University of Alberta

The Accuracy of Panoramic Radiography in the Assessment of Mesiodistal Tooth Angulations at Varying Horizontal and Vertical Head Positions

by

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Do not go where the path may lead, go instead where there is no path and leave a trail.

Ralph Waldo Emerson (1803-1882)

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **The Accuracy of Panoramic Radiography in the Assessment of Mesiodistal Tooth Angulations at Varying Horizontal and Vertical Head Positions** by Ian William McKee in partial fulfillment of the requirements for the degree of Master of Science in Orthodontics.

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Dedication

To my wife Robin, whose unerring love and understanding made this project and all the challenges of the last two years feel like an adventure. Your encouragement, support, and strength were boundless. And to my daughter Chloe, who always reminds me of the most important things in life!

To my parents, I thank you for your love, friendship, and support and for bestowing the values of confidence, hard work, and character.

Abstract

The first purpose of this study was to compare the true mesiodistal tooth angulations of an anatomic typodont/skull testing device to the image mesiodistal tooth angulations from four contemporary panoramic units at idealized head position. The second purpose was to examine the effect of varying horizontal (5° right, 5° left) and vertical (5° up, 5° down) head rotation of the testing device on image mesiodistal angulations from one panoramic unit, and compare these findings to the image mesiodistal angulations at idealized head position.

A typodont testing device was constructed and the true mesiodistal tooth angulations were determined utilizing a Coordinate Measuring Machine and custom designed software. A dry human skull served as the matrix into which the typodont was fixed into position for panoramic imaging and a custom designed head holder was constructed to ensure validity of the horizontal and vertical head rotation about a reproducible axis of rotation. The images were scanned and digitized with custom software to determine the image mesiodistal angulations.

Results revealed that the majority of image angles were statistically and clinically significantly different from the true angle measurements. Definite trends were recognized between the image angles from the four panoramic units as well as between the five head positions (ideal, 5° right, 5° left, 5° up, 5° down) tested on one panoramic unit.

It appears that the clinical assessment of mesiodistal angulation with panoramic radiography should be approached with extreme caution. An understanding of the inherent image distortion that can be further complicated by aberrant head positioning must be appreciated.

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1.1 Introduction

The goal of modern orthodontics can be defined as the creation of the best possible occlusal relationship within the framework of acceptable facial esthetics and stability of the occlusal result.[1] A major objective of orthodontic treatment is the correction of tooth positions in three planes of space, with the goal of approaching predefined cephalometric and occlusal standards.[2-6]

The importance of establishing appropriate axial inclinations with parallel roots during orthodontic treatment is frequently mentioned in the orthodontic literature. This parallelism is of prime importance if one wishes to obtain a correct alignment of the teeth within their respective apical bases, and a normal occlusion of the upper and lower teeth. From his historic study of 120 casts of non-orthodontic patients with normal occlusions, Andrews related his "six keys to normal occlusion". He stated that the proper mesiodistal inclination (or tip) and facial-lingual inclination (or torque) was required for ideally positioned teeth.[4,7] Proper axial inclinations are necessary for the distribution of occlusal forces with closed contact points.[6,7] This has special significance in the orthodontically closed extraction sites which are more prone to reopen if adjacent teeth are not parallel.[8-13] Jarabak also found that poor root parallelism can result in tooth tipping, rotations, increasing overbite of anterior teeth, and the potential for periodontal injuries caused by thin interradicular cancellous bone.[14]

Before, during, and after orthodontic treatment, it is common practice to assess the overall mesiodistal root angulations in the maxilla and mandible. Examination of the literature reveals that this evaluation if often performed by means of panoramic radiography. In a 1990 survey of orthodontic diagnosis and treatment procedures by

American orthodontists, 92%, 49% and 77% of respondents reported taking pretreatment, progress, and posttreatment panoramic radiographs respectively.[15] It is assumed that an assessment of root parallelism was one of the factors influencing the taking and interpretation of these image.

Panoramic radiography (also called pantomography, orthopantomography, or rotational radiography) was devised and developed by Yrjo Paatero, a Finnish scientist in 1948.[16] This radiographic procedure, developed from the medical process of laminagraphy or body section radiography, produces a single image of the facial structures, including both the maxillary and mandibular arches and their supporting structures.[17] Today, panoramic radiography is used extensively around the world. Aside from the numerous uses in general dentistry, this imaging procedure offers countless diagnostic and prognostic applications to the orthodontist. The principle advantages include the broad anatomic region imaged, the relatively low patient radiation dose, and the convenience, ease, and speed with which the procedure can be performed.[17] Disadvantages of panoramic radiography include the lack of fine detail compared to intraoral films, and the variable magnification and distortion.[17]

Some degree of inherent distortion is present in all panoramic images as panoramic machines have a focal trough (or image layer) thickness and position that conforms to that manufacturer's concept of the ideal dental arch.[18-27] Differences in conformity and size of the jaws and teeth, variation in arrangement of the teeth in the jaws, and asymmetry between the right and left sides all contribute to some degree of distortion. Varying degrees of horizontal, vertical, and angular distortion are present in all panoramic images and this can complicate axial inclination and parallelism interpretation. Furthermore, patient positioning errors as well as technical and processing errors can affect image accuracy and quality.[28]

1.2 Statement of the Problem

The need for this study reflects the orthodontist's frequent use of panoramic images, in addition to clinical evaluation, as an adjunct in the assessment of root angulation and root parallelism before, during, and after orthodontic treatment. The chief reason for selecting a panoramic radiograph over intraoral plane-film radiography rests on the lower irradiation, broader region of coverage, and greater convenience.

However, it has been widely reported in the literature that the main disadvantages of panoramic radiography are magnification and geometric distortion inherent to image generation. The distortion on panoramic images of the angle between inclined teeth will be the result of the combined distortion in the vertical and in the horizontal dimensions. While the panoramic image is a continuous image of the jaws, the successive shifts to changing centers of rotation may introduce positional error in the mesiodistal angulation of teeth at certain segments of the jaws. Furthermore, proper patient positioning in all three-dimensions is required to obtain panoramic images of acceptable detail with minimum distortion. Therefore, it seems reasonable to believe that the angular assessment and measurement of tooth inclinations may not be reliably performed on panoramic images.

1.3 Purpose

The first purpose of this study was to compare the true mesiodistal tooth angulations of an anatomic typodont/skull testing device to the image mesiodistal tooth angulations from four contemporary panoramic units at idealized head position. The second purpose was to examine the effect of varying horizontal and vertical head rotation of the testing device on image mesiodistal angulations from one panoramic unit, and compare these findings to the image mesiodistal angulations at idealized head position.

This was accomplished by utilizing an anatomic tooth-bearing device with construction of appropriate markers to delineate the tooth long axis and a horizontal reference plane. A three-dimensional measuring machine in concert with custom designed software allowed accurate and reproducible measurements of the true mesiodistal angulation of the typodont teeth. A human dry skull acted as a matrix for the typodont dentition, which was placed to conform to established cephalometric standards in all three planes of space. Following panoramic imaging using a custom designed head holder at varying horizontal (5° right, 5° left) and vertical (5° up, 5° down) head positions, custom designed software allowed measurement of the image mesiodistal angulation of the typodont teeth.

The results of this investigation provide useful guidelines and recommendations to assist the orthodontist in determining in what locations and to what extent panoramic radiography can be relied upon in their diagnostic evaluation of mesiodistal root angulation. The effect of both different panoramic image generators and varying vertical and horizontal head positioning is discussed. A determination of the clinical relevance of the findings was made.

1.4 Research Questions

1. Is there a difference between the true mesiodistal tooth angulations of a typodont/skull testing device and the image mesiodistal tooth angulations from each of four panoramic units?

2. Is there a difference between the image mesiodistal tooth angulations from an idealized head position and the image mesiodistal tooth angulations from varying horizontal head rotation (i.e. 5° right and 5° left)?

3. Is there a difference between the image mesiodistal tooth angulations from an idealized head position and the image mesiodistal tooth angulations from varying vertical head rotation (i.e. 5° up and 5° down)?

1.5 Null Hypotheses

1. There is no significant difference between the true mesiodistal tooth angulations of a typodont/skull testing device and the image mesiodistal tooth angulations from each of four panoramic units.

2. There is no significant difference between the image mesiodistal tooth angulations from an idealized head position and the image mesiodistal tooth angulations from varying horizontal head rotation (i.e. 5° right and 5° left).

3. There is no significant difference between the image mesiodistal tooth angulations from an idealized head position and the image mesiodistal tooth angulations from varying vertical head rotation (i.e. 5° up and 5° down).

1.6 Literature Review

1.6.1 Axial Inclination of Teeth

The general arrangement of the dental arches and the inclinations of the individual teeth are interrelated in such a manner as to allow the most efficient use of the forces of mastication, while at the same time stabilizing and protecting the dental arches.[29] The axial position refers to the inclination of a tooth from a vertical axis. This inclination is normally described in the mesiodistal and faciolingual directions, even though it is usually an inseparable combination of the two.[29] These inclinations are necessary for proper occlusal and incisal function of the teeth. When examining the mandibular teeth from the lateral view, both anterior and posterior teeth are mesially inclined (Figure 1.1). In the maxillary arch, a different pattern of inclination exists where the anterior teeth are generally mesially inclined, with the most posterior molars being distally inclined (Figure 1.2). When observing the dental arches from the frontal view, generally the posterior teeth in the maxillary arch have a slightly buccal inclination (Figure 1.3) while the posterior teeth in the mandibular arch have a slight to increasingly moderate lingual inclination as one proceeds posteriorly (Figure 1.4).[30] It is the individual tooth inclinations that together establish the general occlusal curvatures, known as the curve of Spee and curve of Wilson, which permit maximum utilization of tooth contacts during function.[29,30]

From his historic study of 120 casts of non-orthodontic patients with normal occlusions, Andrews developed his "six keys to normal occlusion".[4] He stated that proper crown *angulation* (or mesiodistal tip) and proper crown *inclination* (labiolingual or buccolingual inclination) were required for ideally positioned teeth. For mesiodistal tip, Andrews found that the gingival portion of the long axes of all crowns were more distal than the incisal portion, with the degree of crown tip defined as the angle between the long axis of the crown and a line bearing 90 degrees from the occlusal plane. A "plus reading" was awarded when the gingival portion of the long axis of the crown was distal to the incisal portion while a "minus reading" was assigned when the gingival portion of the long axis of the crown was mesial to the incisal portion.[4] This convention for mesiodistal angulation (or tip) is still used today by orthodontic bracket manufacturers of straight wire prescriptions.

The importance of establishing appropriate axial inclinations with near parallel roots during orthodontic treatment is frequently mentioned in the orthodontic literature. This parallelism is of prime importance if one wishes to obtain a correct alignment of the teeth within their respective apical bases, and a normal occlusion of the upper and lower teeth.[12] At the same time, it may be an important factor in maintaining a stable treatment result.[12] Proper axial inclinations are necessary for the distribution of occlusal forces with closed contact points.[6] This often has special significance in orthodontically closed extraction sites which are prone to open if adjacent teeth are not parallel.[8-13]

Hatasaka studied 20 orthodontically treated extraction cases postretention with periapical and bitewing radiographs and compared finished situations ranging from:

1) over-paralleled roots (apices touching)
2) over-paralleled roots (but root apices not touching)
3) roots parallel and no space between the crowns
4) roots insufficiently paralleled and divergent

Hatasaka found that over-paralleled roots with apices touching did not relapse to the desired upright position while over-paralleled non touching roots tended to upright in retention, but in doing so left spaces between the crowns. Under-paralleled roots tended to maintain their positions or diverge even further. The best postretention results were cases in which roots and crowns were positioned in normal, upright, and parallel positions. Slight spaces remaining in these situations appeared to close evenly.[10]

Jarabak believed that if the roots were not parallel on either side of the extraction site, the distribution of the occlusal loads upon the aforementioned teeth exerted a rotational force which could cause the posterior teeth to tilt and rotate mesially and the canines to rotate distally.[14] Jarabak also claimed that overbite of the anterior teeth can become exaggerated because the curve of Spee may increase in the mandibular arch and cause an opposing curve in the upper arch.[14] He concluded by noting the potential for periodontal injuries in cases where correct parallelism was not obtained in conjunction with poor oral hygiene. In these situations, the thin cancellous bone can readily break down establishing periodontal defects that, in light of the close approximation, present challenges in periodontal instrumentation.[14]

Before, during, and after orthodontic treatment, it is common practice to assess the overall axial inclination and root parallelism in the maxilla and mandible. While clinical intraoral evaluation can provide substantial information in this regard, examination of the literature reveals that this assessment is often performed by means of panoramic radiography. In a 1986 survey of orthodontic diagnosis and treatment procedures of American orthodontists, 86%, 38%, and 69% of respondents reported taking pretreatment, progress, and posttreatment panoramic radiographs respectively.[15] When the survey was repeated in 1990 and the same question was asked, 92%, 49%, and 78% of respondents reported taking pretreatment, progress, and posttreatment panoramic radiographs respectively.[31] While panoramic radiographs are taken for a multitude of reasons in orthodontic diagnosis and treatment planning, it is assumed that the assessment of mesiodistal tooth angulations and root parallelism were factors influencing the taking of these images.

1.6.2 Panoramic Radiography

A) History

Panoramic radiography (also called pantomography, orthopantomography, or rotational radiography) is a radiographic procedure that produces a single image of the facial structures, including both maxillary and mandibular arches and their supporting structures.[17] The principle of panoramic radiography was first described by Numata,[32] but was designed and developed by Yrjo Paatero, a Finnish scientist in 1948.[16,33,34]

Paatero adapted the medical radiographic process of laminagraphy or tomography to the unique curvilinear demands imposed by the dental arches and craniofacial complex".[33,34] In its original form, there existed one center of rotation, with the patient turning and the film rotating, while the source x-ray tube remained motionless. (Figure 1.5).[35] Since the dental arches are not true circles, considerable distortion was created during the radiographic process. Paatero decided to try two centers of rotation, one for each side of the face, believing that a hemisection would produce a more accurate image.[35] At the same time Hudson *et al* developed a panoramic technique utilizing two eccentric axes of rotation in which the patients head remained stationary while the cassette holder and the x-ray source rotated around it.[36] The S.S. White Panorex and Panorex 2 used this principle of image generation. Half of the facial structures were exposed while the x-ray source and film rotated about one center of rotation (the center away from the structures being imaged).[17] Halfway through the exposure, the radiation stopped while the patient and the chair mechanically shifted laterally to the second center of rotation and the second half of the facial structures were imaged (Figure 1.6).[17] However, a study of the structure of the dental arch indicated that the buccal segment described one arc of a circle, while the anterior segment was, in reality, the arc of a smaller circle.[35] For this reason, Paatero combined the two techniques with three centers of rotation, one for each buccal segment and one for the anterior segment, and produced an image more nearly in harmony with the actual shape and, at least in theory, with less distortion of the structures (Figure 1.7).[34,35] The Siemens Orthopantomograph employed these principles of image generation with the added third center of rotation in the midline for the anterior segment. This unit did not interrupt the exposure during its cycle as it shifted to successive centers of rotation and as a consequence, the resultant radiograph was continuous and without anterior redundancies.[17]

Contemporary panoramic machines generally use similar principles as their historic counterparts, but without fixed centers of rotation. Instead, the x-ray source moves continuously in an elliptical path simulating the shape of the dental arches. Because of the capability to adjust the size of the ellipse to correspond with the size of the patient's arch, the resultant radiograph is a continuous image of the jaws with relatively constant horizontal and vertical magnification.[17] Recently, direct digital rotational panoramic radiography has entered the marketplace with the conversion from analog silver halide film to digital systems using either storage phosphor or charge-coupled device (CCD) technologies.[37-42] Digital radiography allows a reduction in the patient radiation dose and the manipulation and magnification of areas of interest on the radiograph may increase the diagnostic yield available from the image.

B) Advantages & Disadvantages : Indications & Contraindications

Today, panoramic radiography is used extensively around the world with multiple applications, and many of the advantages and disadvantages of this diagnostic modality have been described. The principle advantages are (1) the broad anatomic region imaged, (2) the relatively low patient radiation dose, (3) the convenience, ease, and speed with which the procedure may be performed, and (4) the fact that the procedure may be performed on patients who are unable to open their mouths.[17] The main disadvantages of panoramic radiography are that (1) the generated images do not resolve the fine anatomic detail seen on intraoral periapical radiographs, (2) the cost of the machine is approximately two to four times that of an intraoral x-ray machine, and (3) the inability of the machine to produce images that are dimensionally accurate.[17] In other words, varying degrees of horizontal and vertical magnification, geometric distortion, and overlapped images of teeth (especially in the premolar region) are inherent to image generation.[17] In addition, objects whose recognition may be important for the interpretation of the radiograph may be situated outside of the section or plane of focus (known as the focal trough or image layer), resulting in their images being distorted or obscured on the resultant radiograph.[17] All of these factors taken together may limit the usefulness and interpretation of the image, depending on the requirement of the particular application.

Aside from the obvious indications of panoramic radiography in general dentistry, Graber[35] reported that this imaging procedure offers countless diagnostic and prognostic uses in orthodontic diagnosis and treatment planning including the assessment, detection and/or monitoring of:

1) Cysts and neoplasms
2) Supernumerary teeth
3) Congenital absence of teeth
4) Impactions
5) Ankylosis
6) Abnormal retention and premature loss
7) Abnormal paths of eruption
8) Abnormal resorption
9) Periodontal pathosis
10) Axial inclination of erupted, unerupted, impacted, and ectopically positioned teeth
11) Evaluation of tooth development (especially mixed dentition analysis)

Atchison[43] reports that panoramic films are taken by orthodontists almost as frequently as lateral cephalograms and this is supported in the literature by both the 1986 and 1990 *Journal of Clinical Orthodontics* studies of orthodontic diagnosis and treatment procedures.[15,31] Because panoramic films are ordered and taken so routinely, knowledge of their strengths and limitations is essential.

When indicated, the panoramic radiograph is often used as an initial survey film that may provide the required insight or indicate the requirement for more suitable radiographs providing additional discrimination.[17] Panoramic films are not suitable for diagnostic examinations requiring high image resolution, such as the detection of early alveolar bone loss, the detection of incipient dental caries, or the analysis of trabecular bone changes associated with early periapical lesions.[17] Interestingly, when a full-mouth set of radiographs is available for a patient receiving a general screening examination, little or no additional useful information will be gained from a panoramic examination.[43-46] Finally, panoramic radiography has found application in the area of implant dentistry and the need to preoperatively depict and quantify bone height and contour[47-50]

C) Dimensional Accuracy of Panoramic Images

i) Introduction

As mentioned previously, some degree of inherent distortion and magnification is present in all panoramic images.[17] This is unavoidable, since a fixed x-ray source-film relationship is utilized to project structures which vary greatly in the same individual and between individuals. Differences in conformity and size of the jaws and teeth, variations in arrangement of the teeth in the jaws, and asymmetry between the right and left sides all contribute to some degree of distortion.[25] To obtain the most accurate image, it is imperative that the patient's dental arches be placed in the focal trough (or image layer) that has been predetermined by the manufacturer. However, the shape and position of this image layer varies among manufacturers.[51]

Scarfe *et al* states that "ideally, a panoramic machine should have (1) a focal trough which conforms to the shape of the average dental arch and is sufficiently wide anteriorly to adequately image the incisor teeth, (2) a beam projection angle between contact points of all teeth which minimizes overlap, especially in the premolar region, (3) provide adequate sharpness and dimensional accuracy at least at the central plane of the focal trough, and (4) be affordable."[52]

A detailed discussion of the aspects of dimensional accuracy of panoramic images is exceedingly mathematical and involves complex engineering principles. It is the intent of this author to give an overview of the important aspects of image generation that relate to the dimensional accuracy of panoramic images. General areas of discussion will be outlined under the following headings: the image layer, the projection angle, horizontal and vertical magnification, inclined objects (angle distortion), and head positioning for panoramic radiography.

ii) The Image Layer

The image layer (or focal trough) is a three-dimensional curved zone in which structures are reasonably well defined on panoramic radiographs and appear the most sharp.[17] Objects in front or behind this layer are blurred, magnified, or reduced in size and sometimes distorted to the extent of not being recognizable.[17] The shape, width and horizontal thickness of the image layer is unique to every panoramic system and is determined by the scanning geometry and film speed, as well as the size of the focal spot, the width of the x-ray beam, and the screen-film combination.[53]

Panoramic radiography involves movement of the film and x-ray beam to form the image layer of the machine. The central plane of the image layer corresponds to the location within the image layer where vertical and horizontal magnification factors are equal, and where motion "unsharpness" is minimal.[53] Up to a certain distance from the central plane, a range of acceptable images will be produced. Experimental image layer studies have used subjective judgments of unsharpness, and distortion of various test objects to demonstrate the location and borders of the image layer, and to locate the central plane of the image layer.[26,27,55-60]

Lund *et al* studied the focal troughs of three panoramic machines as well as the relationship between dental arches and these focal troughs.[26,54] Using registrations of the dental arches of 240 patients from ages 4 to adulthood, a total composite of all teeth revealed the striking similarity of the arches. Not only did tooth positions vary little between ages and sexes but as the arches lengthened posteriorly, anterior tooth positions showed little variation. Of the three contemporary panoramic machines used at the time (General Electric 3000, Pennwalt Panorex, and Siemens Orthopantomograph), all machines produced focal troughs that could encompass the tooth positions in the occlusal plane despite the varying shapes of the focal troughs. However, it was found that rotation of the tooth positions on the chin axis, such as could occur with aberrant head positioning, tended to move different teeth out of the focal trough on all machines. The margin of error for patient positioning between the three machines was different, but now is obviously of historical significance only, due to advances and developments in panoramic radiographic units.

In a similar study, Hassen *et al* studied the zone of sharpness of three panoramic x-ray machines, but in addition, tested the effect of screen speed on the sharpness zone.[55] In findings similar to Lund *et al*,[26,54] the sharpness zone of the Panorex, Orthopantomograph-5, and Autopan panoramic machines covered the great majority of tooth positions despite varying anterior and posterior focal trough widths. Medium and high-speed screens produced focal troughs with little difference in size.

Razmus *et al* compared the image layer location among panoramic machines of the *same* manufacturer by making radiographs of a spherical test object placed in different positions.[56] The results revealed inconsistency in location of the central plane of the image layer and indicated the need for establishing a quality assurance test to verify consistent image layer location before patient exposure. The unique method of image formation of panoramic machines requires synchronization and alignment of a complex mechanical system. The proper relationship between the film and the x-ray beam may be lost through maladjustment of the film-drive mechanism, through the horizontal misalignment of the beam, or through failure to synchronize the film movement with that of the beam.[56] Without such a quality assurance test, Razmus *et al* reports that "there is no way to determine if variation from one radiograph to the next is the result of an error in patient positioning or of problems with the machine."[56]

In a recent study, Scarfe *et al* investigated the imaging characteristics of the Orthopantomograph (OP 100) and compared them with the average form of the arch.[52] While the vertical and horizontal magnification and beam projection angle results will be discussed later in this paper, Scarfe *et al* found that the OP 100 provided a focal trough conforming well to the overall geometry of the average dental arch (Figure 1.8). The width of the focal trough varied from 17 mm in the anterior region to 44 mm in the posterior region (Figure 1.9).

McDavid *et al* studied the imaging characteristic of seven panoramic x-ray units.[53] With regard to image layer, they found that in all cases the manufacturers had attempted to design a layer conforming in its overall geometry to the structure of the dental arch that was sufficiently wide to provide a reasonably sharp portrayal of the anatomy. However, they noted that considering the fact that all machines were built to radiograph the same object (the dental arches and adjacent structures), the variation in shape of the layers in the different units was surprisingly great.[53] It appears as though the layers are wide enough to allow for satisfactory positioning of a great majority of patients with individually different jaw shapes inside the boundaries of the layers.[53]

iii) The Projection Angle

Of equal importance as the shape, width, and thickness of the image layer is the selection of a path of the beam during the excursion that creates an optimum projection of the object.[60] The main objective is to design a beam direction that is as close as possible to perpendicular to all parts of the object, such that the projection of the jaws will become favorable both for interpretation and measurements.[60] In other words, the angle between the beam and the image layer should preferably be 90 degrees. This would result in a projection that would be orthoradial to all parts of the object and would have the added benefit of minimizing the overlap between adjacent teeth[60]

Tronje *et al* studied the projection angle of seven panoramic x-ray units to determine the deviation from the ideal situation where the central ray of the beam is at right angles to each successive part of the object.[59] Starting in the midline at distance zero on the film plane, where the angle is consistently 90 degrees, the angulation between the central ray of the beam and the central plane of the layer increased to a value between 110 degrees and 120 degrees. This maximum value in all units was found at 3 to 4 centimeters from the midline, and corresponded to the region of the premolars. From this region, the angulation decreased and reached a value varying between 40 degrees and 70 degrees. This minimum value was found at 12 to 13 centimeters from the midline and corresponded to the region of the ascending rami and the temporomandibular joints. Tronje *et al* found that despite the different shapes of beam paths and layers, the variation of the angle between the central ray of the beam and the central plane of the layer was basically the same in all machines.[59]

Scarfe *et al* studied the projection angle of eight panoramic machines and compared these angulations to the optimal angulation of the tangent of interproximal contacts to the average arch form and the midsagittal plane (Figure 1.10).[60] Using the axial radiographs of 160 subjects, intermeatal and midsagittal lines together with coordinate axes and polynomial curves representing the average dental arch form were overlaid on each radiograph. Coordinate references for interproximal tangents at 3154 contacts along the average dental arch form were digitized and angulations between the arch form and midsagittal plane calculated. In support of the previous study by *Tronje et al*,[59] results revealed that optimal beam angulations were considerably different from central ray angulations of current panoramic machines.[60] Although most machines demonstrated favorable interproximal beam angulation in the anterior region, discrepancies in the premolar region ranged from 15 degrees to over 40 degrees.

Van der Stelt *et al* studied the effect of angulation of the incident beam on the ability of the observer to diagnose interproximal caries in bite-wing radiography.[61] They showed that the direction of the beam does not have to be exactly parallel to the optimal tangent line, and up to 7.5 degrees deviation in a horizontal plane from the optimal angle is acceptable to produce a diagnostic radiograph. Although image resolution in rotational panoramic radiography is inferior to intraoral bite-wing radiography, a number of authors have suggested that extraoral screen-film combinations possess adequate resolution for the diagnosis of interproximal dental caries.[62-64] Considering only projection geometry, application of this 7.5 degree tolerance level to panoramic radiography and the previous study by Scarfe *et al*[60] reveals that about 80 percent of all interproximal angles in subjects would fit within this variation and would be displayed adequately in the panoramic image. This would occur only if the panoramic machine was manufactured to reproduce optimal angles and there were no positioning or technical errors.[56]

In a recent study, Scarfe *et al* investigated the beam projection angle with respect to both the central plane of the focal trough and the average dental arch shape for the Orthopantomograph (OP 100).[52] The beam projection angle increased from 90 degrees anteriorly to 115 degrees in the premolar region with respect to the central plane of the focal trough, and from 90 degrees anteriorly to 110 degrees in the premolar region with respect to the average dental arch (Figure 1.8 and Figure 1.9).[52]

It is a general aim in radiography to image any object using the most favorable projection angle. In the vast majority of cases, the image that is best suited for interpretation and measurements are obtained when the object and the film are parallel to one another, and at right angles to the central beam.[59] Panoramic radiographs are no exception to this general rule. On the contrary, an orthoradial projection of the dental arches resulting in free projection and separation of the teeth on the image is obviously preferable.[59] Provided an object or an object detail is positioned in a plane perpendicular to the central ray of the beam and coinciding with the central plane of the image layer, its image is not distorted. Any deviation from the perpendicular projection will cause distortion effects to appear in the image, which makes the interpretation of object morphology uncertain, and reliable measurement impossible.[59]

iv) Horizontal and Vertical Magnification

Magnification in panoramic radiography, and its distorting effects on the image, has been thoroughly studied in theory. Mathematical expressions defining the horizontal and vertical magnification, as well as their combined effect on image properties, have been documented.[65] The magnitude of the magnification of commercially available panoramic units is only partially known. While data on the average magnification along the central plane of the layer are available from the manufacturers, the continuous variation of the magnification factors in the two dimensions (horizontal and vertical) have not been published for any commercial unit.[65]

In the central plane of the image layer, the same magnification factor is valid for both the horizontal and vertical dimensions. Small flat objects positioned along the central plane of the image layer perpendicular to the beam will be portrayed in the image with their correct proportions, although the images will be magnified.[65] In any position outside the central plane of the image layer, different magnification factors apply for the horizontal and vertical dimensions. This causes distortion, which can be defined as "a discrepancy between the projected length and height of the object."[65] Therefore, the fundamental cause of all distortion effects in panoramic radiography is the different magnification in the horizontal and vertical dimensions. Magnification can vary greatly from one part of the film to the next, and it is generally worse in the horizontal than in the vertical dimension.[66] The significance of all this for the orthodontist is that measurements cannot be made from a panoramic film, even one technically well taken, with the degree of accuracy necessary for orthodontic diagnosis.[66]

Tronje *et al* studied the horizontal and vertical magnification factors of seven panoramic x-ray units.[65] Results revealed that all panoramic x-ray units employing the continuous image technique had the same *qualitative* variation of the horizontal and vertical magnification factors, although there were some *quantitative* differences. In the central plane of the layer, the horizontal magnification factor was essentially constant throughout the image but was greater in the anterior region than in the lateral regions. In the different units, the horizontal magnification factor at the midline varied between about 1.2 and 1.4. Outside the central plane of the layer, the horizontal magnification factor varied greatly with object depth. At object depths toward the rotation center of the beam, there was a marked increase in the anterior region with values ranging from 1.7 to 2.5. Toward the film, the horizontal magnification factor decreased in relation to that of the central plane of the layer and in the anterior region varied between 0.8 to 1.1 in the different units. At the central plane of the layer, the horizontal and vertical magnification factors are identical. Outside the central plane of the layer, the vertical magnification factor did not vary greatly between different parts of the image. At different object depths, the variation of the vertical magnification factor was considerably less pronounced than that of the horizontal magnification factor. Compared to its value at the central plane of the layer, the vertical magnification factor became slightly greater on the focal spot side of the layer and slightly smaller on the film side.[65]

Larheim and Svannes found acceptable reproducibility of the left and right sides on images taken at different intervals, and a consistent 18% to 21% magnification factor for vertical variables.[67] In contrast, they found that measurement of horizontal variables was unreliable because of inconsistent magnification, due to a distortion effect caused by both a projection factor and a motion factor.

Serman and Buch discovered how the inherent distortions present in panoramic radiographs could be used to localize impacted teeth.[68] They found that an impacted canine which appeared larger than the contralateral non-impacted canine lay palatal to the dental arch, while an impacted tooth which appeared smaller and more fuzzy or indistinct on the panoramic image than the contralateral canine was positioned labial to the dental arch.[68]

Wyatt *et al* compared the accuracy of dimensional and angular measurements from three different panoramic machines and two lateral oblique projections.[69] Results revealed that the assessment of vertical and horizontal measurements were more accurately made from lateral oblique projections, however there was no difference in angular measurement accuracy found between any of the projections. Wyatt concluded that while panoramic radiography is convenient for dimensional and angular assessments, lateral oblique radiographs taken with a standard cephalometric apparatus are an alternative when greater clinical accuracy is needed.[69]

Using theoretical mathematical calculations confirmed by an experimental test, Tronje *et al* analyzed the reliability of the reproduction of vertical dimensions in panoramic films.[70] The motivation of this study were that knowledge of dimensions such as the height of the alveolar process or the distance from the alveolar crest to the maxillary sinus or the mental foramen are often of interest when planning prosthetic or surgical treatment. Using a Siemens Orthopantomograph 3, it was demonstrated that, within certain limits, the panoramic film may be used for vertical measurements in clinical practice, provided the patient has been properly positioned in the equipment.[70]

Distortion in the mesiodistal width of teeth has been investigated by means of the panoramic radiograph. The findings have indicated that different percentages of distortion occur in different regions of the dental arch.[10,71] An attempt at tooth-size analysis on panoramic radiographs has also been described.[72] In the mandible, the greatest degree of linear image distortion has been reported to occur in the premolar and molar regions.[22,73]

In a recent study, Scarfe *et al* investigated the vertical and horizontal magnification factor and distortion index for the Orthopantomograph (OP 100) using a reference object placed at various resolution limits of the focal trough.[52] The vertical magnification factor of each resolution limit within the focal trough showed a linear increase along the beam path from 1.24 to 1.37, while the horizontal magnification varied from 1.01 to 1.63. The horizontal magnification and vertical magnification were identical at the center of the focal trough (1.28) and essentially constant throughout the image. The distortion index, defined as the ratio of the vertical magnification factor to the horizontal magnification, corrected for the tomographic layer varied from 0.84 to 1.24.[52]

v) Inclined Objects (Angle Distortion)

In clinical dentistry, knowledge of the angulation between different teeth and surrounding structures is often of great importance. Information on the inclination of impacted teeth for instance, may well affect whether a certain tooth should be removed, transplanted, or moved to its proper position by means of orthodontic treatment.[74,75] The importance of establishing appropriate axial inclinations with near parallel roots after orthodontic treatment is frequently mentioned in the orthodontic literature. This parallelism is of prime importance if one wishes to obtain a correct alignment of the teeth within their respective apical bases, and a normal occlusion of the upper and lower teeth.[12] At the same time, it is an important factor in maintaining a stable treatment result.[12] Proper axial inclinations are necessary for the distribution of occlusal forces with closed contact points.[6] This often has special significance in the orthodontically closed extraction sites which are prone to open if adjacent teeth are not parallel.[8-13]

Angular distortion can be defined as "the deviation of angles on the film from the true angles in the object."[76] The distortion on panoramic films of the angle between inclined teeth will be the result of the combined distortion in the vertical and in the horizontal dimensions. With this knowledge, it seems reasonable to believe that angular measurements may not be reliably performed on panoramic films.[20] However, studies of distortion in panoramic radiography have demonstrated a great tolerance with respect to angle distortion.[18-20] Using theoretical models of the rotational panoramic system, Frykholm *et al* concluded that provided a certain angle distortion may be accepted in clinical practice, there is a space on both sides of the central plane of the image layer within which the object may be positioned without the occurrence of a significant distortion.[18] He noted that the object may be positioned about 5mm towards the rotation center of the beam, and about 6mm towards the film without the angle distortion exceeding ±5 degrees.[18] Using both mathematical analysis and experiments with an

Orthopantomograph 3, Tronje *et al* reported that angle distortion was most marked when the mesiodistal inclination of the object was 45 degrees, and decreased when the angle was increased or decreased.[20] Tronje *et al* noted that there could be no angular distortion when the mesiodistal inclination was 0 degrees or 90 degrees. Since the angle of the beam to the horizontal plane affects the angle distortion, the tolerance limits decrease when the angle of the beam increases. Thus, Tronje *et al* concluded that the tolerance limits against angle distortion were greater in the lower jaw than in the upper jaw.[20] Based on these studies, it has been claimed that mesiodistal inclination of an object may be measured in panoramic radiographs when a moderate error (e.g. ±5 degrees) can be tolerated. A prerequisite condition is that the object is positioned within the image layer and that it does not have an extreme buccolingual inclination.[18-20]

Welander *et al* analyzed mesiodistal angular distortion for seven panoramic units.[76] Prior to this point, studies of angular distortion in panoramic radiography had been performed using simplified theoretical models utilizing stationary rotation centers and cylindrical layers.[18-20] It was not known whether these calculations, valid for such simplified systems, could be applied to real systems. Welander *et al* used panoramic units with non-cylindrical image layers, whereby different sliding transitions of the effective rotation center of the beam were applied, sometimes in combination with stationary rotation centers.[76] Welander *et al* results can be summarized as follows:

1) There was a tendency toward angle distortion in the canine and premolar regions.
2) Angular distortion was more marked when the object was inclined at 45 degrees than when it was inclined at 15 or 75 degrees. Angle distortion

became successively smaller when the object inclination decreased or increased from 45 degrees, being nonexistent at 0 degrees and 90 degrees.

3) When the inclined object was moved ±5 mm away from the central plane of the layer, the angle distortion became more marked. The portrayed angle decreased when the object was displaced toward the film and increased when the object was displaced toward the rotation center of the beam.

In conclusion, Welander *et al* stated that the proper use of the panoramic radiograph should give a value of the mesiodistal angulation of inclined objects that is within ±5 degrees of the correct value.[76]

Lucchesi *et al* used a plexiglass mandibular model to investigate the suitability of both panoramic and plane-film radiography for the assessment of the mesiodistal angulation of teeth in the buccal segments of the mandible.[77] Mesiodistal steel pin angulation values were selected with computer generated random numbers confined to a range of -20 degrees to +20 degrees, and experimental measurements were made with varying degrees of buccolingual inclination ranging from 0 degrees to 25 degrees of lingual crown torque. Not surprisingly, results revealed that the degree of deviation from the actual angulation was greater with panoramic radiography than that of plane-film radiography. Panoramic images tended to accentuate pin angulation at increased levels of lingual crown inclination although errors occurred in both positive and negative directions. Lucchisi *et al* noted that, based on the results of Tronje *et al*,[20] an explanation for this finding was difficult to deduce since it would be expected that machine errors should occur in either a positive *or* negative direction. Tronje *et al*[20] stated that alterations in buccolingual inclination did not contribute to angulation errors in the panoramic image because compensation would occur in the relative magnification and diminution of various parts of the image. The apparent bidirectional error in angulation between the panoramic image and the object implies that the application of a correction factor, as suggested by Tronje *et al*,[20] would be difficult, if not impossible to implement. Lucchesi *et al*[77] reconciles this contradiction between their results and Tronje's mathematical theories by noting that their own study used a single type of panoramic generator as well as lingual inclinations that were in one direction only, and hence further research was required to delineate the angulation recording capabilities of other panoramic generators. They concluded that this would be especially important in generators with split-image characteristics, different focal troughs, and different axes of rotation.[77]

Ursi *et al* investigated the mesiodistal axial inclination of forty-two patients with untreated "normal" occlusions defined as Class I cuspid and molar relationships with maximum overbite of 3mm and overjet of 1mm.[78] A total of 74 radiographs were taken with four different units (Two Funk X-15 units, Siemens Orthopantomograph, and Yoshida Panoura) with the subjects positioned in a standardized manner. The angles formed by an upper and lower reference line and the long axes of each tooth were measured from each radiograph and same tooth comparisons with t-tests were applied to the data. Results revealed that about 25% of the tooth inclinations were statistically significantly different between the Funk-Siemens and Funk-Yoshida machine combinations. However, for clinical purposes, variations of as much as 5 degrees in the angulation of two adjacent teeth or 2.5 degrees between two exposures of the same tooth is supported in the literature as not constituting a serious objection to the use of the radiograph.[18,23,79] With the application of these tolerance limits of clinical significance, Ursi *et al* concluded that the mean difference exceeded the clinically acceptable value of 5 degrees for only three out of 140 tooth comparisons made.[78]

Wyatt *et al* compared the accuracy of dimensional and angular measurements from three different panoramic machines and two lateral oblique projections.[69] Acrylic test models with wires positioned to represent the position and angulations of teeth were used and ten images were taken with the Oralix Pan DC/1, Panelipse, and Orthophos panoramic machines and fourteen lateral oblique radiographs were taken using an Orthophos and Quint Sectograph. The models were repositioned between each exposure. Results revealed no differences in angular measurement accuracy between any of the projections.[69]

vi) Head Positioning for Panoramic Radiography

To obtain adequate panoramic radiographs with acceptable detail and minimum distortion, proper patient positioning requires placing the patient so that the dental arches are located in the central plane of the image layer (or focal trough) that has been predetermined by the manufacturer. This is usually accomplished by centering the head to the midsagittal plane, placing Frankfort horizontal parallel to the floor, and having the patient place the incisal edges of the maxillary and mandibular incisors into a notched positioning device (usually referred to as the 'bite block').[17,80,81]

The bite block ensures the proper anteroposterior relation of the dental arches, especially in the anterior dental region where the geometry of the panoramic orbit results in the focal trough being the narrowest.[24,82] This is due to the fact that the effective projection radius is consistently smaller in that region than in other regions.[53] Failure to position the midsagittal plane in the midline of the focal trough results in a distorted panoramic image with unequally magnified right and left sides in the horizontal dimension.[17] The image of the structures farthest from the film will be magnified, whereas, on the opposite side, the structures imaged closest to the film will be minified.[28] Placing Frankfort plane parallel to the floor helps ensure that the patients chin and occlusal plane will be properly positioned to minimize distortion. The occlusal plane should be positioned so that it is lowered anteriorly, angled 20 to 30 degrees below the horizontal plane.[17] Proper patient positioning also requires positioning the patient's back and spine in an erect position with the neck extended. Slumping causes a large opaque artifact created by the superimposition of an increased mass of cervical spine which can obscure the entire symphyseal region.[17]

Schiff *et al* outlined common positioning and technical errors from a sample of randomly selected panoramic films.[28] Of the 1000 films examined, only 20% were error free. Positioning errors occurred with a much greater frequency than technical errors. The authors emphasized the need for a quality assurance regimen with adequate training and time spent in properly positioning patients.[28] To ensure undistorted symmetrical images, the use of a cephalostat in panoramic radiography has been studied.[83,84] Richardson *et al* designed a cephalostat to examine the reliability of the head positioning procedure.[83] The results of their work suggested that it may be sufficiently reliable to make longitudinal studies of vertical and horizontal measurements within limited segments of the jaws.[83]

Phillip and Hurst studied the relation between the cant of the occlusal plane and distortion in the panoramic radiograph using a mounted, hinged testing device with a horizontal reference wire and parallel wires representing the teeth.[79] As the angular settings on the device were varied from –4 degrees to +20 degrees (perpendicular to a line parallel to the floor), they found that three types of distortion were present: parallelism errors between teeth, errors in expression of the long axis of teeth to the occlusal plane, and elongation errors. All three types of distortion had a fairly high degree of correlation with the cant of the occlusal plane. The following conclusions were made:

1) As the occlusal plane was tipped from –4 to +20 degrees, the maxillary tooth roots converged away from the occlusal plane and the mandibular tooth roots diverged away from the occlusal plane.
2) The largest amount of distortion of parallelism was in the canine-premolar region of both arches.
3) The largest amount of distortion of the tooth long axis to the occlusal plane was in the molar region with maxillary teeth angulated to the mesial and the mandibular teeth angulated to the distal.
4) The smallest amount of distortion occurred when the occlusal plane was located at +6 degrees.
5) Elongation was more pronounced in the maxilla and increased in the molar region. Magnification ranged from 22.5% to 28%.

Phillip and Hurst concluded that angulation differences in the range of 2 to 5 degrees may not carry any clinical significance. Previous investigators have also noted that for clinical purposes, variations of as much as 5 degrees in the angulation of two adjacent teeth or 2.5

degrees between two exposures of the same tooth is supported in the literature as not constituting a serious objection to the use of the radiograph.[18,23]

Samawi and Burke studied angular distortion using a wire-mesh frame shaped to represent the curvature of the dentition in the jaws, with lead shot representing the long axes of the teeth as well as certain skeletal landmarks.[23] Angular parameters were used to identify and assess both the magnitude and distribution of angular distortion of the radiographic image. They concluded that following anterior tilt of the head, the canine and premolar teeth of both arches expressed the largest amount of distortion, and the molar teeth the smallest. In addition, any change in the inclination of the teeth in the buccolingual plane would be projected on the radiograph as a change in the mesiodistal angulation. Once again the canine-premolar region proved to be the most crucial and susceptible area. Finally, skeletal structures representing the lower border of the mandibular body and posterior border of the ramus were determined to be relatively stable.[23]

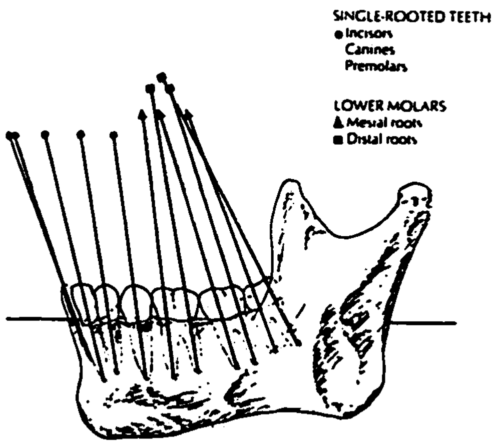
Xie *et al* assessed whether it was possible to make accurate vertical measurements of the jaws from panoramic radiographs.[85] Panoramic radiographs of five skulls were obtained in nine different combinations of sagittal shifting and tilting: the ideal position, shifted 5mm forwards and backwards, and tilted 5 degrees up and down. A PM 2002 CC (Planmeca Co.) panoramic unit was utilized and the reproducibility of skull positioning and measurement error were calculated. Xie *et al* found that a line joining the articular eminences was unsuitable as a reference line for measurements in the tooth bearing areas. A line using the inferior points of the orbits was unsuitable for measurements in the anterior part of the maxilla in the tilted skulls, but was acceptable in the posterior maxilla.

Shifting forwards or backwards by 5 mm had little effect on measurements. They recommended utilizing a horizontal reference line that is located anatomically directly above or below the point being measured, in the plane of the center of the image layer. They concluded that a slight misalignment of the head, such as occurs frequently in everyday practice, would not significantly affect vertical measurements in the posterior mandible, posterior maxilla, or the anterior mandible as long as the reference lines are in the same vertical plane as the teeth.[85]

vii) Summary

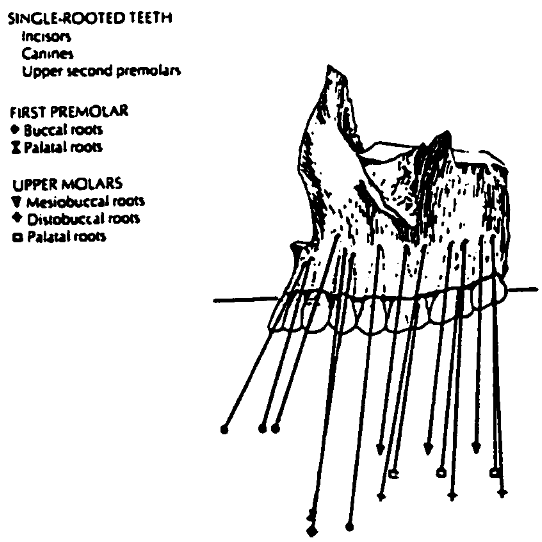
A panoramic radiograph is a distorted, and two-dimensional representation of a complex and variable three-dimensional structure. The machinery has a curved, sharply depicted image layer, with other parts of the structure being to a greater or lesser degree blurred. Background information and a review of the literature of the important aspects of image generation that relate to the dimensional accuracy of panoramic images have been provided. These include discussions on image layer, projection angle, horizontal and vertical magnification, angular distortion of inclined objects, and head positioning.

Figure 1.1 Angulation of the Mandibular Teeth (Lateral View)



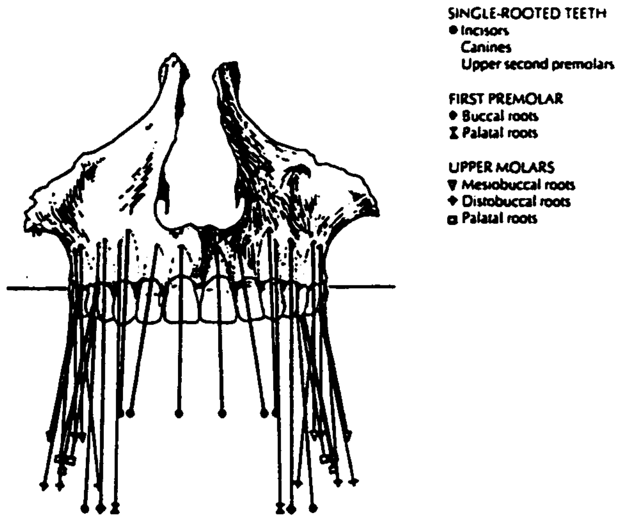
Angulation of the mandibular teeth.. Note that both anterior and the posterior teeth are mesially inclined. (From Dempster WT et al: J Am Dent Assoc 1965;67:779)

Figure 1.2 Angulation of the Maxillary Teeth (Lateral View)



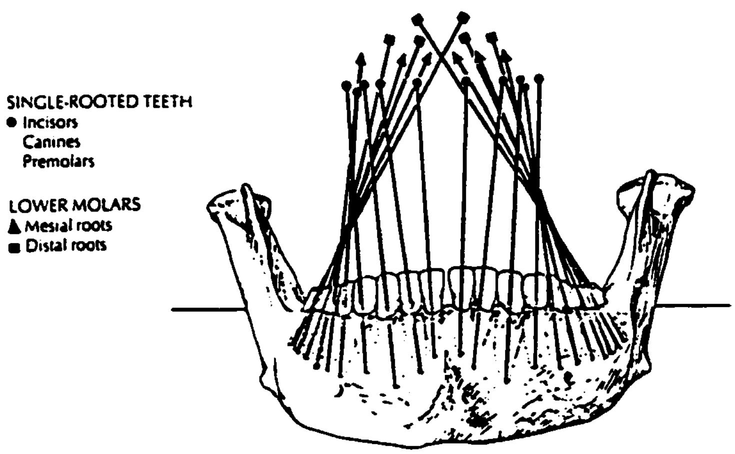
Angulation of the maxillary teeth. Note that the anteriors are mesially inclined while the most posterior teeth become more distally inclined with reference to the alveolar bone. (From Dempster WT et al: J Am Dent Assoc 1965;67:779)

Figure 1.3 Angulation of the Maxillary Teeth (Frontal View)



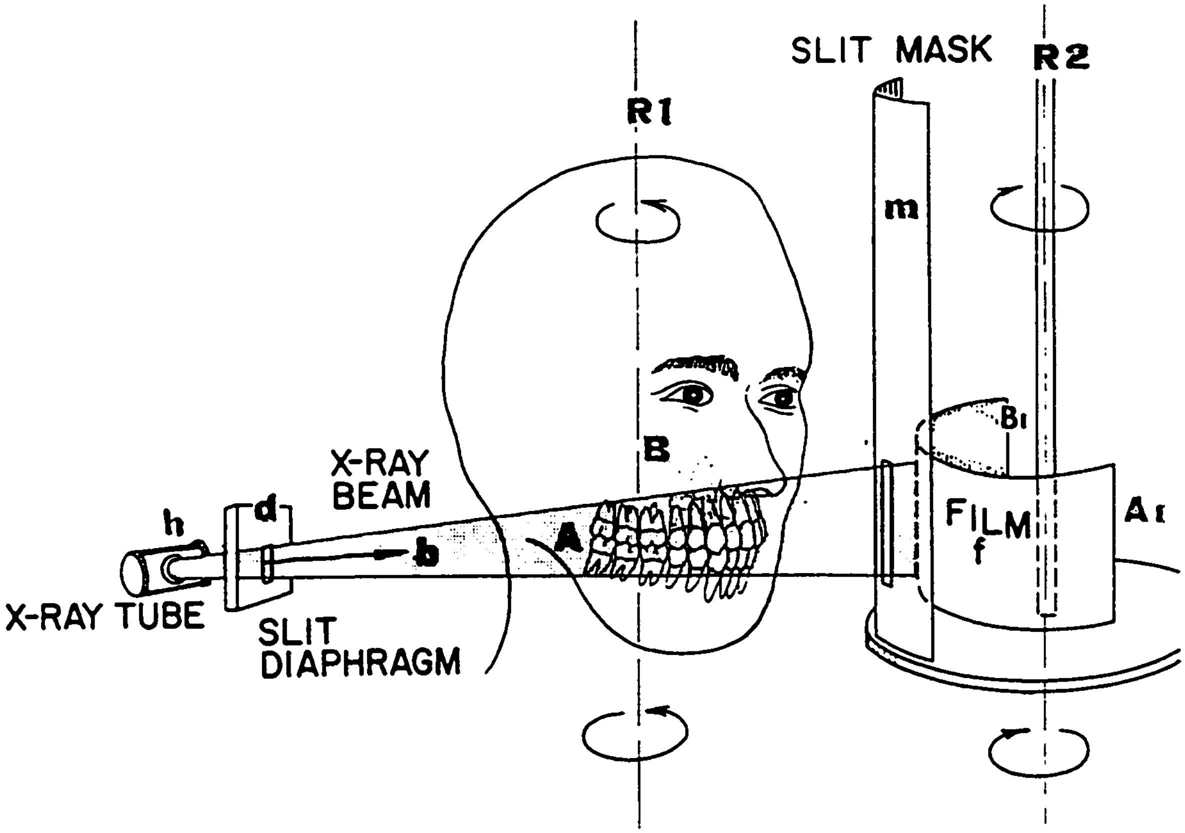
Angulation of the maxillary teeth. Note that all the posteriors are inclined slightly buccally. (From Dempster WT et al: J Am Dent Assoc 1965;67:779)

Figure 1.4 Angulation of the Mandibular Teeth (Frontal View)



Angulation of the mandibular teeth. Note that all the posteriors have slight to increasingly moderate lingual inclination as one proceeds posteriorly. (From Dempster WT et al: J Am Dent Assoc 1965;67:779)

Figure 1.5 Pantomography Unit with One Center of Rotation



Drawing demonstrates tomographic principle of Watson rotagraph, employing one center or rotation. Patient rotates on axis R1 while curved film in flexible cassette (f) rotates in the opposite direction on axis R2. X-ray tube (h) sends x-ray beam (b) through slit (d) penetrating orofacial structures from right to left (A and B), passing through slit (m) and sensitizing rotating film. Motion is so synchronized that structures on patient's right (A) strike curved film in A1 region. (From Kumpula JW: J Am Dent Assoc 1961;63:194)

Figure 1.6 Pantomography Unit with Two Centers of Rotation

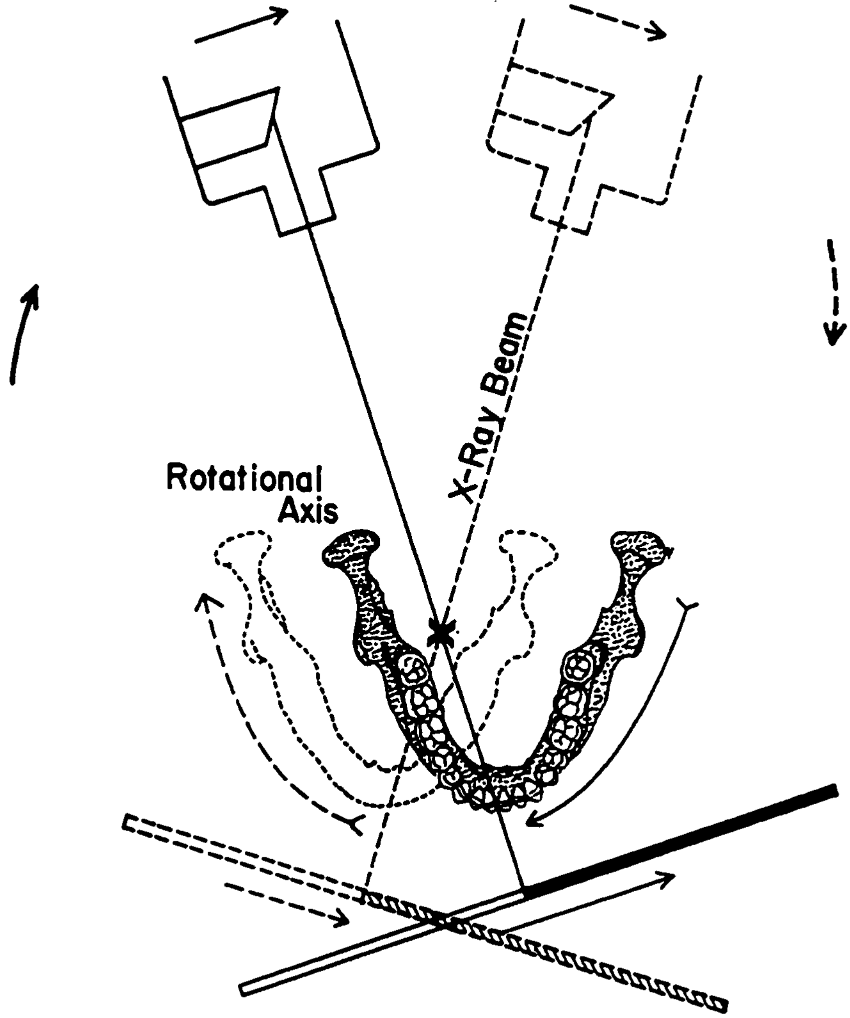


Diagram illustrates single rotational axis (X), modified by a lateral shift of the patient halfway through the exposure, to give an eccentric or two-centers-of-rotation effect. Center behind the right molar area is axis for radiation of the left side of the face. After the chair shift, X is located behind the left molar area (see dotted mandibular outline) and exposes orofacial structures on the right side of the face. Dotted and curved arrow shows the direction of travel of the x-ray beam after the chair shift, around from the midline to the condyle on right side. (From Updegrave WJ: Pennsylvania DJ 1961;20:10)

Figure 1.7 Pantomography Unit with Three Centers of Rotation

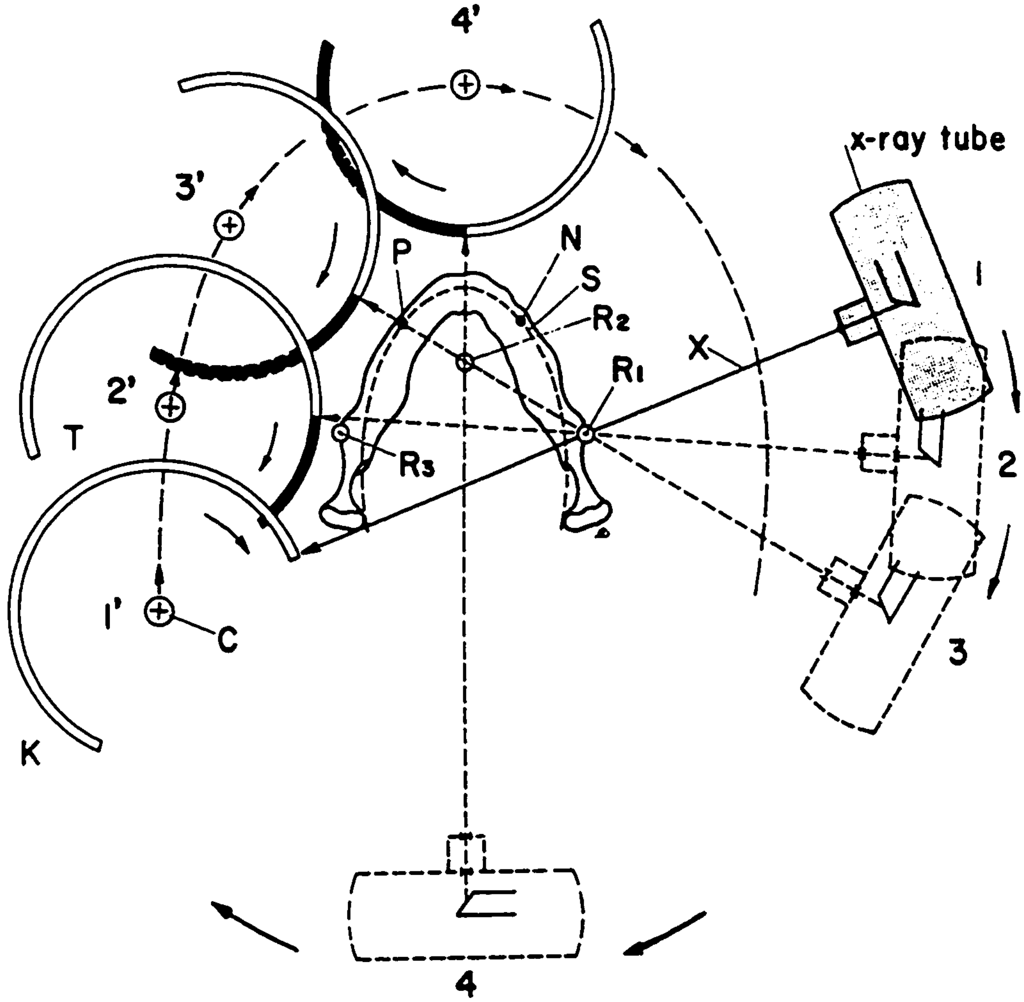
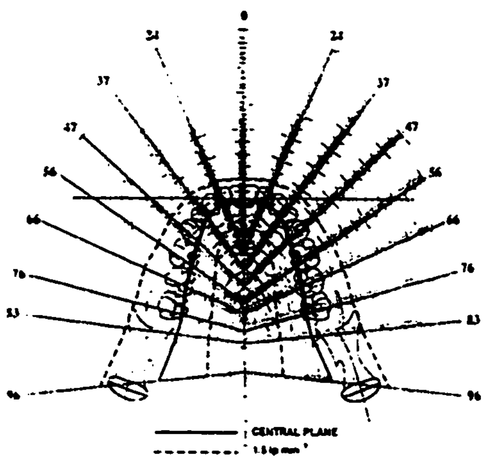


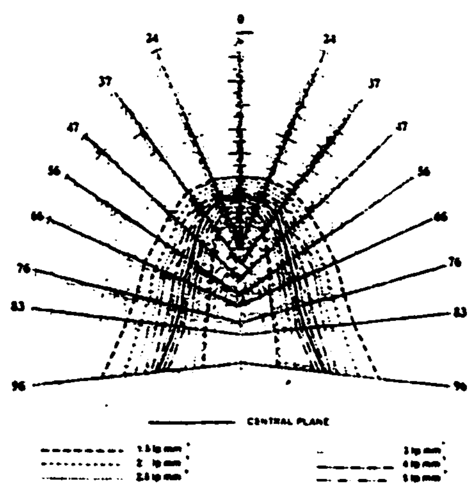
Diagram illustrates combined concentric and eccentric tomographic principle with three rotational centers; one for the left buccal segment, one for the anterior segment, and one for the right buccal segment. The orthopantomograph works on this principle, changing axes in the cuspid-first bicuspid regions. The x-ray beam turns around rotational center R1 first to radiograph the left side. At the cuspid-first bicuspid region, the axis changes to R2 to radiograph the anterior maxillary and mandibular portions; structures from P to N are in focus. As the beam reaches S, it swings over to rotational center R3 and projects an image of the right side on the rotating film cassette with all structures from S to the right condyle in focus. (From Paatero YV: Oral Surg Oral Med Oral Pathol 1961;14:951)

Figure 1.8 Focal Trough for the OP 100 vs. Average Dental Arch Form



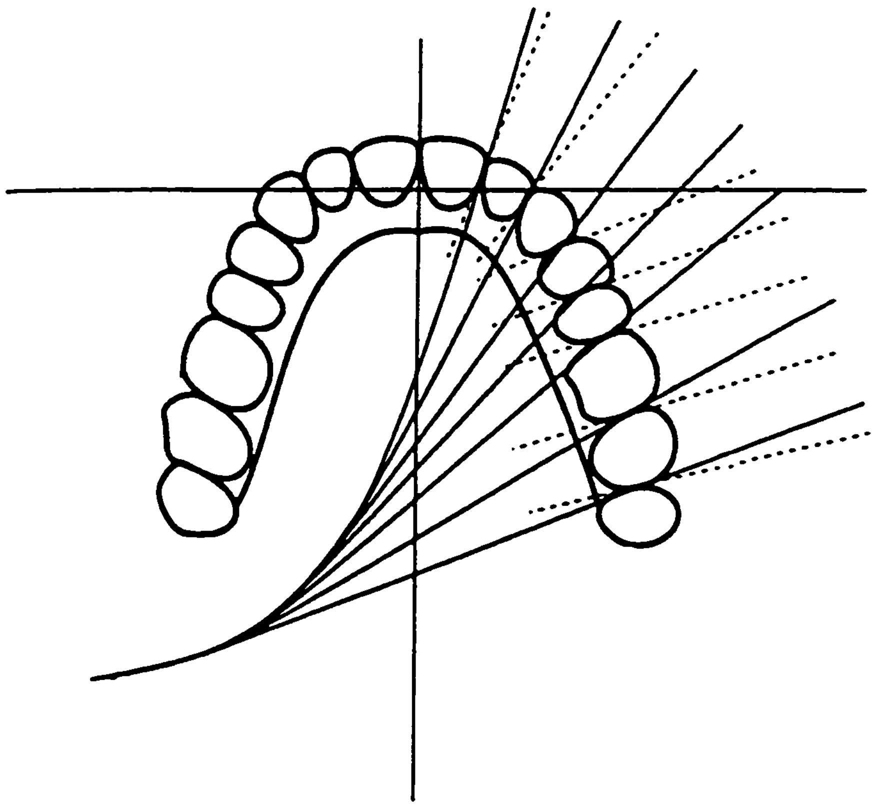
The central plane of the focal trough and 1.51 p mm^{-1} resolution limits for the OP 100 superimposed over the 'average' dental arch form. The plane designated as central is that of maximum resolution and was generally placed lingual to the actual center of the focal trough. (From Scarfe et al: Dentomaxillofac Radiol 1998;27:54)

Figure 1.9 Focal Trough for the OP 100



Focal trough, beam projection angle, and resolution limits at midsagittal for the OP 100. (From Scarfe et al: Dentomaxillofac Radiol 1998;27:53)

Figure 1.10 Projection Angle vs. Interproximal Tooth Contacts



Typical beam direction in rotational panoramic radiography compared with interproximal tooth contacts along the average dental arch. (From Scarfe et al: Oral Surg Oral Med Oral Pathol 1993;76:665)

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Chapter Two

Paper #1

The Accuracy of Four Panoramic Units in the Projection of Mesiodistal Tooth Angulations

2.1 Introduction

A major objective of orthodontic treatment is the correction of tooth positions in three planes of space, with the goal of approaching predefined cephalometric and occlusal standards.[1-5]

The importance of establishing appropriate axial inclinations with near parallel roots is frequently mentioned in the orthodontic literature. This parallelism is of prime importance if one wishes to obtain a correct alignment of the teeth within their respective apical bases, and a normal occlusion of the upper and lower teeth.[6] From his historic study of 120 casts of non-orthodontic patients with normal occlusions, Andrews stated that the proper mesiodistal inclination (or tip) and facial-lingual inclination (or torque) was required for ideally positioned teeth.[3,7] Proper axial inclinations are necessary for the distribution of occlusal forces through tight interproximal contacts and are an important factor in maintaining a stable treatment result.[6] This has special significance in orthodontically closed extraction sites which are prone to open if adjacent teeth are not parallel.[6,8-13]

In 1948, Paatero developed panoramic radiography from the medical process of laminagraphy or body section radiography.[14-16] The principle advantages of this radiographic technique include; the broad anatomic region imaged, the relatively low patient radiation dose, and the convenience, ease, and speed with which the procedure can be preformed.[17] One of the many uses of panoramic radiography includes the assessment of mesiodistal angulation of erupted, unerupted, impacted, and ectopically positioned teeth. Panoramic radiography, in addition to clinical evaluation, is often used before, during, and after orthodontic treatment to assess root parallelism and mesiodistal tooth angulation.[6,18,19]

However, disadvantages of panoramic radiography include the lack of fine detail compared to intraoral films, and the variable magnification and geometric distortion that are inherent to image generation.[17] Various investigators have studied aspects of image generation that relate to the dimensional accuracy of panoramic images including image layer (or focal trough), projection angle, horizontal and vertical magnification, angular distortion and patient positioning.[18-48] Distortion on panoramic films of the angle between inclined teeth will be the result of combined distortion in the vertical and horizontal dimensions.[33] Considering the inherent dimensional inaccuracy of panoramic images, it seems reasonable to believe that the assessment of mesiodistal angulations of teeth cannot be reliably performed on panoramic films.

The purpose of this study was to compare the true mesiodistal tooth angulations of an anatomic typodont/skull testing device to the image mesiodistal tooth angulations from four contemporary panoramic units at a standardized head position. The results should provide the clinician with practical guidelines to help determine the location and extent that panoramic images can be relied upon in the diagnostic evaluation of root position.

2.2 Materials and Methods

2.2.1 Test Device Design

The test device consisted of a clear anatomic maxillary and mandibular typodont (Ormco Corporation, U.S.A.) with idealized occlusion from second molar to second molar (Appendix A). For each tooth, two chromium steel balls (Commercial Bearing, Edmonton, AB.) measuring 1.58mm in diameter were glued into position following preparation with a #2 round bur. The occlusal ball was placed in the buccolingual and mesiodistal midpoint of the crown on the occlusal/incisal surface while the placement of the apical ball into the root surface depended on the tooth being prepared. Excluding maxillary and mandibular first and second molars and maxillary first bicuspids, the apical ball was placed into the buccolingual and mesiodistal midpoint of the root in the apical third. For teeth displaying dilaceration in the apical third, the apical dilaceration was removed with a diamond disc to remove the effect of dilaceration on long axis determination. For the remaining teeth, the apical ball was placed in the center of the bifurcation/trifurcation. These steel balls would serve as reference markers for both true and image angle determination and an imaginary line joining the center of the occlusal and apical balls would represent the long axis of each typodont tooth.

The maxillary and mandibular typodont was then bonded with .022 slot clear orthodontic brackets (Spirit, Ormco Corporation, U.S.A.) to idealized bracket positions and a passive .020 round stainless steel archwire (Permachrome resilient/Orthoform III, 3M-Unitek, U.S.A.) was ligated into position with elastomeric modules. The clear bases of the typodont were modified to provide access to the apical steel balls for true angle determination (Appendix A).

2.2.2 True Angle Determination

A Coordinate Measuring Machine (HGC Model, Starrett Corporation, U.S.A.) was utilized, along with custom designed software (Mechanical Engineering, University of Alberta), to determine the true mesiodistal angulation of each typodont tooth relative to the reference archwire (Appendix B & C). The Coordinate Measuring Machine (C.M.M.) provides X, Y, and Z coordinate values for each digitized point from an established origin. Following initial calibration, a pilot project was undertaken to verify the accuracy and measurement replication error of this measurement device (Appendix D). A true right-angle was measured five times at various orientations to establish accuracy and three mandibular teeth (one incisor, one cuspid, and one bicuspid) were each measured five times to establish measurement replication error. The machine was found to be accurate to within 0.04° and the reproducibility (as shown by the standard deviations from the three teeth measured) ranged from 0.24° to 0.46°.

The maxillary and mandibular study typodont were then digitized separately using varying orientations of the machines' external probes. The typodont was attached to a Ney surveyor table (Ney Co., U.S.A.) to prevent typodont movement and permit access to the occlusal/apical steel reference balls and reference archwire. Each series of tooth measurements were repeated five times by the principal investigator and consisted of the following four digitized points:

1. T^C (tooth crown)-contact of the C.M.M. probe with the most superior surface of the steel ball on the occlusal surface of the typodont tooth
2. T^R(tooth root)-contact of the C.M.M. probe with the most inferior surface of the steel ball at the apical/furcal point of the typodont tooth
3. W^D(wire distal)-contact of the C.M.M. probe with the occlusal aspect of the reference archwire perpendicular to the distal contact of the typodont tooth with its adjacent tooth

4. W^M(wire mesial)-contact of the C.M.M. probe with the occlusal aspect of the reference archwire perpendicular to the mesial contact of the typodont tooth with its adjacent tooth

The X,Y, and Z coordinate values for each point were entered into a custom designed spreadsheet and the true mesiodistal angulation of each typodont tooth relative to the reference archwire were generated for all teeth from first molar to first molar (Appendix C). A mesiodistal angulation value greater than 90° indicated a distal inclination to the root while a value greater than 90° indicated a mesial inclination to the root.

The true mean mesiodistal angulation and standard deviation for each of the twenty-four teeth of the maxillary and mandibular typodont were calculated (Table 2.1).

2.2.3 Typodont Positioning into Skull

A dried adult human skull with complete natural dentition and class I skeletal and dental relation served as the matrix into which the typodont dentition was fixed for subsequent panoramic imaging (Appendix E).

The glenoid fossa was remodeled with cold cure acrylic resin to provide positive seating of the condyle. This ensured reproducible mandibular opening/closing and a stable centric occlusion supported by both typodont tooth intercuspation and condyle/glenoid fossa fit. Chromium steel balls measuring 1.58mm in diameter were fixed to the skull at the following positions to confirm that the vertical, anterioposterior, and transverse position of the typodont dentition conformed to pre-established norms:

1. Nasion – the junction of the nasal and frontal bones at the most posterior point on the curvature of the bridge of the nose

2. Right and left anatomic porion – the most superior point of the external auditory canal (anatomic porion)
3. Pogonion – the most anterior point on the contour of the chin

The natural maxillary dentition, supporting bone, and portions of the skeletal maxilla were removed and the maxillary typodont dentition was temporarily wired into place with ligature wires. Multiple anthropometric, lateral and posterioranterior cephalometric measurements were made with subsequent movements of the maxillary typodont until the following position was obtained:

1. *Transverse* – bisection of the midpoint of the incisal steel balls on typodont teeth #11 and #21 with a line joining the steel balls placed at nasion and pogonion (measured on PA cephalometric image)
2. *Anterio-Posterior* – Nasion perpendicular to Frankfort Horizontal (PoOr) to upper incisor edge = 5mm* (measured on lateral cephalometric image)

   (* Modification of the M^c^Namara analysis measurements calculated by adding the 14 year old norm for nasion perpendicular to Frankfort Horizontal to A-point (3.8mm) to the 14 year old norm for A-point parallel to nasion perpendicular to Frankfort Horizontal to facial surface of upper incisor (1.2mm); total distance nasion perpendicular to Frankfort Horizontal to facial surface of upper incisor=5mm)
3. *Vertical*
   (a) Nasion to maxillary central incisor edge = 76 mm (linear distance measured on skull)
   (b) Occlusal plane cant to Frankfort horizontal (PoOr) = 9° (measured on lateral cephalometric image)

The maxillary typodont was then rigidly fixed to the skull.

The position of the mandibular typodont dentition in all three planes of space was determined by its centric occlusion articulation with the maxillary typodont. The dental relationship of the articulated typodont was a fully interdigitated class I molar and cuspid relation with 2mm overjet, 2mm overbite, and coincident dental midlines. The mandibular typodont dentition was firmly ligature tied to the maxillary typodont dentition and the natural mandibular dentition, supporting bone, and portions of the skeletal mandible were removed. The skeletal mandible was then rotated upwards (ensuring full seating of the condyle in the glenoid fossa) until the pre-existing vertical dimension of the skull was achieved (distance nasion to pogonion = 108 mm). The mandibular typodont was then rigidly fixed to the skeletal mandible and the intermaxillary ligature wires were released. Lateral and posterioranterior cephalometric analysis of the finalized movements revealed attainment of positioning goals and a remarkably 'normal' dental to skeletal and dental to dental relation as shown below:

1. Upper incisor to Frankfort Horizontal (PoOr) = 108°
2. Lower incisor to mandibular plane (GoMe) = 94°
3. Interincisal angle = 132°

2.2.4 Panoramic Radiographs

The skull was positioned five separate times into *each* of the following four panoramic units and exposed:

Unit 1: OP 100 (Instrumentarium, Tuusula, Finland)

Unit 2: Cranex 3+ (Orion Co. Soredex, Helsinki, Finland)

Unit 3: Orthophos (Siemens, Munich, Germany)

Unit 4: PM 2002 EC Proline (Planmeca Co., Helsinki, Finland)

For each panoramic unit, the manufacturer's instructions on patient positioning were precisely followed utilizing all patient positioning guides. The object was to position the skull to simulate the desired position of the patient's head in the panoramic unit. For all units this involved centering the skull to the midsagittal plane, with Frankfort horizontal parallel to the floor, and the upper and lower incisors placed into the notched bite block. Markings placed on the lateral and frontal aspects of the skull representing Frankfort horizontal and the midsagittal plane respectively, assisted in alignment with the horizontal and vertical positioning light guides. Test exposures were made on each unit to establish KVP, mA, and time settings that provided images with sufficient density and contrast for future landmark identification and measurement.

2.2.5 Image Angle Determination

Custom designed software (Mechanical Engineering, University of Alberta) was utilized to calculate the mesiodistal angulation of the typodont teeth relative to the reference archwire from the twenty panoramic images (Appendix C). The radiographs were scanned with a resolution of 600 d.p.i. and magnification of 200% (Hewlett Packard Scan Jet 6100 C/T, HP Desk Scan II, Corel Photopaint 6.0) and digitized (Panoramic Angulator, Crusher Software) on a Dell Dimension XPS D433 PII IBM compatible PC. The order of landmark identification was standardized for all radiographs and involved the following four points for each tooth angle determination:

1. $T^{C'}$ (tooth crown)-the center of the occlusal steel ball
2. $T^{R'}$(tooth root)-the center of the apical/furcal steel ball

3. $W^{D'}$(wire distal)-intersection of a computer generated vertical midpoint between adjacent teeth (on the distal side of the tooth being measured) and the image of the reference archwire
4. $W^{M'}$(wire mesial)- intersection of a computer generated vertical midpoint between adjacent teeth (on the mesial side of the tooth being measured) and the image of the reference archwire

Upon completion of digitization of each panoramic image, the program generated an Excel spreadsheet of the image mesiodistal angulations for the 24 teeth.

2.2.6 Error of the Method and Statistical Analysis

All typodont/skull modifications, skull positioning, and true/image angle measurements were undertaken by the principal investigator.

The total error of each image angle measurement was a combination of the error of measurement (i.e. digitization) and the error of repeated head positioning for each panoramic unit. To determine the error of digitization, one of the twenty images was randomly selected and each tooth was digitized five consecutive times. The error of digitization ranged from 0.45° to 0.86°. The total error for each panoramic units' image angle measurements ranged from 0.4° to 3.0° (OP 100), 0.2° to 1.8° (Cranex 3+), 0.4° to 3.0° (Orthophos), 0.7° to 2.4° (PM 2002 EC).

One sample *t*-tests were completed for *each tooth* to detect the mean difference between the true mesiodistal angulations and *each* of the four panoramic units image mesiodistal angulations. Comparison of the standard deviations of the true angle measurements with the image angle measurements revealed that the true angle measurement standard deviations were generally significantly smaller. This allowed statistical analysis with one sample *t*-tests whereby the mean of the true mesiodistal angulation (from the C.M.M.) was compared to each of the five measurements for each tooth and from each panoramic unit to establish a mean difference. Significance levels less than 5% were considered to be statistically significant.

2.3 Results

The mean and standard deviation values for the true and image mesiodistal angulations for all 24 teeth are presented in Table 2.1. One sample *t*-tests comparisons showing the mean difference and significance between the image and true mesiodistal angulations by tooth number is presented in Table 2.2.

The majority of maxillary and mandibular image angles (74%) from the four panoramic units were statistically significantly different from the true angle measurements. Examination of Figures 2.1 and 2.2 revealed that there was a definite trend or similarity between the panoramic units in their overestimation and underestimation of the tooth angulations. For the maxillary teeth, the image angle typically underestimated the central and lateral incisor and canine, while overestimating the premolars and first molar bilaterally. This had the effect of projecting the anterior roots more mesially and the posterior roots more distally, creating the illusion of exaggerated root divergence between the canine and first premolar. In the maxilla it was noted that the largest angular difference between adjacent teeth occurred between the canine and first premolar, where the average angular difference between the true angle and each of the four panoramic units was 7.0° (OP 100), 5.4° (Cranex3+), 5.5°

(Orthophos), and 5.5° (PM 2002 EC). One-way ANOVA for machine differences for the angular difference between the upper canine and first bicuspid revealed that there were no differences between the four panoramic units. For the mandibular teeth, almost all image angles underestimated the true angles with the canine and first premolar teeth being the most severely underestimated bilaterally. This had the effect of projecting all the roots, except those of tooth# 41, more mesially than they are in truth. In the mandible, it was noted that the largest angular difference between adjacent teeth occurred between the lateral incisor and canine, where the average angular difference between the true angle and each of the four panoramic units was 5.7° (OP 100), 5.2° (Cranex3+), 3.7° (Orthophos), and 4.2° (PM 2002 EC). One-way ANOVA for machine differences for the angular difference between the lower lateral incisor and canine revealed that there were no differences between the four panoramic units. Finally, it was noted that the average discrepancy between the image angles and true angles were larger for mandibular teeth as compared to maxillary teeth.

2.4 Discussion

The results of this study relate only to the particular models of panoramic units utilized. In addition, while every attempt was made to create an anatomic tooth bearing testing device with clinically reasonable tooth angulations, it is not possible to confidently extrapolate the results of this experiment to the population in general. Variations in the size and shape of the jaws and differences in the mesiodistal and buccolingual inclinations of individual teeth that would be present in the general population would influence the geometry of the radiographic system, and hence the image shifts produced. However this study did utilize a test device with tooth angulations that are likely applicable to clinical situations. Previous investigators have relied heavily on non-anatomic testing devices such as Plexiglas blocks or steel wire meshes to represent arch form and dimension.[18,25,46] The steel pins or lead shot utilized to represent tooth angulations were usually orientated with total disregard for the unique mesiodistal and buccolingual inclinations represented in the human dentition.[49] While the true buccolingual inclinations of the typodont used in this study were not determined, visually they conformed to a very realistic tooth set-up. In addition, confirming lateral cephalometric images of the typodont position in the skull revealed a remarkably normal interincisal angle, upper incisor to Frankfort horizontal angle, and lower incisor to mandibular plane angle. Previous studies have also noted that, provided the object is positioned within the image layer and does not have an extreme buccolingual inclination, the mesiodistal inclination may be measured in panoramic radiography when a moderate error (±5 degrees) can be tolerated.[20-22]

The results of this study revealed that most of the image mesiodistal angulations from the four panoramic units were statistically significantly different from the true mesiodistal angulations. The application of clinically significant tolerance limits should be applied to this research. Previous investigators have reported that for clinical purposes, variations of as much as 2.5° (in either direction) between a tooth and an established reference plane does not constitute a serious objection to the use of the radiograph.[20,25,46] Application of these arbitrary clinically significant tolerance limits revealed that 61% of the maxillary and mandibular image angles were still clinically significantly different from the true angle measurements. However, it must be remembered that root parallelism and root angulation interpretation from radiographs is a subjective assessment. The degree of disagreement between the actual situation and panoramic projection may be of greater or lesser clinical significance. Perhaps the degree of error associated with the use of panoramic radiographs is within the error of perception of the practitioner. Further research directed towards the practitioner's ability to discriminate different degrees of root angulation (and parallelism) should be contemplated.

The importance of evaluating the axial inclination of erupted, unerupted, impacted, and ectopically positioned teeth has significant relevance to orthodontics and other areas of dentistry. One of the goals of orthodontic treatment is the establishment of appropriate axial inclinations of teeth with near parallel roots. This has special significance in the orthodontically closed extraction sites which are more prone to open if adjacent teeth are not parallel.[6,8-12] In the maxilla, the largest angular difference between adjacent teeth occurred between the canine and first premolar and relative root parallelism or convergence in this area was projected as root divergence. Therefore, treating to the pan radiograph would result in excessive convergence of the roots of the canine and first premolar. In the mandible, the canine and first premolar discrepancy in angulation was much smaller than in the maxilla, however these adjacent teeth were the most severely underestimated of all lower teeth in relation to the true angulations. The largest angular difference between adjacent teeth occurred between the mandibular lateral incisor and canine, with relative root parallelism being projected as root convergence. Treating to the pan radiograph in this region would result in excessive divergence of these roots. These findings are similar to those of Welander *et al*[33] and Philipp and Hurst[46] who found the largest amount of angle distortion in the canine and premolar region of both arches. The clinical relevance may mean that the use of panoramic radiographs to assess tooth angulation and root parallelism in the first premolar extraction case may be of dubious value. At the very least, a clear understanding of the panoramic unit's limitations in this area must be kept in mind.

Of particular interest were the trends observed between the four panoramic units. Despite the fact that different manufacturers utilize varying focal trough dimensions and beam projection angles, the machines appeared to systematically overestimate and underestimate true angulations in a similar manner. One-way ANOVA revealed equally poor representation of parallelism between the maxillary cuspid and first premolar and mandibular lateral incisor and canine for all four panoramic units.

This is the first study to utilize an orthodontic archwire as a reference plane for angular assessment of teeth. Previous investigators have chosen such reference planes as (1) the upper and lower margins of the film, (2) the palatal plane, (3) the occlusal plane, (4) the mandibular plane, (5) the ramal plane, (6) the inferior orbital plane, and (7) the articular eminences.[18,25,46,48] While the occlusal plane and the archwire plane would be anatomically similar, use of a radiopaque wire offers less subjectivity than determination of an occlusal plane. Furthermore, the close proximity of both the archwire segment and the tooth long axis to each other, and to the central plane of the image layer, would likely result in image projection with less distortion as opposed to a reference plane distant from the site of measurement. From a practical standpoint, use of an orthodontic archwire is a convenient reference plane in the angular assessment of teeth during orthodontic treatment. Provided the archwire does not have first and second order positioning bends, it can be left in place during panoramic imaging.

The possibility that aberrant head positioning or measurement error could have been responsible for true/image angle differences must be considered. However, great care was taken in the utilization of all machine guides for skull positioning. In addition, the skull positioning was repeated five times for each machine to establish a data set of five measurements for each tooth. Subjectivity of landmark identification on the scanned pantomography images was reduced by utilizing the center of the radiopaque steel ball for identification as well as a computer generated midpoint between adjacent teeth.

2.5 Conclusion

The following conclusions can be drawn from this study:

1. Statistically significant differences were noted for the majority (74%) of maxillary and mandibular image mesiodistal angulations as compared to the true mesiodistal angulations. The significant differences were reasonably evenly distributed amongst the four panoramic units.
2. A similar trend was noted between the four panoramic units in their overestimation and underestimation of tooth angulations.
3. For the maxilla, the image angle typically underestimated the central and lateral incisor and canine, while overestimating the premolars and first molar. The largest angular difference between adjacent teeth occurred between the canine and first premolar and created the illusion of increased divergence between these teeth.
4. For the mandible, almost all image angles underestimated the true angles with the canine and first premolar teeth being the most severely underestimated. The

largest angular difference between adjacent teeth occurred between the lateral incisor and canine.

5. The discrepancy between image angles and true angles were larger for mandibular teeth as compared to maxillary teeth.

6. Application of clinically significant tolerance limits of ±2.5° in the mesiodistal angulation of teeth to the reference archwire still resulted in the majority (61%) of maxillary and mandibular image angles being clinically significantly different from the true angle measurements.

7. The clinical assessment of mesiodistal tooth angulation with panoramic radiography should be approached with extreme caution with an understanding of the inherent image distortions.

Table 2.1 **Mean and standard deviation values for the true and image mesiodistal angulations by tooth number (in degrees)***

Tooth No.	TRUE ANGLES		IMAGE ANGLES (4 MACHINES)							
			OP 100		Cranex 3+		Orthophos		PM 2002 EC	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
16	92.4	1.2	96.9	1.0	93.1	0.3	92.9	1.1	96.3	1.2
15	93.3	0.4	98.7	0.7	95.4	1.1	93.9	1.6	96.5	1.5
14	94.6	0.3	98.9	0.5	95.8	1.1	93.4	1.4	97.6	1.2
13	99.2	0.2	96.7	0.6	94.6	1.3	92.5	0.4	96.7	2.2
12	95.0	0.2	92.8	1.0	90.3	1.4	88.8	0.9	91.2	0.9
11	91.9	0.4	90.1	0.5	90.3	0.5	87.7	0.6	90.2	1.1
21	94.1	0.6	92.8	1.1	91.2	0.7	91.4	0.6	91.8	0.7
22	95.4	0.2	93.6	0.6	90.5	1.3	89.7	0.6	91.3	1.1
23	93.3	0.9	92.6	1.1	90.5	1.0	88.6	1.4	92.0	1.2
24	92.6	0.2	99.0	0.7	94.7	1.1	93.4	2.0	96.7	2.2
25	90.5	0.5	93.2	0.4	90.6	0.6	88.9	1.0	91.4	1.3
26	89.6	0.1	94.6	0.9	91.9	0.9	90.5	1.1	93.8	1.2
36	89.2	0.2	85.4	0.8	87.7	0.2	86.8	2.1	85.9	0.9
35	91.9	0.3	87.6	0.8	88.5	0.3	88.8	2.2	86.8	1.3
34	92.6	0.3	85.9	0.8	87.6	1.0	88.8	3.0	84.3	1.3
33	92.2	0.4	83.3	1.2	85.9	0.6	86.0	2.7	80.3	2.2
32	91.1	0.1	87.0	3.0	90.2	0.8	88.6	2.2	82.2	1.2
31	91.5	0.3	89.6	2.5	91.6	1.8	91.1	0.6	88.0	1.7
41	91.7	0.2	95.2	1.8	93.7	1.0	93.6	0.7	93.0	2.3
42	91.3	0.2	91.4	1.2	91.4	1.2	90.1	1.6	87.1	2.1
43	94.5	0.3	88.0	0.8	89.5	0.8	89.7	2.1	85.0	2.4
44	94.2	0.3	87.2	0.6	87.2	1.1	89.1	2.1	85.9	1.4
45	94.2	0.2	88.8	0.8	91.1	0.4	92.2	2.5	88.3	1.0
46	89.2	0.4	86.2	0.7	88.6	0.8	87.9	1.1	85.8	0.7

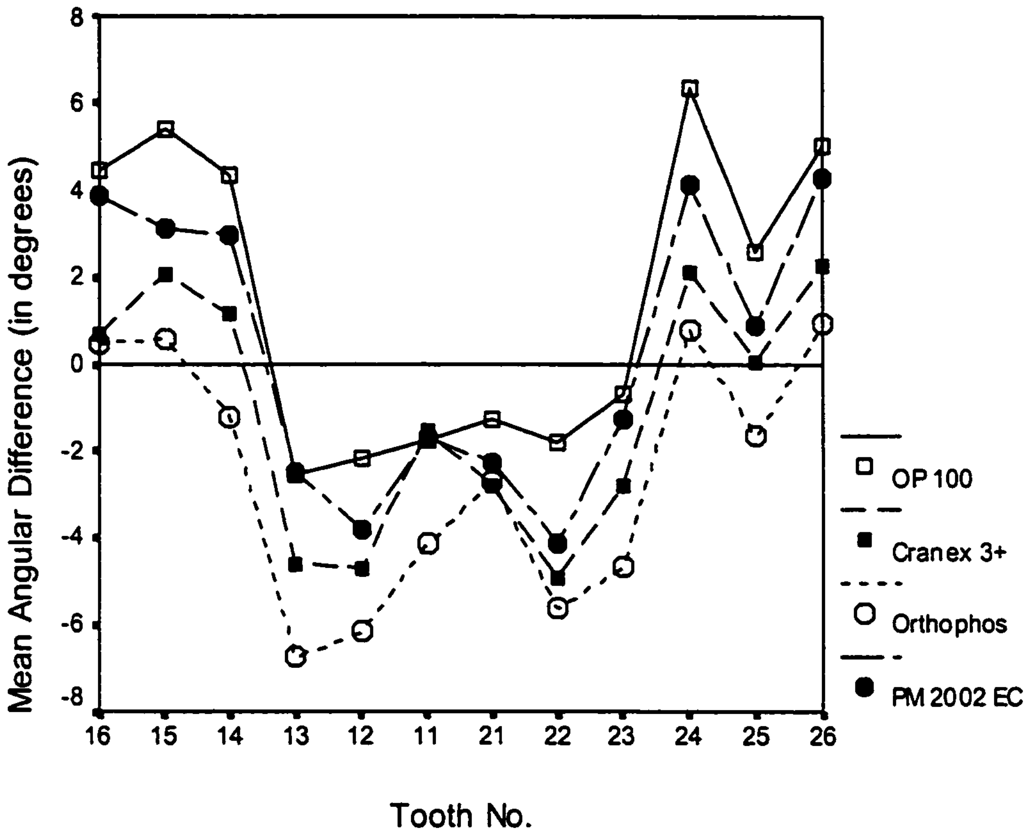
A mesiodistal angulation value *greater* than 90° indicates a distal inclination to the root:
A mesiodistal angulation value *less* than 90° indicates a mesial inclination to the root.
*** Based on 5 measurements for each panoramic machine, and 5 measurements for each true tooth angulation**

Table 2.2 One sample t-test comparisons of image vs. true mesiodistal angulations by tooth number (mean difference in degrees)**

Tooth No.	OP 100 vs. True		Cranex 3+ vs. True		Orthophos vs. True		PM 2002 EC vs. True	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
16	4.5	0.000*	0.7	0.009*	0.5	0.379	3.8	0.002*
15	5.4	0.000*	2.1	0.013*	0.6	0.467	3.1	0.010*
14	4.3	0.000*	1.1	0.083	-1.2	0.124	3.0	0.006*
13	-2.5	0.001*	-4.6	0.001*	-6.7	0.000*	-2.5	0.066
12	-2.2	0.008*	-4.7	0.002*	-6.2	0.000*	-3.8	0.001*
11	-1.7	0.002*	-1.6	0.003*	-4.2	0.000*	-1.7	0.030*
21	-1.3	0.053	-2.8	0.001*	-2.7	0.001*	-2.3	0.002*
22	-1.8	0.002*	-4.9	0.001*	-5.6	0.000*	-4.1	0.001*
23	-0.7	0.211	-2.8	0.003*	-4.7	0.002*	-1.2	0.074
24	6.3	0.000*	2.1	0.012*	0.8	0.419	4.1	0.015*
25	2.6	0.000*	0.1	0.830	-1.7	0.020*	0.9	0.190
26	5.0	0.000*	2.3	0.005*	0.9	0.137	4.3	0.001*
36	-3.9	0.000*	-1.5	0.000*	-2.4	0.063	-3.3	0.001*
35	-4.4	0.000*	-3.4	0.000*	-3.2	0.032*	-5.1	0.001*
34	-6.8	0.000*	-5.1	0.000*	-3.8	0.049*	-8.3	0.000*
33	-8.9	0.000*	-6.3	0.000*	-6.2	0.006*	-11.9	0.000*
32	-4.2	0.350	-1.0	0.050	-2.5	0.065	-8.9	0.000*
31	-1.8	0.182	0.1	0.878	-0.4	0.243	-3.4	0.011*
41	3.5	0.012*	2.0	0.012*	2.0	0.003*	1.4	0.261
42	0.1	0.823	0.1	0.806	-1.1	0.193	-4.2	0.011*
43	-6.5	0.000*	-5.0	0.000*	-4.8	0.007*	-9.5	0.001*
44	-7.0	0.000*	-6.9	0.000*	-5.1	0.005*	-8.2	0.000*
45	-5.4	0.000*	-3.1	0.000*	-2.1	0.140	-5.9	0.000*
46	-3.0	0.001*	-0.6	0.172	-1.3	0.062	-3.4	0.000*

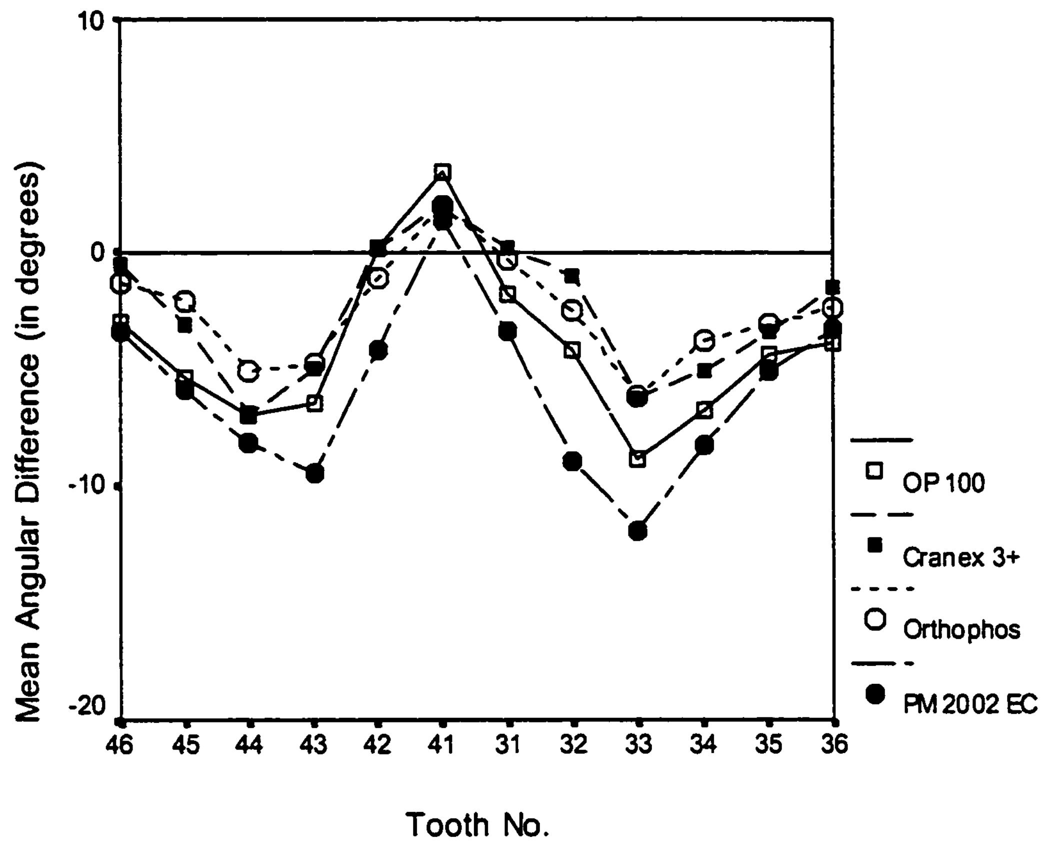
Mean difference = (image mesiodistal angle) – (true mesiodistal angle)
*** A P-value of less than .050 is considered statistically significant**
**** Based on 5 measurements for each panoramic machine, and 5 measurements for each true tooth angulation**

Figure 2.1 Mean angular difference of the image (four panoramic units) vs. true mesiodistal angulations for maxillary teeth by tooth number



Mean Angular Difference = (image mesiodistal angle) – (true mesiodistal angle)

Figure 2.2 Mean angular difference of the image (four panoramic units) vs. true mesiodistal angulations for mandibular teeth by tooth number



Mean Angular Difference = (image mesiodistal angle) – (true mesiodistal angle)

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Chapter Three

Paper #2

The Effect of Vertical and Horizontal Head Positioning in Panoramic Radiography on Mesiodistal Tooth Angulations

3.1 Introduction

Orthodontists critically evaluate crown and root position before, during, and after orthodontic treatment in the pursuit of excellence of the occlusal result. While this assessment if often performed clinically, panoramic radiography is frequently utilized to visualize root parallelism and mesiodistal tooth angulation.[1-3]

In his well known study, Andrews stated that normal occlusion is dependant, among other factors, on the correct mesiodistal inclination (or tip).[4] Other investigators have found that appropriate axial inclinations and root parallelism are important for proper occlusal and incisal function of the teeth, and are an important component in maintaining a stable treatment result.[1,5-10] This has special significance in the orthodontic extraction case where extraction sites are prone to open if roots are insufficiently paralleled.[5,7,10]

While panoramic radiography offers numerous diagnostic and prognostic uses in orthodontic diagnosis and treatment planning, the machinery produces images with variable magnification factors (both horizontal and vertical) resulting in angular distortion.[11] Various investigators have studied panoramic image generation in an attempt to quantify the dimensional accuracy of the images.[2,3,12-40]

Although convenient to take, the panoramic radiograph is extremely technique and operator sensitive. Schiff *et al* reported that the most frequent errors in panoramic radiography occurred in patient positioning.[22] In a study of 1000 panoramic films, the relative frequency of positioning errors were as follows: 14% chin too low, 4% head tilted, 4% head turned, and 1% chin too high.[22] The image layer is significantly narrower in the anterior region in conventional panoramic radiography, and blurring and distortion are least in the center of the image layer.[18,24,25,27,29,39] Failure to position the patient's dental arches accurately causes variation in both vertical and horizontal magnification, resulting in angular distortion of the image.[25] Investigations into the effect of vertical and horizontal rotation of a skull or testing device on angular measurements revealed that the canine/premolar region of both arches expressed the largest amount of distortion.[17,38] Xie *et al* assessed the accuracy of vertical measurements taken from panoramic radiographs.[40] They recommended selecting a horizontal reference line that is located anatomically directly above or below the point being measured, in the plane of the center of the image layer, rather than a reference plane distant from the site of measurement.[40]

Considering that the inherent dimensional inaccuracy of panoramic images is compounded by the variability of patient positioning, it seems reasonable to believe that the assessment of mesiodistal angulations of teeth cannot be reliably performed on panoramic films. The purpose of this study was to examine the effect of varying horizontal and vertical head rotation of an anatomic typodont/skull testing device on image mesiodistal angulations from the Orthopantomograph (OP 100), and compare these findings to the image mesiodistal angulations from an idealized head position.

3.2 Materials and Methods

3.2.1 Test Device Design

The test device consisted of a clear anatomic maxillary and mandibular typodont (Ormco Corporation, U.S.A.) with idealized occlusion from second molar to second molar (Appendix A). For each tooth, two chromium steel balls (Commercial Bearing, Edmonton, AB.) measuring 1.58mm in diameter were glued into position following preparation with a #2 round bur. The occlusal ball was placed in the buccolingual and mesiodistal midpoint of the crown on the occlusal/incisal surface while the placement of the apical ball into the root surface depended on the tooth being prepared. Excluding maxillary and mandibular first and second molars and maxillary first bicuspids, the apical ball was placed into the buccolingual and mesiodistal midpoint of the root in the apical third. For teeth displaying dilaceration in the apical third, the apical dilaceration was removed with a diamond disc to remove the effect of dilaceration on long axis determination. For the remaining teeth, the apical ball was placed in the center of the bifurcation/trifurcation. These steel balls would serve as reference markers for image angle determination and an imaginary line joining the center of the occlusal and apical balls would represent the long axis of each typodont tooth.

The maxillary and mandibular typodont was then bonded with .022 slot clear orthodontic brackets (Spirit, Ormco Corporation, U.S.A.) to idealized bracket positions and a passive .020 round stainless steel archwire (Permachrome resilient/Orthoform III, 3M-Unitek, U.S.A.) was ligated into position with elastomeric modules.

3.2.2 Typodont Positioning into Skull

A dried adult human skull with complete natural dentition and class I skeletal and dental relation served as the matrix into which the typodont dentition was fixed for subsequent panoramic imaging (Appendix E).

The glenoid fossa was remodeled with cold cure acrylic resin to provide positive seating of the condyle. This ensured reproducible mandibular opening/closing and a stable centric occlusion supported by both typodont tooth intercuspation and condyle/glenoid fossa fit. Chromium steel balls measuring 1.58mm in diameter were fixed to the skull at the following positions to confirm that the vertical, anterioposterior, and transverse position of the typodont dentition conformed to pre-established norms:

1. Nasion – the junction of the nasal and frontal bones at the most posterior point on the curvature of the bridge of the nose
2. Right and left anatomic porion – the most superior point of the external auditory canal (anatomic porion)
3. Pogonion – the most anterior point on the contour of the chin

The natural maxillary dentition, supporting bone, and portions of the skeletal maxilla were removed and the maxillary typodont dentition was temporarily wired into place with ligature wires. Multiple anthropometric, lateral and posterioranterior cephalometric measurements were made with subsequent movements of the maxillary typodont until the following position was obtained:

1. *Transverse* – bisection of the midpoint of the incisal steel balls on typodont teeth #11 and #21 with a line joining the steel balls placed at nasion and pogonion (measured on PA cephalometric image)
2. *Anterio-Posterior* – Nasion perpendicular to Frankfort Horizontal (PoOr) to upper incisor edge = 5mm* (measured on lateral cephalometric image)

   (* Modification of the McNamara analysis measurements calculated by adding the 14 year old norm for nasion perpendicular to Frankfort Horizontal to A-point (3.8mm) to the 14 year old norm for A-point parallel to nasion perpendicular to Frankfort Horizontal to facial surface of upper incisor (1.2mm); total distance nasion perpendicular to Frankfort Horizontal to facial surface of upper incisor=5mm)

3. Vertical

(a) Nasion to maxillary central incisor edge = 76 mm (linear distance measured on skull)

(b) Occlusal plane cant to Frankfort horizontal (PoOr) to occlusal plane = 9° (measured on lateral cephalometric image)

The maxillary typodont was then rigidly fixed to the skull.

The position of the mandibular typodont dentition in all three planes of space was determined by its centric occlusion articulation with the maxillary typodont. The dental relationship of the articulated typodont was a fully interdigitated class I molar and cuspid relation with 2mm overjet, 2mm overbite, and coincident dental midlines. The mandibular typodont dentition was firmly ligature tied to the maxillary typodont dentition and the natural mandibular dentition, supporting bone, and portions of the skeletal mandible were removed. The skeletal mandible was then rotated upwards (ensuring full seating of the condyle in the glenoid fossa) until the pre-existing vertical dimension of the skull was achieved (distance nasion to pogonion = 108 mm). The mandibular typodont was then rigidly fixed to the skeletal mandible and the intermaxillary ligature wires were released. Lateral and PA cephalometric analysis of the finalized movements revealed attainment of positioning goals and a remarkably 'normal' dental to skeletal and dental to dental relation as shown below:

1. Upper incisor to Frankfort Horizontal (PoOr) = 108°
2. Lower incisor to mandibular plane (GoMe) = 94°
3. Interincisal angle = 132°

3.2.3 Head Holder

A custom designed radiolucent head holder (Mechanical Engineering, University of Alberta) was constructed to ensure the validity of the horizontal and vertical head rotation about a reproducible axis of rotation (Appendix F). The head holder consisted of three components:

1. Hollow cyclinder - permanently attached to the exterior surface of the skull at foramen magnum
2. Solid cyclinder - precision machined end attached into hollow cyclinder and connected at its base via internal screw threads to the mounting screw on the camera tripod
3. Camera tripod - fully adjustable vertical and horizontal controls

3.2.4 Panoramic Radiographs

The skull and head holder assembly was positioned into an Orthopantomograph OP 100 (Instrumentarium, Munich, Germany) five separate times at *each* of the following five head positions and exposed:

1. *Ideal Position* - (0° horizontal rotation: 0° vertical rotation)
2. *5° Right* - (5° 'right' horizontal rotation: 0° vertical rotation)
3. *5° Left* - (5° 'left' horizontal rotation: 0° vertical rotation)
4. *5° Up* - (0° horizontal rotation: 5° 'head up' vertical rotation)
5. *5° Down* - (0° horizontal rotation: 5° 'head down' vertical rotation)

Optimum image density and contrast was achieved at exposure settings of 57 KVP, 2.0 mA, and 17.6 seconds. The object was to position the skull to simulate both the desired position of the patient's head in the panoramic unit, as well as to represent common patient positioning errors (Appendix G). For the idealized head position, Frankfort horizontal was aligned with the horizontal light guide, the midsagittal plane was aligned with the vertical light guide, and the incisal edges of the maxillary and mandibular incisors were placed into the notched bite block. For the horizontal (right and left) rotations, markings placed on the frontal bone of the skull at 5° 'right' and 5° 'left' assisted in alignment with the panoramic unit's vertical light guide, while keeping Frankfort horizontal aligned with the horizontal light guide. For the vertical (up and down) rotations, markings placed on the lateral surface of the skull at 5° 'head up' and 5° 'head down' assisted in alignment with the panoramic unit's horizontal light guide, while keeping the midsagittal plane aligned with the vertical light guide.

The combined head holder and tripod assembly ensured that the right and left rotation occurred about the center of foramen magnum (i.e. vertical axis of rotation) and that the up and down rotation occurred about the incisal edges of the maxillary and mandibular incisors and bite block assembly (i.e. horizontal axis of rotation).

3.2.5 Image Angle Determination

Custom designed software (Mechanical Engineering, University of Alberta) was utilized to calculate the mesiodistal angulation of the typodont teeth relative to the reference archwire from the twenty-five panoramic images (Appendix C). The radiographs were scanned with a resolution of 600 d.p.i. and magnification of 200% (Hewlett Packard Scan Jet 6100 C/T, HP Desk Scan II, Corel Photopaint 6.0) and digitized (Panoramic Angulator, Crusher Software) on a Dell Dimension XPS D433 PII

IBM compatible PC. The order of landmark identification was standardized for all radiographs and involved the following four points for each tooth angle determination:

1. $T^{C'}$ (tooth crown)-the center of the occlusal steel ball
2. $T^{R'}$(tooth root)-the center of the apical/furcal steel ball
3. $W^{D'}$(wire distal)-intersection of a computer generated vertical midpoint between adjacent teeth (on the distal side of the tooth being measured) and the image of the reference archwire
4. $W^{M'}$(wire mesial)- intersection of a computer generated vertical midpoint between adjacent teeth (on the mesial side of the tooth being measured) and the image of the reference archwire

Upon completion of digitization of each panoramic image, the program generated an Excel spreadsheet of the image mesiodistal angulation for the 24 teeth.

3.2.7 Error of the Method and Statistical Analysis

All typodont/skull modifications, skull positioning, and image angle measurements were undertaken by the principal investigator.

The total error of each image angle measurement was a combination of the error of measurement (i.e. digitization) and the error of repeated head positioning for each of the five head positions. To determine the error of digitization, one of the twenty-five images was randomly selected and each tooth was digitized five consecutive times. The error of digitization ranged from 0.45° to 0.86°. The average total error and standard deviation (SD) for each head positions' image angle measurements were as follows: ***ideal***

0.96° (0.57°), ***5° right*** 1.32° (1.03°), ***5° left*** 1.38° (0.97°), ***5° up*** 0.99° (0.47°), ***5° down*** 2.28° (3.05°).

Paired *t*-tests were completed for *each tooth* to detect angular differences between the idealized head position and *each* of the four head positions (5° right, 5° left, 5° up, and 5° down). Significance levels less than 5% were considered to be statistically significant.

3.3 Results

The mean and standard deviation values for the image mesiodistal angulations for all 24 teeth is presented in Table 3.1. Paired *t*-tests comparing the idealized head position individually to 5° right, 5° left, 5° up, and 5° down head positions is presented in Table 3.2.

The majority of maxillary and mandibular image angles (64%) from the four head positions were statistically significantly different from the idealized head position. Examination of Figure 3.1 and 3.2 revealed a common pattern between the varying head positions. For the maxillary teeth, 5° up and down head rotations had a much more pronounced effect on deviations from idealized head position than did 5° right and left head rotations. While 5° up resulted in a mesial projection of all maxillary roots (teeth[#] 11 and 21 remained unchanged), 5° head down resulted in a distal projection of all maxillary roots. The maxillary canine and first and second premolars displayed the most distortion and the maxillary central incisor the least distortion for the up and down head rotations. For the mandibular teeth, 5° right caused the anterior roots to incline to the right, thereby increasing the mesiodistal angulation of teeth[#] 41, 42, and 43 while decreasing the mesiodistal angulation of teeth# 31, 32, and 33. Similarly, 5° left caused the anterior roots to incline to the left, thereby increasing the mesiodistal angulation of teeth# 31 and 32 while decreasing the mesiodistal angulation of teeth# 41, 42, and 43. As mentioned previously, 5° up and down had less of an effect on mandibular root projection than did 5° right and left rotations.

Table 3.3 reports the total envelope of angulation error separately for horizontal head rotation and vertical head rotation. Horizontal head rotation had the greatest distorting effect on the mandibular anterior teeth with a perceived angular difference between 5° right and 5° left rotation of 4° to 22.3°. Vertical head rotation had the greatest distorting effect on the maxillary anterior and posterior teeth (excluding teeth #11 and #21) with a perceived angular difference between 5° up and 5° down rotation of 7.6° to 14.9°.

3.4 Discussion

Considering that one panoramic unit was utilized in this study, the results can only be applied to the Orthopantomograph OP 100. However, a companion study implementing four different panoramic units with the same testing device at a standardized head position revealed striking similarities and trends between panoramic units in their overestimation and underestimation of tooth angulations.[41] In addition, while the results can only be applied to the typodont tooth angulations represented, the skull/typodont testing device was reasonably anatomic in design. The arch form, arch dimensions, and positioning of the dentition within the skull could represent a clinical situation. While the true buccolingual angulations of the typodont were not determined, lateral cephalometric measurements of the upper and lower incisor angulations revealed positioning well within a range of normal.

This testing device is contrasted by previous studies utilizing non-anatomic tooth angulations with considerably less attention to jaw positioning within the panoramic unit's image layer.[2,17,38] Lucchesi *et al* used a plexiglass mandibular model with steel pins placed at mesiodistal angulations selected randomly but confined to a range of –20 to +20 degrees.[2] Three dimensional positioning of the model into the panoramic unit did not utilize a skull but rather placement within the unit's chin rest. Other investigators have relied on steel wire meshes to depict arch form and dimension.[17,38] The lead shot utilized to represent tooth angulations were usually orientated with total disregard for the unique mesiodistal and buccolingual inclinations represented in the human dentition

The results of this study revealed that most of the image angulations from the four aberrant head positions were statistically significantly different from the image angulations at the ideal head position. The application of clinically significant tolerance limits should be applied to this research. Previous investigators have reported that for clinical purposes, variations of as much as 2.5° (in either direction) between a tooth and an established reference plane does not constitute a serious objection to the use of the radiograph.[12,17,38] Application of these clinically significant tolerance limits revealed that 53% of the maxillary and mandibular image angles from the four head positions were still clinically significantly different from the image angles at ideal head position.

The relative sensitivity of the maxillary tooth angulations to up/down skull rotation and the mandibular tooth angulations to right/left rotation is difficult to explain. Horizontal head rotation alters the object/film and source/object distances resulting in varying degrees of horizontal and vertical magnification, and therefore angle distortion. Horizontal head rotation also alters beam projection angle. With the image layer being narrowest in the lower anterior dental region, it is possible that the mandibular anterior teeth are less tolerant to horizontal rotation.

The possibility that aberrant head positioning or measurement error could have been responsible for true/image angle differences must be considered. However, great care was taken in the utilization of all machine guides for skull positioning. Use of a custom designed head holder ensured the validity of the horizontal and vertical head rotation about a reproducible axis of rotation. In addition, the skull positioning was repeated five times for each machine to establish a data set of five measurements for each tooth. Subjectivity of landmark identification on the scanned pantomography images was reduced by utilizing the center of the radiopaque steel ball for identification as well as a computer generated midpoint between adjacent teeth.

The decision to select 5° vertical and horizontal head rotation was based on an attempt to be as clinically relevant as possible. It appeared from markings on the skull that this degree of aberrant head positioning in clinical practice would likely represent the upper limit of improper patient positioning by qualified personnel.

This is the first study to utilize an orthodontic archwire as a reference plane for angular assessment of teeth. Previous investigators have chosen such reference planes as the upper and lower margins of the film, the palatal plane, the occlusal plane, the mandibular plane, the ramal plane, the inferior orbital plane, and the articular eminences.[2,17,38,40] While the occlusal plane and archwire plane would be anatomically similar, use of a radiopaque wire offers less subjectivity than determination of an occlusal plane. Furthermore, the proximity of the reference archwire and tooth to each other, and to the plane of the image layer may result in less distortion than the use of a reference plane distant from the site of measurement. In a practical sense, use of an orthodontic archwire is very convenient in the angular assessment of teeth during orthodontic treatment as it can be left in place during panoramic imaging.

3.5 Conclusion

The following conclusions can be drawn from this study:

1. The majority of maxillary and mandibular image angles (64%) from the four head positions were statistically significantly different from the idealized head position.
2. Vertical head rotation (5° up and 5° down) had a much more pronounced effect on the deviation of maxillary angle projection. Conversely, horizontal head rotation (5° right and 5° left) had a much more pronounced effect on the deviation of mandibular anterior angle projection from truth.
3. Application of clinically significant tolerance limits of ±2.5° revealed that 53% of the maxillary and mandibular image angles from the four head positions were still clinically significantly different from the image angles at ideal head position.
4. The clinical assessment of mesiodistal tooth angulation with panoramic radiography should be approached with extreme caution with an understanding of the inherent image distortions that are further complicated by the potential for aberrant head positioning.

Table 3.1 Mean and standard deviation values for the image mesiodistal angulations by tooth number (in degrees)

Tooth No.	IMAGE ANGLES (5 HEAD POSITIONS)									
	Ideal Position		5° Right		5° Left		5° Up		5° Down	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
16	97.1	0.4	98.9	0.5	96.5	1.0	92.7	0.4	102.8	0.6
15	98.3	0.9	101.3	0.9	99.9	1.1	92.7	0.6	105.3	0.9
14	98.0	0.4	99.1	0.7	101.0	1.4	90.7	0.8	104.9	0.9
13	97.0	0.9	97.2	0.7	99.2	0.7	91.2	0.7	101.7	0.7
12	92.6	0.7	92.2	0.6	94.3	0.8	90.1	0.6	97.7	0.6
11	90.0	0.9	89.3	0.8	89.9	0.3	89.6	1.0	91.1	0.7
21	94.1	1.2	94.0	0.6	93.8	0.6	94.0	0.9	95.4	0.6
22	94.0	0.8	96.1	0.6	95.2	0.8	91.2	0.6	98.9	0.6
23	93.1	1.0	94.5	1.4	95.9	1.2	87.9	1.2	100.4	1.3
24	98.2	0.6	99.0	1.2	100.9	0.8	91.3	0.8	106.2	1.1
25	93.0	0.8	91.4	0.6	96.4	0.6	86.9	0.6	99.6	0.4
26	94.7	0.6	93.9	0.7	97.9	0.8	90.6	1.3	100.0	0.5
36	85.3	0.6	88.7	0.6	81.1	0.6	87.5	0.7	84.3	1.4
35	87.0	0.6	89.3	0.6	82.9	0.9	89.8	0.8	86.0	1.0
34	86.3	0.7	86.6	1.1	82.9	0.6	88.5	1.4	86.3	1.1
33	84.5	1.1	80.5	2.3	84.5	0.7	87.8	1.4	87.1	1.8
32	89.1	1.6	80.8	3.9	95.3	2.8	89.8	1.4	97.1	5.5
31	92.7	2.3	85.6	3.2	102.9	2.1	92.8	2.0	101.6	9.1
41	91.7	2.4	100.3	3.9	78.0	3.1	89.8	2.2	90.4	12.0
42	90.0	1.9	94.6	2.3	75.9	2.2	87.6	1.4	91.0	7.4
43	87.8	1.2	89.4	1.6	76.0	3.5	89.3	1.3	90.2	2.6
44	86.8	0.3	85.1	1.1	80.9	3.3	89.4	0.9	87.3	0.8
45	89.3	0.9	86.7	0.8	91.8	2.2	93.3	0.5	89.2	1.7
46	86.0	0.5	83.4	1.0	89.4	0.8	89.0	0.5	84.8	1.3

A mesiodistal angulation value *greater* than 90° indicates a distal inclination to the root.
A mesiodistal angulation value *less* than 90° indicates a mesial inclination to the root.

Table 3.2 Paired t-test comparisons of mesiodistal tooth angulations at varying vertical and horizontal head positions vs. idealized head position (mean difference in degrees)

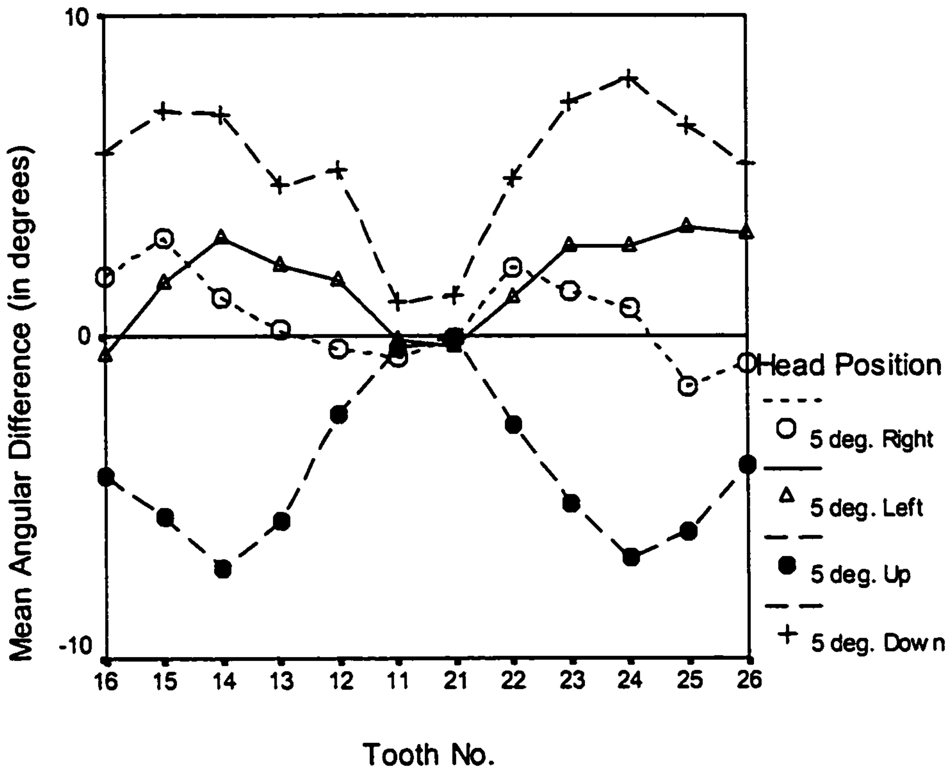
Tooth No.	5° Right vs. Ideal		5° Left vs. Ideal		5° Up vs. Ideal		5° Down vs. Ideal	
	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value	Mean Difference	P-value
16	1.9	0.000*	-0.6	0.191	-4.4	0.000*	5.7	0.000*
15	3.0	0.014*	1.6	0.090	-5.6	0.000*	7.0	0.000*
14	1.2	0.031*	3.0	0.004*	-7.2	0.000*	6.9	0.000*
13	0.2	0.736	2.2	0.023*	-5.8	0.000*	4.7	0.000*
12	-0.4	0.454	1.7	0.008*	-2.4	0.004*	5.2	0.000*
11	-0.7	0.372	-0.1	0.820	-0.4	0.372	1.0	0.168
21	-0.1	0.903	-0.4	0.617	-0.1	0.925	1.3	0.072
22	2.2	0.014*	1.2	0.088	-2.8	0.009*	4.9	0.000*
23	1.4	0.053	2.8	0.012*	-5.2	0.000*	7.3	0.001*
24	0.9	0.243	2.8	0.000*	-6.9	0.000*	8.0	0.000*
25	-1.6	0.014*	3.4	0.001*	-6.1	0.000*	6.6	0.000*
26	-0.8	0.038*	3.2	0.002*	-4.1	0.006*	5.3	0.000*
36	3.5	0.001*	-4.1	0.002*	2.2	0.002*	-0.9	0.069
35	2.3	0.005*	-4.1	0.000*	2.8	0.004*	-1.0	0.126
34	0.3	0.563	-3.4	0.002*	2.2	0.062	0.0	0.988
33	-4.0	0.005*	0.0	0.987	3.3	0.005*	2.6	0.068
32	-8.3	0.008*	6.2	0.006*	0.8	0.290	8.0	0.044*
31	-7.2	0.006*	10.2	0.000*	0.1	0.906	8.9	0.119
41	8.6	0.019*	-13.7	0.003*	-1.9	0.261	-1.3	0.798
42	4.6	0.042*	-14.1	0.001*	-2.4	0.122	1.0	0.725
43	1.6	0.208	-11.8	0.003*	1.5	0.198	2.4	0.035*
44	-1.7	0.013*	-5.9	0.016*	2.6	0.003*	0.4	0.383
45	-2.5	0.021*	2.6	0.054	4.1	0.001*	-0.1	0.958
46	-2.6	0.003*	3.4	0.003*	3.0	0.001*	-1.2	0.069

Mean difference = (deviated head position i.e. 5°R, 5°L, 5°Up, or 5°Down) – (idealized head position)
*** A P-value of less than .050 is considered statistically significant**

Table 3.3 Total envelope of error for combined horizontal (5° right/5°left) and combined vertical (5° up/5° down) head rotation (mean angular difference in degrees)

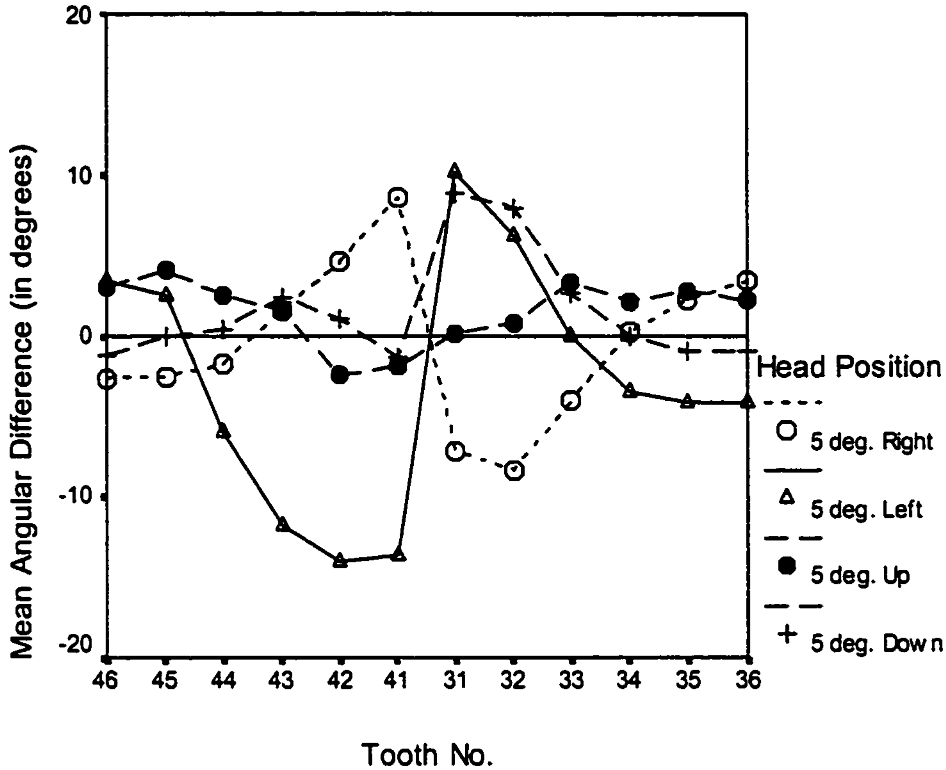
Tooth No.	Horizontal Head Rotation		Vertical Head Rotation	
	Mean Angular Difference	S.D.	Mean Angular Difference	S.D.
16	2.5	0.6	10.1	0.8
15	1.4	1.1	12.6	1.2
14	1.8	1.2	14.1	1.5
13	2.0	0.7	10.5	0.7
12	2.1	1.1	7.6	0.4
11	0.6	0.6	1.4	1.2
21	0.3	0.6	1.4	1.1
22	1.0	0.7	7.7	1.2
23	1.4	2.3	12.5	2.1
24	1.9	1.6	14.9	1.2
25	5.0	0.8	12.7	0.6
26	4.0	1.0	9.4	1.6
36	7.6	0.7	3.1	1.4
35	6.4	1.3	3.8	0.6
34	3.7	1.4	2.2	1.7
33	4.0	2.3	0.7	3.0
32	14.5	3.0	7.2	6.9
31	17.4	1.8	8.8	10.7
41	22.3	2.4	0.6	13.6
42	18.7	0.5	3.4	8.6
43	13.4	3.1	0.9	3.7
44	4.2	3.7	2.2	1.2
45	5.1	2.0	4.2	1.9
46	6.0	1.3	4.2	1.5

Figure 3.1 Mean angular difference of the image (four varying head positions) vs. image (idealized head position) mesiodistal angulations for maxillary teeth by tooth number



Mean Angular Difference = (image mesiodistal angle from the deviated head position i.e. 5° R, 5° L, 5° Up, or 5° Down) – (image mesodistal angle from idealized head position)

Figure 3.2 Mean angular difference of the image (four varying head positions) vs. image (idealized head position) mesiodistal angulations for mandibular teeth by tooth number



Mean Angular Difference = (image mesiodistal angle from the deviated head position i.e. 5°R, 5°L, 5°Up, or 5°Down) – (image mesodistal angle from idealized head position)

3.6 References

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Chapter Four

Discussion

And

Recommendations

4.1 General Discussion

One of the major objectives of orthodontic treatment is the correction of tooth positions in three planes of space.[1-5] The general arrangement of the dental arches and the inclinations of the individual teeth are interrelated in such a manner to allow the most efficient use of the forces of mastication, while at the same time providing stabilization and protection of the dental arches.[6] One of the keys to ideally positioned teeth, according to Andrews, was proper mesiodistal axial inclination (or tip).[3] Proper axial inclination and relative root parallelism are necessary to establish a correct alignment of the teeth within their respective apical bases, and a normal occlusion of the upper and lower teeth.[7] This often has special significance in the orthodontically closed extraction sites, which are more prone to open if adjacent teeth are not parallel.[8] Jarabak also found that poor root parallelism can result in tooth tipping, rotations, increasing overbite of anterior teeth, and the potential for periodontal injuries caused by thin interradicular cancellous bone.[9]

The use of panoramic radiography by orthodontists to assess root angulation and root parallelism before, during, and after orthodontic treatment is well established. This imaging procedure offers the advantage of broad anatomic coverage, a reasonably low patient radiation dose, and can be performed with relative convenience, ease, and speed.[10] However, the main disadvantage of panoramic radiography in the assessment of root angulation is the inability of the machinery to produce images that are dimensionally accurate.[10] While the panoramic image is a continuous image of the jaws, the successive shifts to changing centers of rotation introduces positional error in the mesiodistal angulation of teeth at certain segments of the jaws. Varying degrees of horizontal and vertical magnification and geometric distortion are inherent to image generation. Furthermore, it is imperative that the patient be positioned properly so that the dental arches are placed in the focal trough (or image layer) that has been predetermined by the manufacturer.[10] Therefore, all these factors taken together may limit the usefulness and interpretation of mesiodistal angulation and root parallelism on panoramic images.

Given the importance of mesiodistal tooth angulation to the orthodontic result and the frequent use of panoramic images to assess this dimension, there is a surprising paucity of studies that have evaluated this application of panoramic radiography. This presents an important clinical question to answer. Knowing the inherent limitations of the technology, to what extent can we rely on panoramic images in the assessment of mesiodistal angulation? Furthermore, what effect do different panoramic image generators and varying vertical and horizontal head positioning have on the projection of mesiodistal angulation?

The purpose of this study was two-fold. The first purpose was to compare the true mesiodistal tooth angulations of a constructed typodont/skull testing device to the image mesiodistal tooth angulations from four comtemporary panoramic units. The second purpose was to examine the effect of varying vertical and horizontal head positions of the testing device on image mesiodistal angulations from one panoramic unit, and compare these findings to the image mesiodistal angulation at idealized head position. It was hoped that this investigation would provide useful clinical guidelines and recommendations to assist the orthodontist in determining in what locations and to what extent panoramic radiography can be relied upon in their diagnostic evaluation of mesiodistal tooth angulation.

The true mesiodistal angulations of the typodont teeth were calculated using a Coordinate Measuring Machine (HGC Model, Starrett Corporation, U.S.A.). There is a report in the literature utilizing this machinery for the comparison of intermaxillary tooth size discrepancy among different malocclusion groups.[11] This machine is used extensively in the precision machine tool industry and utilizes frictionless air bearings and a touch trigger probe to record the X, Y, and Z coordinates with a reported linear accuracy of 0.0038mm (Appendix B).[12] Through the calculations of a custom designed computer program (Mechanical Engineering, University of Alberta), entry of the four digitized points per tooth generated the mesiodistal angulation of each typodont tooth relative to the reference archwire (Appendix C). A pilot project verified the accuracy of the machinery to within 0.04° and the reproducibility ranged from 0.24° to 0.46°(Appendix D). The Coordinate Measuring Machine featured a manual indexable probe head that permitted the required orientations of the probe to gain access to the digitized points. Each series of tooth measurements (for all 24 teeth) were recorded on five separate occasions to allow determination of an error of measurement and provide a data set for comparison with the image mesiodistal angulations.

The main objective of typodont positioning into the human skull was to create a clinically relevant testing device (Appendix E). While great care was taken to position the typodont in all three planes to conform to cephalometric normals, the primary goal was to create a tooth setup that was aligned to the midsagittal plane with an occlusal plane cant and incisal angulations that were reasonably 'normal'. While the bite block of the panoramic unit determines the anterioposterior and vertical positioning of the typodont dentition, abnormal occlusal plane cants or incisal angulations would likely impact on the image angular measurements.

Skull positioning for panoramic imaging utilized each manufacturers unique positioning guides. However the positioning goals were the same for each unit and consisted of centering the skull to the midsagittal plane, with Frankfort horizontal parallel to the floor, and the upper and lower incisors placed into the notched bite block. Markings placed on the lateral and frontal aspects of the skull assisted in alignment with the positioning lights and therefore it could be argued that skull positioning was likely more accurate than patient positioning would be in a clinical setting. For the varying vertical and horizontal skull positioning, the custom Plexiglas head holder/tripod assembly was utilized to ensure the validity of the axis of skull rotation (Appendix F).

Exposure settings and processing conditions for the four panoramic units could not be standardized. One panoramic unit featured fully customized KVP, mA and time settings allowing exposure without beam attenuation. The three other units permitted some customization but required lead shield beam attenuation to provide images of sufficient density and contrast. Test exposures were made on each unit until images of optimum quality were achieved. It is unlikely that differences in image density and contrast accounted for angular measurement differences. The subjectivity of landmark identification on the scanned images was reduced by utilizing the center of the radiopaque steel balls for digitization of the tooth long axis, while the intersection of the reference archwire with a computer generated midpoint between adjacent teeth provided the horizontal reference plane. Had more subjective landmarks been chosen, such as occlusal plane or tooth long axis determination via root canal visualization, then measurement error would likely have increased.

The results of this study revealed that panoramic radiography should be used with extreme caution in the evaluation of mesiodistal tooth angulation. The first part of the study found that 74% of the image angles from the four panoramic units were statistically significantly different from the true angle measurements. Application of clinically significant tolerance limits, as suggested by previous researchers[13-15], found that 61% of image angles were still clinically significantly different from the true angle measurements. Equally interesting were the similarities between the four units in their overestimation and underestimation of tooth angulations. The projection of the maxillary anterior roots more mesially and the posterior roots more distally resulted in the appearance of more root divergence in the canine and first premolar region than was present in the typodont. The mandibular roots were almost all projected more mesially with the canine and first premolars displaying the greatest deviation from true angulation. The largest angular difference between adjacent teeth occurred between the mandibular lateral incisor and canine, with relative root parallelism being projected as root convergence. These findings are in agreement with those of Welander *et al*[16] and Philipp and Hurst[15] who found the largest amount of angle distortion in the canine and premolar region of both arches. Since many extractions for orthodontic purposes are performed in the first premolar region, the use of panoramic radiographs to assess root angulations of teeth in this region following root paralleling must involve an understanding of these limitations.

The second part of this study examined the effect of four different head positions (5° right, 5° left, 5° up, 5° down) on image angle determination and compared these results to the image angles from ideal head position for the OP 100. It was found that 5° 'head up' caused a mesial projection of all maxillary roots (teeth# 11 and 21 remained unchanged) while 5° 'head down' caused a distal projection of all maxillary roots. Horizontal rotation (5° right and left) had very little effect on maxillary root projection. For the mandibular teeth, 5° 'right' caused the anterior roots to incline to the right, thereby increasing the mesiodistal angulation of teeth# 41, 42, and 43 while decreasing the mesiodistal angulation of teeth# 31, 32, and 33. Similarly, 5° 'left' caused the anterior roots to incline to the left, thereby increasing the mesiodistal angulation of teeth# 31 and 32 while decreasing the mesiodistal angulation of teeth# 41, 42, and 43. Vertical rotation (5° up and down) had less of an effect on mandibular root projection.

It is important to note that the results of this study can only be applied to the typodont testing device and panoramic models employed. While every attempt was made to create an anatomic tooth bearing testing device with clinically reasonable tooth angulations, variations in the dimensions of the jaws and mesiodistal and buccolingual inclinations of individual teeth could influence the angular projection on the image. However, understanding this limitation, this was the first study to construct a testing device that was based on anatomical principles of the dentition. Lucchesi *et al*[17] utilized a Plexiglas block mandibular phantom with steel pins placed in a straight line to represent the tooth angulations of the canine to second molar. Pin mesiodistal angulation values were selected with computer generated random numbers confined to a range of –20° to +20°. Samawi and Burke[14] used a wire mesh frame shaped to represent the curvature of the dentition in the jaws with lead shot to represent the long axes of the teeth. The actual angular relationship of the teeth was not reproduced but instead kept parallel both in the mesiodistal plane and buccolingual plane. These previous studies utilized non-anatomic testing devices with tooth angulations oriented with total disregard for the unique mesiodistal and buccolingual inclination represented in the human dentition. While the true buccolingual inclinations of the typodont used in this study were not determined, visually they conformed to a very realistic tooth set-up. In addition, confirming lateral cephalometric images of the typodont/skull position revealed a remarkably normal interincisal angle, upper incisor to Frankfort horizontal angle, and lower incisor to mandibular plane angle.

Of particular interest were the trends observed between the four panoramic units in the first part of this study. Despite the fact that different manufacturers utilize varying focal trough dimensions and beam projection angles, the machines appeared to systematically overestimate and underestimate true angulations in a similar manner. The poor representation of parallelism between the maxillary cuspid and first premolar and the large underestimation of the true mesiodistal angulations of the mandibular cuspid and first premolar were shortcomings of all four panoramic units.

This is the first study to utilize an orthodontic archwire as a reference plane for angular measurements. Previous investigators have selected such reference planes as upper and lower margin of the film, the palatal plane, the occlusal plane, the mandibular plane, the ramal plane, the inferior orbital plane, and the articular eminences.[14,15,17,18] An orthodontic archwire offers a uniquely convenient method of angular measurement during orthodontic treatment and offers less subjectivity than determination of an occlusal plane due to its radiopacity. Concerns that the archwire may be located too buccal to the central plane of the image layer and therefore undergo significant distortion are warranted. However focal trough dimension studies indicate that the sharply depicted layer is sufficiently wide to provide a reasonably sharp portrayal of the anatomy.[16,18-20] In addition, Welander *et al*[16] concluded that angular distortion becomes successively small when the object inclination decreases or increases from 45°, being nonexistent at 0° and 90°. Seeing that the orthodontic archwire is essentially orientated horizontally, it would appear that the degree of distortion would be minimal. Finally, the fact that the archwire and the tooth being measured are in close proximity, it is believed that the two will undergo distortion of a similar magnitude rendering any angular measurement still valid.

4.2 Recommendations for Future Studies

While this study examined the effect of image projection from four panoramic units at an idealized head position, only one panoramic unit (Orthopantomograph OP 100) was utilized for examining the effect of varying horizontal and vertical head position on image angle determination. The focus of this investigation could be expanded to include all four head position (i.e. 5° right, 5° left, 5° up, and 5° down) on all four panoramic units. This would clarify whether the same trends found between machines at an idealized head position also occurred at varying head positions.

This investigation could also be expanded to include more varied degrees of horizontal and vertical head rotation in addition to replicating other common patient positioning errors. Positioning errors such as transverse bodily shift, anterioposterior bodily shift, and lateral tilt could be examined with the existing typodont/skull testing device and custom designed head holder. These image angulations could then be compared to both true angle measurements and to the results from other panoramic units at the same head positions.

Other avenues of investigation could involve manipulation of the *true* mesiodistal and/or buccolingual tooth angulations in the typodont testing device with subsequent imaging at the ideal head position. This would provide valuable information that this study could not produce due to the limitations imposed by a single testing apparatus. The results of this study could also be compared to the image angulations from plane-film techniques (i.e. periapical films), the other conventional means of assessing root angulation. Plane-film radiography would be expected to be more suited to accurate measurements of the mesiodistal tooth angulation because the object-film distance is minimized. However, such issues as the exposure dosage of multiple plane-film techniques would need to be taken into consideration in a clinical setting.

4.3 References

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Appendices

Appendix A
Typodont Testing Device

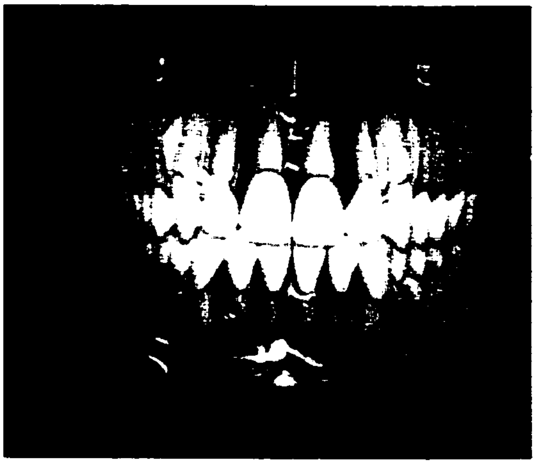


Figure A.1 Typodont (frontal view)

Figure A.2 Typodont (lateral view)

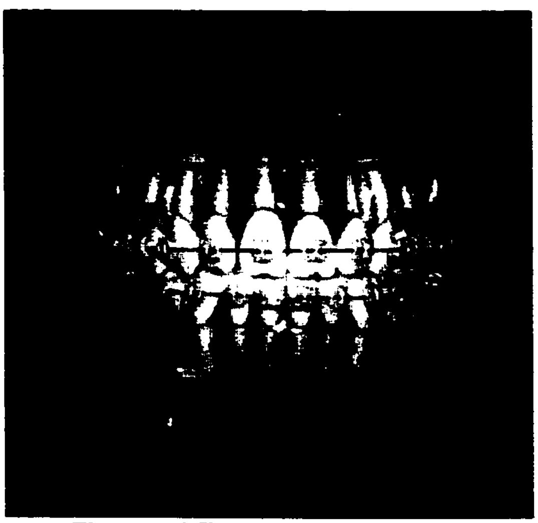
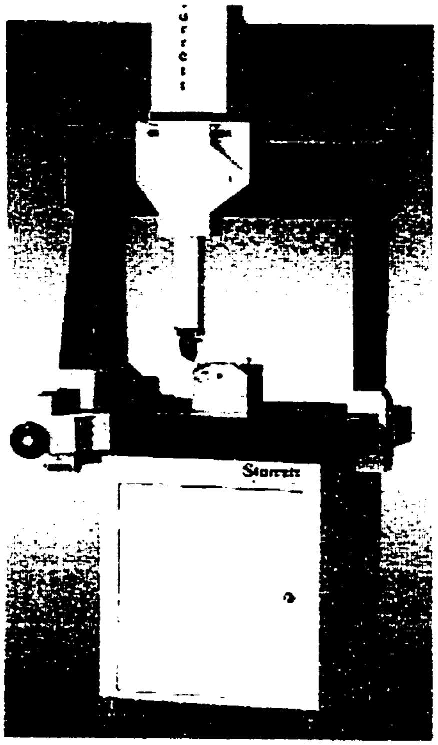


Figure A.3 Typodont (frontal view)

Figure A.4 Typodont (lateral view)

Appendix B
Coordinate Measuring Machine (Actual Angle Determination)



HGC Manual Model.

Figure B.1 Coordinate Measuring Machine (C.M.M.)

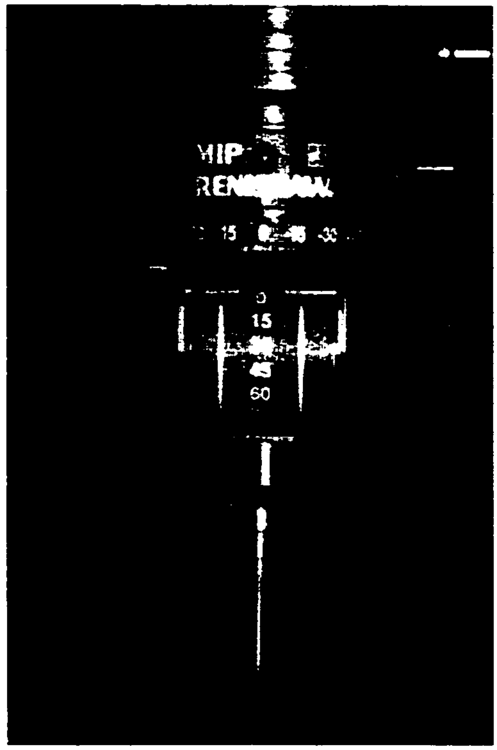


Figure B.2 Manual indexable probe head

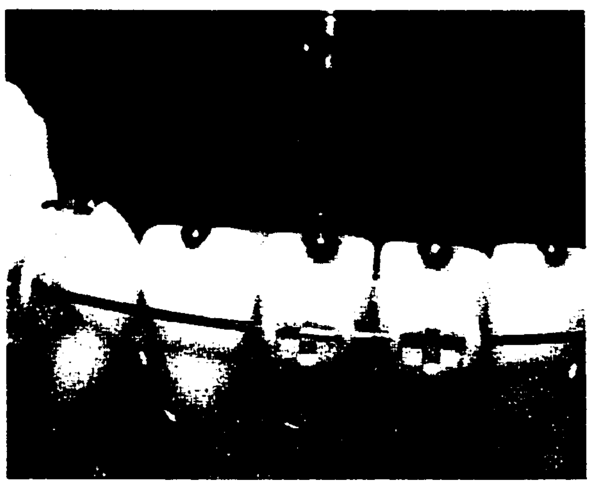


Figure B.3 Digitization of chromium steel balls (pilot project)

Appendix C
Mathematical Design (True and Image Angle Determination)

The purpose of the mathematical design was to determine the angle formed by two lines in 3 dimensional space and compare this angle to the same angular measure when the two lines are projected onto radiographic film.

Figure 1 shows a schematic of the problem, representing two teeth and an archwire that are projected onto a radiograph (i.e. image angle determination). Determining the β angles on the radiograph is fairly straightforward; a tooth long axis is formed by the a and b points of teeth 21 and 22 and an archwire approximating line is formed by joining successive computer generated midpoints between adjacent teeth (points i, ii and iii). The angle of each tooth axis line with respect to the archwire approximating line segment can be calculated using simple geometry.

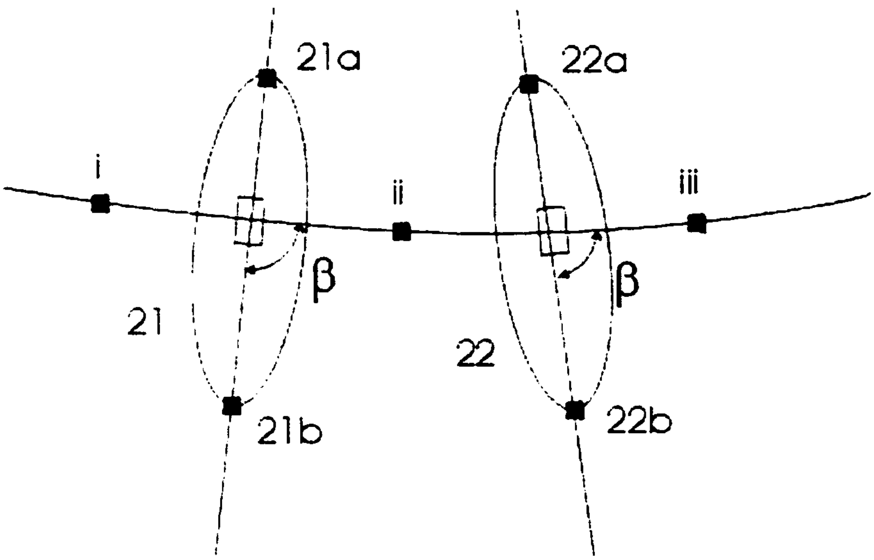


Figure C.1

Defining the β angles for the 3 dimensional case (i.e. true angle determination) is illustrated by considering both Figures 1 and 2. The front view of Figure 1 shows the archwire and the tooth axis points. Figure 2 shows the situation from the side of one of the teeth. Again, successive points on the archwire forms an approximation to the section of archwire contacting each tooth to be measured. The tooth long axis line is similarly formed – in this case points 21a and 21b form the line, which is, inclined at angle ϕ with respect to vertical.

The angle that we wish to measure is the angle β of Figure 1, projected onto a plane representing the 'face' of the tooth. Since two lines can be used to define a unique plane, the tooth axis line and the archwire line will be used to define a 'face' plane. Stipulating that the tooth axis line lies in the plane and the archwire line is parallel to the plane forms the plane. This constructed plane contains the tooth axis line (which is assumed parallel to an edge of the tooth bracket) and is parallel to the archwire line at the point of contact between archwire and bracket. The angle β is then defined as the line angle between the long axis line and the archwire line when it's projected back onto the constructed plane. Fortunately this angle can be easily measured using a vector operation known as the dot product.

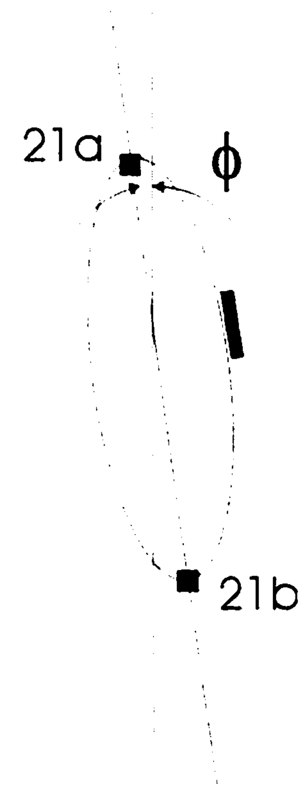


Figure C.2

The dot product computes the amount that one vector 'overlaps' another when the two vectors are placed tail to tail. Figure 3 shows a planar example of the dot product of two vectors, where the quantity 'length' represents the dot product:

$length = A \bullet B = A.x * B.x + A.y * B.y + A.z * B.z$

of vectors *A* and *B*. The vector A is translated in space to location A' so that it's tail is coincident with the tail of B. The dot product is the amount that A' projects onto B in this configuration.

The dot product has the useful property that the angle between the two vectors can be written as:

$$\phi = \cos^{-1}\left(\frac{A \bullet B}{\|A\| \times \|B\|}\right).$$

For the true angle determination (i.e. three-dimensional case) the end points of A (the tooth long axis) and B (the archwire approximating line) are fully specified using the coordinate measuring machine. For the image angle determination (i.e. two-dimensional planar case) the end points are digitized from the radiograph, therefore the z-components of the points have zero value. In either case the formula for computing the angle between the two vectors is the same.

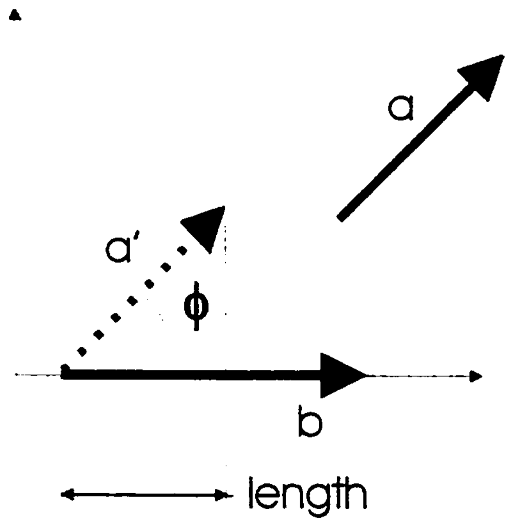


Figure C.3

Mathematical theory and custom software design by Kent West (Mechanical Engineering, University of Alberta)

Appendix D

Pilot Project Data (Accuracy and Reproducibility Studies of the Coordinate Measuring Machine)

Table D.1 Raw data (in m.m.) and angle calculation (in degrees) for the accuracy determination for the coordinate measuring machine using a right-angle test device

Trial No.	Point #1			Point #2			Point #3			Point #4			Angle (degrees)
	x	y	z	x	y	z	x	y	z	x	y	z	
1	176.012	34.729	2.878	176.161	68.323	4.253	178.868	73.363	0.110	205.412	73.205	0.142	90.083
2	175.970	27.667	4.011	176.151	66.642	4.371	178.900	73.342	-0.042	216.486	73.140	-0.161	90.043
3	186.170	4.366	67.520	182.224	43.792	67.350	185.307	49.956	63.948	217.315	53.126	63.933	90.059
4	167.800	27.995	64.009	162.760	77.547	63.554	166.942	87.971	67.754	202.704	91.609	68.141	90.004
5	139.181	48.890	63.929	133.910	101.078	62.926	168.875	88.199	68.545	187.373	90.071	68.725	90.001

Table D.2 Mean and standard deviation for coordinate measuring machine accuracy determination

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
ANGLE	5	.08200	90.00138	90.08338	90.03810	3.55E-02	1.261E-03
Valid N (listwise)	5						

Table D.3 Mean and standard deviation for coordinate measuring machine reproducibility determination

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
ANGLE#41	5	1.26441	92.65533	93.91974	93.38884	.4634490	.215
ANGLE#33	5	.58010	93.82990	94.41000	94.15164	.2434240	5.926E-02
ANGLE#35	5	.90709	91.83379	92.74088	92.36834	.3469330	.120
Valid N (listwise)	5						

Mean = angle (in degrees) formed between reference arch wire and tooth long axis
Measurements carried out on pilot typodont on mandibular left cusid and second bicuspid and mandiublar right central incisor.

Appendix E
Typodont/Skull Testing Device

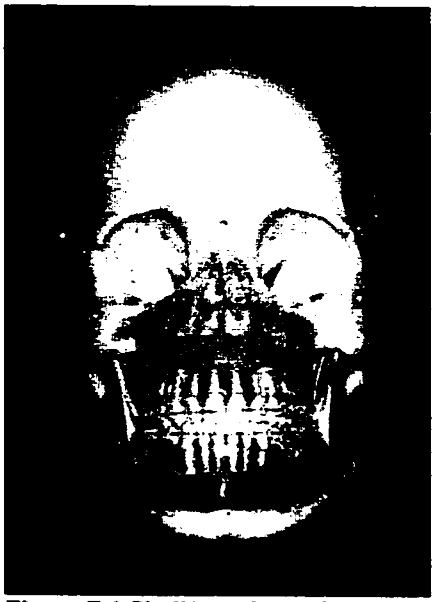


Figure E.1 Skull/typodont (frontal view)

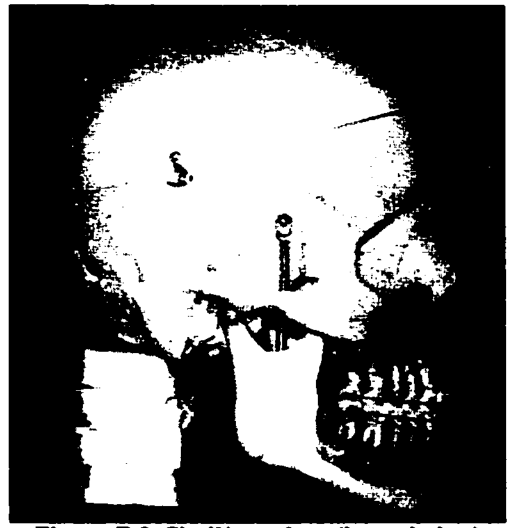


Figure E.2 Skull/typodont (lateral view)

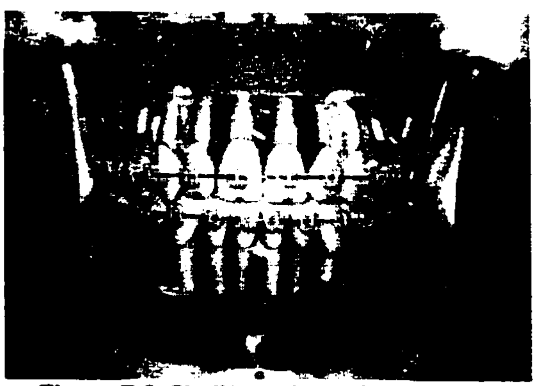


Figure E.3 Skull/typodont (frontal view)

Figure E.4 Glenoid fossa reconstruction

Appendix F
Head Holder for Panoramic Imaging

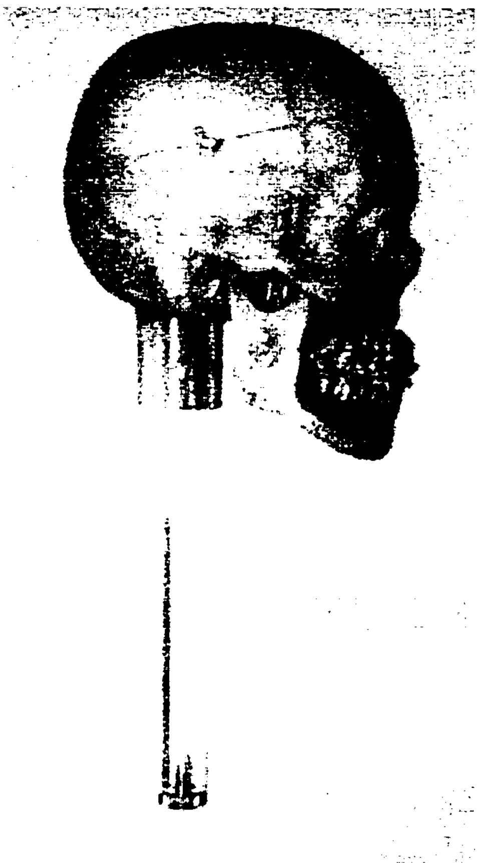


Figure F.1 Skull and head holder

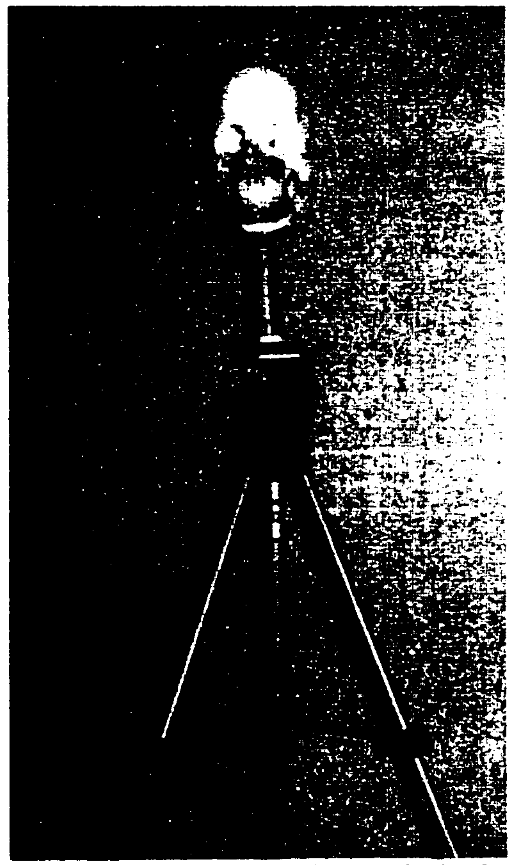


Figure F.2 Skull, head holder, and tripod

Appendix G
Panoramic Images at each of the Five Head Positions

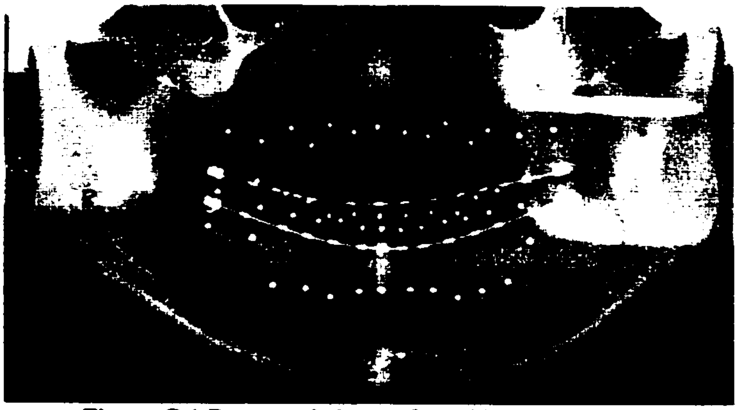


Figure G.1 Panoramic image from ideal head position

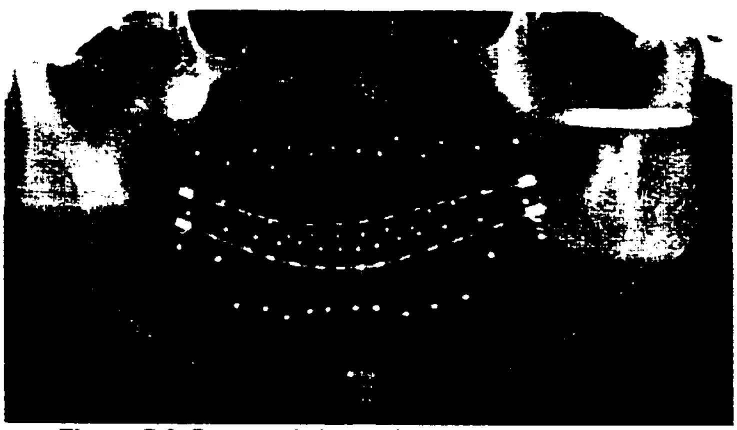


Figure G.2 Panoramic image from head position 5° right

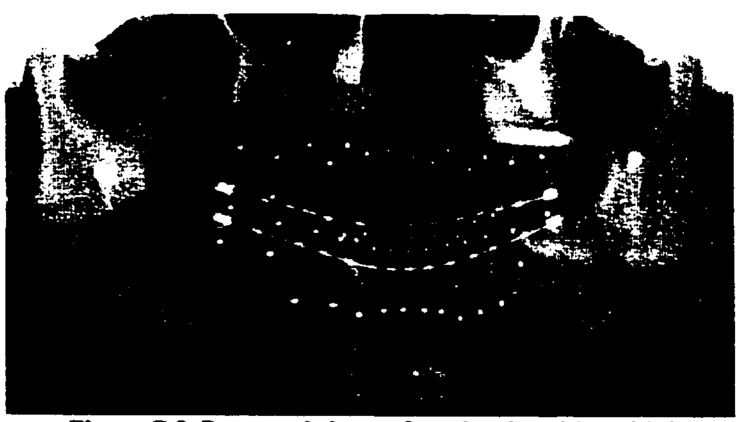


Figure G.3 Panoramic image from head position 5° left

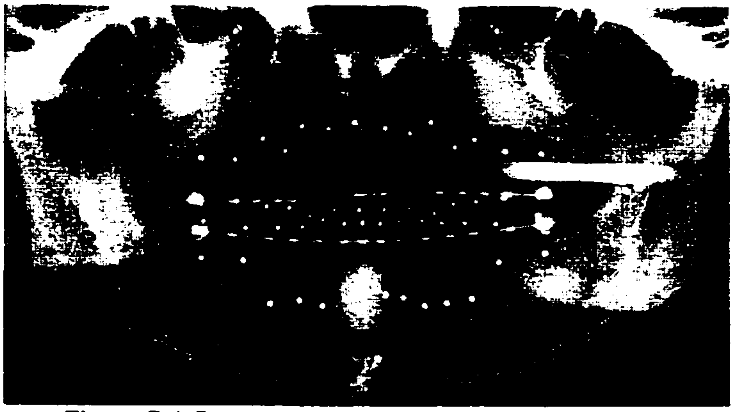


Figure G.4 Panoramic image from head position 5° up

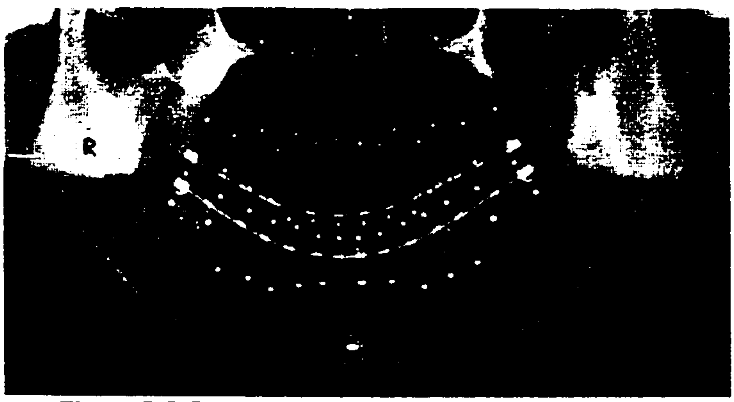


Figure G.5 Panoramic image from head position 5° down