same tooth on two different OPG's taken before (tooth A - black line) and after orthodontic tooth movement (tooth D-red line). The long axis of the tooth was determined by constructing a horizontal line connecting points on the mesial and distal of the CEJ viewed from the buccal – the CEJ line. The midpoint of this line was then determined (C and F) and bisected by a vertical line (B and E respectively) passing through the apex of the tooth. This line determines the long axis of the tooth irrespective of the angulation.
Figure 18: Diagram illustrating the radiographic appearance of a second and third molar. The long axis is determined by drawing a horizontal line through the CEJ points on the mesial and distal of the tooth (CEJ line). The midpoint of this line is measured (A) and a second vertical line bisects point A and passes through the furcation area (point B) in a multi-rooted tooth and through the apex of a single rooted molar (C).

4.5.3.2 Determining the long axis of Implants

The long axes of the implants were determined in a similar way to those of the teeth. The junction between the standard abutment and the implant base, namely the standard abutment-implant base junction (SIJ), was located and a horizontal line was drawn through the most mesial and distal aspects of the SIJ. A vertical line representing the long axis of the implant was then constructed bisecting the centre of the SIJ points and passing through the entire length of the implant.
Figure 19: Photograph of an implant similar to that used in this study. Labels A and G demonstrate the coronal and apical corners and C represents the junction between the standard abutment (B) and the implant base (D), namely the SIL. The midpoints of the horizontal lines C and G were bisected by a vertical line (E), representing the long axis of the implant. It was essential that the implant base threads (F) were clearly defined on the radiographic image for the implant to have been suitable for assessment.
4.5.3.2 Constructing reference lines in the maxilla and mandible

Angulation changes of teeth were measured relative to reference lines constructed in the maxilla and mandible. Maxillary teeth were measured relative to a maxillary reference line and the mandibular teeth relative to a reference line constructed in the mandible. The landmarks selected for the construction of this reference line needed to be valid, reliable and clearly visible bilaterally on both radiographs T1 and T2.

In the maxilla, a line was drawn tangent to the most inferior point of the maxillary tuberosity on the left and right side of the panoramic radiograph. Alternatively, if the third molar was encroaching on the tuberosity, a second reference line was constructed tangent to the most inferior part of the articular eminence bilaterally (Fig. 20).

The mandible reference line was drawn through constructed gonion. If constructed gonion could not be located, a second reference line was constructed tangent to the most superior part of the mandibular condyles bilaterally, provided the condyles on both T1 and T2 were anatomically well defined.

The alternative reference line in both jaws was used only if the anatomical landmarks defining the first one were poorly defined. The angle between the reference lines and the long axes of the teeth and implants on radiographs T1 and T2 were then measured and compared.
4.6 Determination of linear, ratio and angular measurements

4.6.1 Error of measurement

The reliability of locating landmarks accurately was tested on two separate occasions by the author under the same conditions. Three dentate and three implant cases were randomly selected. Fiducial lines were marked on the panoramic radiographs and
three separate acetate sheets all superimposed on fiducial lines. On each OPG 10 teeth, 10 implants and all the anatomical landmarks used for the reference lines were tested. The tooth or implant points selected were the cusp tip or coronal part, the CEJ or ISJ and the apex or apical part respectively.

Once all the landmarks had been selected, the radiographs were put aside and the acetate sheets were superimposed on each other using the fiducial lines. The landmark points were compared and the range of error was found to be less than 1mm.

4.6.2 Linear measurements

Only vertical linear dimensions were recorded in this study. Crown and root lengths as well as coronal and apical implant-segment (standard abutment and implant base) lengths of ten teeth or ten implants were recorded using the landmarks described in section 4.5.1. Measurements were recorded using a manual caliper to the nearest 0.1mm. They were then transferred to a spreadsheet for statistical analysis.

4.6.3 Crown-root and implant-segment ratio calculations

4.6.3.1 Crown-root ratio calculations

Once the teeth had been selected they were numbered 1-10 on radiographs T1 and T2. The landmark points were identified and marked. The linear crown and root lengths were measured. The measurements were carried out on three different occasions by the same operator under the same working conditions, the mean values were tabled and the crown-root ratios calculated.

4.6.3.2 Implant-segment ratio calculations

The same procedure as in section 4.5.1 was followed for locating the landmarks and carrying out the measurements on the implant-segments.
4.6.4 Angular measurements

4.6.4.1 Angular measurements of teeth and implants relative to the reference lines

The reference lines in the maxilla and mandible and the long axis of the teeth and implants on their respective radiographs were drawn in. The lines were extended and the angles between the long axis of the teeth and implants and the reference planes were measured. The inside angles i.e. the angle closest to the midline on either the left or right sides were recorded (Fig 19).

4.6.4.2 Angular measurements of teeth and implants relative to each other in the same segment

The long axis of the teeth and implants determined in section 4.5.3.1 were extended and used to measure the angulations between teeth and implants in the same segment on their respective OPG's. Two angles were measured per quadrant and compared.

4.7. Statistical Analysis

The SPSS 8.1 (Statistical Package for the Social Sciences, California, USA) and Minitab for Windows release 12.1 statistical packages was used to analyze the results. The accuracy and reliability of measuring vertical linear dimensions, ratio calculations and angular measurements were examined by means of paired Students t test. 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 mean differences and standard deviations arising from repeated measurement of the radiographs were calculated and the statistical significance of the differences were assessed with two-tailed $t$ test. The values in each figure are presented as the mean $\pm$ standard deviation (SD) for each group.

The dentate and implant groups were assessed in two ways. Firstly, by analyzing the
different variables individually on each OPG (n = 10 for each variable) and comparing the mean differences between T1 and T2 (sections 5.2 and 5.3). Secondly a comparison was made by combining the T1 and T2 values for each variable (n = 100 per variable) for all 10 cases in dentate and implant groups and comparing the differences between the T1 and T2 values over the entire group (section 5.4).