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University of Alberta

The Effect of Bucco-lingual Root Angulation on the Mesio-distal Image Perception for Panoramic Images

by

Mariano García-Figueroa ©

A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfillment of the requirements for the degree of

Master of Science

in

Orthodontics

Department of Dentistry

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Dedication

A mi esposa Carolina, por su amor, apoyo y comprensión durante toda esta aventura.

Porque se que a ciencia cierta puedo contar contigo, en las buenas y las malas.

A mi familia, por su incondicional ayuda y cariño. Gracias por haber forjado los valores que me han guiado en la vida.

To my friends in Edmonton

A Dios...por todo.

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Abstract

The purpose of this study was to asses the effect of buccolingual root orientation on the perception of mesiodistal root angulation and parallelism for panoramic images. A phantom was constructed so that the tooth buccolingual orientation of eight different teeth could be easily modified. The true mesiodistal and buccolingual tooth angulations relative to an orthodontic archwire were calculated with a tri-dimensional coordinate measuring machine. The panoramic films were scanned and digitized with custom-designed software to determine the image mesiodistal angulations. The results of this study revealed that almost all the image angles for each tooth had at least one angle measurement that was statistically different from the other mesiodistal angles with different buccolingual orientations. The roots with buccal root orientations were projected more distally than they were in reality and roots lingually positioned were projected more mesially. This phenomenon was more pronounced in the maxilla than the mandible. The largest root parallelism differences for adjacent teeth occurred between the upper canine and first premolar followed by the mandibular canine/premolar area. Bucco-lingual orientation changes do not seem to affect the root parallelism expression on the incisor area.

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Table of Contents

Chapter One – Introduction and Literature Review **Page No.**

1.1 Statement of the problem 2

1.2 Significance of the Study 4

1.3 Research Questions 4

1.4 Null Hypothesis 5

1.5 Glossary 6

1.6 Literature Review 7

1.6.1 Axial Tooth Inclination 7

1.6.1.a The importance and description of tooth axial inclinations 7

1.6.1.b Factors influencing orthodontically generated bucco-lingual angulations 12

1.6.2 Panoramic Radiography 15

1.6.2.a Indications and contraindications 15

1.6.2.b Principles of image acquisition 16

1.6.2.c The focal trough 17

1.6.2.d The Projection angle 21

1.6.2.e Magnification and Distortion 23

Figure 1.1 31

Figure 1.2 32

Figure 1.3 33

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Table of Contents(continued)

Chapter one (cont.)– Introduction and Literature Review	Page No.
Figure 1.4	34
Figure 1.5	34
Figure 1.6	35
Figure 1.7	35
1.7 References	36

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Table of Contents(continued)

Chapter Two – Research Paper		Page No.
2.1	Introduction	42
2.2	Materials and Methods	46
	2.2.1 Phantom Design	47
	2.2.2 Actual Angle Determination	49
	2.2.3 Panoramic Imaging	51
	2.2.4 Image Angle Determination	52
2.3	Statistical Analysis	54
2.4	Results	55
2.5	Discussion	58
2.6	Conclusions	66
	Table 2.1	68
	Table 2.2	69
	Table 2.3	71
	Figure 2.1	71
	Table 2.5	72
	Figure 2.2	73
2.7	References	74

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Table of Contents

Chapter Three – General Discussion **Page No.**

3.1 Importance and Control of Buccolingual Tooth Inclinations 78

3.2 Panoramic radiography and Buccolingual angulation 81

3.3 Recommendations and Limitations 91

3.4 References 94

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List of Tables

Table #	Title	Page No.
Table 2.1	Buccolingual angulations settings	67
Table 2.2	Mean and standard deviations for phantom teeth angulations	68
Table 2.3	Mean and standard deviations for image mesio-distal angulations including mean differences for pairwise comparisons.	69
Table 2.4	Mean angular differences among delta angles.	71

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List of Figures

Figure #	Title	Page No.
Figure 1.1	Terminology of tooth orientations	34
Figure 1.2	Root angulations for maxillary teeth	35
Figure 1.3	Root angulations for mandibular teeth	36
Figure 1.4	Panoramic radiograph	37
Figure 1.5	Types of Panoramic radiograph	37
Figure 1.6	Focal Trough	38
Figure 1.7	Beam angulation	38
Figure 2.1	Image mesio-distal angulations according to bucco-lingual angulation by tooth number	70
Figure 2.2	Mean delta angulation differences.	72

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List of Appendices

Appendix A: Picture of Typodont Testing Device 98

Appendix B: Picture of Typodont Buccolingual Angulation changes 99

Appendix C: Picture of Coordinate Measuring Machine 100

Appendix D: Mathematical Models 101

1. True and image mesio-distal angle determination 101

2. Buccolingual angle determination 104

3. Root parallelism determination 106

Appendix E: Delta Angles 107

Appendix F: Sample size calculation 107

Appendix G: Picture of Mesiodistal image expressions at different buccolingual angulations 108

Appendix H: Intraclass coefficient correlation table for determination of intrarater reliability 109

Appendix I: T-test tables for differences between true and image angulations 110

Appendix J Mean and standard deviations for delta angles 112

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Chapter 1

Introduction

and

Literature Review

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Olvídate del mundo.
Piensa solamente en lo que llevas piel adentro
y sabrás qué dulce y qué sabroso es, de pronto, vivir.

Jorge de Bravo

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1.1 Statement of the Problem

Orthodontists use 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. Achieving root parallelism is critical to obtain correct alignment of the teeth, a normal occlusion of the upper and lower teeth and in maintaining a stable orthodontic result [1]. The American Board of Orthodontics recommends using panoramic x-rays to assess root inclination and parallelism as a means to evaluate the adequacy of the orthodontic finishing [2].

A number of investigators have examined the relationship between tooth position and angular distortion in panoramic radiographs. It has been confirmed that panoramic films have limitations when assessing the angulations of tooth inclination due to magnification and geometric distortion inherent to image generation. These studies showed significant differences for the majority of maxillary and mandibular mesio-distal angulations represented on these images, as compared with the actual mesio-distal angulations[3-7]. Although many studies have been done to evaluate distortion of mesio-distal root angulations, few studies found in the literature have assessed the effect of buccal-lingual root angulations on the perception of mesio-distal angulations for panoramic x-ray projections [4, 7, 8].

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The resultant image on a panoramic radiograph is a two-dimensional representation of a three-dimensional object. Evident overlapping of the teeth occurs normally, making interpretation of dental pathologies cumbersome. This radiographic phenomenon is associated with the deviation between the projection angle of the beam and the interproximal surfaces between the teeth in the dental arch. Since the projection of the jaws is not truly orthogonal to the average arch form, the successive shifts of changing centers of rotation and angulations of the x-ray beam may introduce erroneous expressions of tooth angulations on the radiograph. The depicted mesio-distal representation of a tooth on the film might in fact correspond to the combined expression of both its bucco-lingual and mesiodistal angulation. Thus, it seems reasonable to believe that bucco-lingual angulations may have an influence on the perception of mesio-distal tooth inclinations and root parallelism on panoramic radiographs.

This research will be directed to assess the validity of panoramic radiographic projections with regards to mesio-distal axial inclination expression given different bucco-lingual root angulations. The validity of this radiographic technique will be tested using a phantom with various buccal-lingual root angulations to assess whether or not this variable has a bearing on the assessment validity of mesio-distal root angulations.

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1.2 Significance of the Study

The results of this study will provide clinical guidelines to the practitioner as to what to expect and at what locations bucco-lingual angulations should be taken into consideration when assessing mesiodistal root angulations on panoramic images. Previous investigations have not used anatomical models and realistic tooth angulations to assess angular distortion with different buccal-lingual axial root inclinations. This study directly tests the validity of pantomography using an anatomic arch form with clinically achievable and realistic tooth angulations.

1.3 Research Questions

1. Do the mesio-distal tooth angulations on a panoramic radiograph of a phantom significantly differ when the bucco-lingual angulations are altered and the mesio-distal angulations are fixed?
2. Does root parallelism from adjacent teeth of a typodont/skull apparatus significantly differ when the bucco-lingual angulations are altered and the mesio-distal angulations are fixed?

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1.4 Null Hypothesis

1. There is no difference between the mesiodistal tooth angulations from a panoramic radiograph of a phantom when the buccolingual angulations are altered and the mesiodistal angulations are fixed.
2. There is no difference between the true root parallelism expression from adjacent teeth of a phantom and the image root parallelism depiction on a panoramic radiograph when the bucco-lingual angulations are altered and the mesio-distal angulations are fixed.

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1.5 Glossary

Bracket: An orthodontic attachment that is secured to a tooth (either by bonding or banding) for the purpose of engaging an arch wire. Brackets can be fabricated from metal, ceramic or plastic.

Buccal: Toward the cheeks.

Distal: A direction oriented along the dental arch away from the dental midline; right or left in the anterior segment, posteriorly in the buccal segments.

Frontal plane: A vertical plane parallel to the long axis of the body situated at the anterior or frontal art of the body.

Lingual: Of or pertaining to the tongue. A term used to describe surfaces and directions toward the tongue.

Mesial: Toward or facing the midline, following the dental arch. It is used to describe surfaces of teeth, as well as direction.

Panoramic radiograph: A radiographic tomograph of the jaws, taken with a specialized machine designed to present a panoramic view of the full circumferential length of the jaws on a single film.

Sagittal plane: A plane parallel to the median plane of the body. Relating to a section dividing the body into equal right and left parts.

Torque A force that moves the crown in one direction and the root in the opposite direction.

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1.6 Literature Review

1.6.1 Axial Tooth Inclination

1.6.1.a The importance and description of tooth axial inclinations

Occlusion can be defined as the relationship of the maxillary and mandibular teeth as they are brought into functional contact. The main objective of orthodontics is the improvement of tooth positions in three planes of space in order to attain predefined occlusal relationships within the framework of acceptable facial esthetics and stability of the occlusal result. Accomplishing good root parallelism is crucial if one wishes to obtain a correct alignment of the teeth within their respective apical skeletal bases and a normal occlusion of the upper and lower teeth. At the same time, root parallelism could be an important factor in maintaining a stable result[1] Andrews in 1973 published his "six keys to normal occlusion" which stated that the proper mesio-distal axial inclination was required for ideally positioned teeth.[9] Proper axial inclinations are necessary for the distribution of occlusal forces with closed contact points.[10] This is most important because orthodontically closed extraction sites are more susceptible to open again if adjacent teeth roots are not parallel.[1] [11, 12] [13-15]

According to Kurth and Kokich[16] patients with open gingival embrasures have more root divergence than those with normal gingival embrasures. This study reports that when mesial crown form, alveolar process interproximal contact and interproximal contact-incisal edge variables are constant, a primary increase in root divergence between central incisors increased the odds of a gingival embrasure by 14% to 21%.

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Contemporary orthodontic edgewise appliances are designed to control tooth positions and inclinations in four different directions in the space (figure 1.1). Orthodontics use brackets to transfer the forces applied by the archwires to the teeth. Brackets are designed differently for each tooth with the goal of minimizing bends in the archwire so that a straight wire can fit passively into the slot when all the teeth are ideally positioned. The bends in the archwire can be classified into three main groups:

1. First order bends, or in-out bends are offsets in the arch wire that are used to accommodate the bucco-lingual thickness of teeth or to produce horizontal forces.
2. Second order bends can be defined as archwire offsets in the vertical plane used to tip and upright teeth. In other words they are used to adjust the mesiodistal inclination of the teeth.
3. Third order bends can be defined as a twist in a rectangular arch along the long axis of the archwire producing torque. Torque is a third order couple that moves the crown in one direction and the root in the opposite direction.

The need for first, second and third order bends has been reduced by modifying the bracket placed on individual teeth, in order to create a custom bracket. A bracket is customized by modifying the thickness of the bracket base, the inclination of the bracket slot and torque of the slot. The aforementioned modifications on each tooth bracket define what is called appliance prescription.

Appliance prescriptions are based on data obtained by anthropometrical analysis of "normal" occlusions. Normal values for mesio-distal and bucco-lingual tooth inclinations were obtained by different methods. The original straightwire appliance was designed by Andrews in 1972 [9].

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Andrews measured more than 100 normal dental arches and supplied reference values of size, shape, and inclinations of the facial (or buccal) axis of the clinical crown (FACCs). The angulations were measured as tip (mesio-distal inclination) and torque (bucco-lingual inclination) with reference to the occlusal plane. All the measurements were performed directly on the dental casts using protractors and calipers[9].

New techniques have been developed to determine the normal or average axial inclinations of the teeth. Ferrario et al. [17] measured the 3-dimensional inclination of the FACCs, relative to anatomical planes, intrinsic to the dental cast in a normal, healthy population. The data was obtained from cast models of 22 girls and 21 boys, ages 13–15 years (adolescents), and 31 women and 26 men, ages 16–26 years (adults). All subjects had a sound, full permanent dentitions. The main objective was to obtain data that could be used as normal reference values for the assessment of patients seeking orthodontic treatment. Three-dimensional coordinates of dental landmarks from the dental casts were obtained with a computerized electromagnetic digitizer. Clinical crowns heights and FACC inclinations in the anatomical frontal and sagittal planes were calculated. On average, in all groups, the dental inclinations in the frontal plane were negative, ie, the cervical-to-occlusal facial axis was directed toward the lingual. (Figure 1.2 and 1.3). Exceptions were found for the incisors, which, in about half the cases, showed positive axes (diverged from the midsgittal plane) or nearly vertical axes (inclinations near to 0°). When the dental inclinations of the single subjects were observed, about 40–50% of the mandibular incisors had positive inclinations. Similar inclinations were found in about 20–30% of the maxillary incisors. Within each quadrant, the inclinations of the posterior teeth progressively became more negative toward the first (maxillary) or the second (mandibular) molar. Overall, inclinations in the frontal plane were more negative in the mandibular than in the maxillary arch, with differences up to 15°–18° (first molars).

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The inclinations of the FACCs in the frontal plane showed significant sex- and age-related differences. In particular, the canines, premolars, and molars were more inclined in adolescents than in adults, with differences up to 12° and 14° (mandibular second molars in males). In the sagittal plane, the inclinations of the FACCs showed large within-group variability (high standard deviations) together with several significant sex- and age-related differences. Indeed, the observed differences cannot be easily classified. Most maxillary teeth were, on average, nearly upright, with cervico-to-occlusal inclinations of the FACCs within 6 to 8°. [17]

Other methods to measure bucco-lingual angulations have being proposed. Ghahferokhi and Richmond, in independent articles [18-20], suggested using a disposable intraoral tooth inclination protractor (TIP) to record incisor crown inclinations. They compared this method with an acrylic extraoral TIP and traditional lateral cephalograms. The device consisted of a plastic covered paper platform with a 180° plastic-covered paper protractor suspended below it. The platform was perforated to receive a stainless steel wire that could lie against the buccal surface of the incisor. The reading on the scale reflected the bucco-lingual inclination of the buccal surface of the maxillary and mandibular incisors to their respective occlusal planes. They concluded that the disposable TIP is a reliable and valid tool to assess incisor crown inclination. Nonetheless there were statistically significant differences between the TIP and the radiographic assessment. The TIP tended to record maxillary incisor inclination an average of 14° less than upper incisor to palatal plane and recorded mandibular crown inclination 19° less with mandibular incisor to occlusal plane. These differences could be explained by the discrepancies that may exist between root axial inclination and crown axial inclinations.

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Tsunori et al. evaluated the relationships between morphological characteristics of vertical sections of the mandibular body from images acquired with CT scans of 39 dry skulls[21]. The skulls were divided into two groups according to their vertical facial type (short-faced group and long-faced group). Cephalometric parameters obtained from lateral cephalogram tracings were used to categorize vertical facial type. According to their results, the second premolar and the first and second mandibular molars are more inclined lingually in the short faced-group than the long-face group. They suggest that because long-face individuals have narrow mandibles, as opposed to the short-face individuals, the lower dentition receives a stronger tongue pressure. This increased pressure uprights the molars, despite the narrow dental arch. Their results contradicted the previous findings from Janson et al. [22]

Janson et al carried out a study to compare the bucco-lingual angulations of posterior teeth in subjects with short lower anterior facial height with those of subjects with a long lower anterior facial height[22]. The sample included the pretreatment dental study models of 70 subjects. The posterior occlusal plane was used as a reference line to estimate the bucco-lingual angulations from photocopies of transversal sections of the dental casts. Only the first molar and second premolars from both arches were measured. The long axis of each molar and premolar was represented by a perpendicular line to the occlusal surface. According to their results, the maxillary posterior teeth in subjects with vertical growth patterns have a statistically significant greater buccal inclination as opposed to horizontal growth patterns. Yet, no statistically significant differences in the angulation of the mandibular posterior teeth were found. A limitation of this study is that the measured angle does not correspond to the actual long axis inclination, rather, to the occlusal surface inclination.

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Despite the fact that several studies have evaluated the normal bucco-lingual tooth inclinations, by using different reference points and methodologies, little agreement exists as to what can be defined as normal and if "normality" differences exist among different facial types. Moreover the reference points used to determine these angulations might not be valid enough. Most of these measurements are based on crown inclinations and not on crown-root inclinations. Further studies are still required to provide accurate normality values for teeth buccolingual angulations.

1.6.1b Factors influencing orthodontically generated bucco-lingual angulations

From all the positions that a tooth can assume in space, axial positioning of teeth in the bucco-lingual plane is the most controversial. Correct bucco-lingual inclinations are considered necessary to provide proper occlusal relationships and stability[23]. Most probably torque also positions the roots to best withstand the forces of occlusion[24]. Torque of the maxillary incisors is particularly crucial in establishing proper anterior guidance and an esthetic smile line. Furthermore inadequately inclined teeth can create arch length discrepancies in the anterior segment and constriction and/or inappropriate cusp to fossa relationships in the posterior segments.

Torque control and consistency are required to achieve the aforementioned goals. In spite of the need of adequate torque, there is a significant variability among various orthodontic bracket prescriptions and in particular with respect to the anterior dentition. For instance the maxillary central incisor torque in preadjusted appliances ranges from 12° in the Roth prescription to 22° in the Bioprogressive prescription, a variation of almost 100%. Other sources of torque variation include material properties, manufacturing processes and clinical procedures. [23] As with any other product, the manufacturing of orthodontic brackets undergoes processes that create variability in dimensional accuracy and torque consistency.

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It has been shown that reported manufacture torque differs from actual value by 5% to 10%, which represents about an 1° to 5° difference [23]. Furthermore imperfections, particles and roughening in the slot internal walls incorporate more dimensional inaccuracies in the slot components, which may cause subsequent alterations of the bucco-lingual position of the crown. It has been demonstrated that deeper slots tend to displace the crown more bucally, whereas shallower slots would probably apply a lingual orientation [23]. The stiffness of the arch wire can modulate the transfer of the loads that originate from the activation of a wire engaged to a preadjusted slot.

According to Gioka et al. [23] Ni-Ti arch wires require torque values exceeding prescriptions in order to achieve full bracket torque expression. Titanium molybdenum alloy wires can be effective in expressing torque provided some extra torque is applied to the archwire before it's inserted into the slot. They suggest using rectangular, large cross section stainless steel wires to fully express the torque values built into the bracket. Torque control can be also affected by the mode of ligation. Elastomeric ligatures have shown a force decay-degradation pattern reaching 40% in the first 24 hours [23]. As a result the engagement of the wire into the slot is incomplete and supple. The use of steel ligatures for torque is recommended.

When a straight wire technique is used, it is assumed that each point on the facial contour of each specific tooth is the same for all patients. It has been demonstrated in the literature that teeth facial contours of are not identical among patients. Germane et al [24] analyzed the surface contours of 600 maxillary and mandibular teeth, including 50 of each type of tooth from central incisors to first molars. Their findings suggest that facial contours do vary but not in a regular manner from occlusal to gingival areas.
Any given torque placed in a bracket will result in the placement of the same teeth at different long axis according to variations in facial surface contours.

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A second factor affecting the bucco-lingual orientation of the tooth in the space is the superior/inferior positioning of the bracket on the curvature of the labial surface. Since bucco-lingual contour varies from gingival to occlusal, different locations of the same bracket on the same tooth will result in different buccolingual orientations. Germane et al [17] propose that vertical placement errors of 1mm can alter torque values up to 10 °. Even if the facial contours were constant, the variation between the long axes of the root and the crown would result in different root positions with constant crown positions. According to Germane et al. [24] the use of a prescribed bracket torque may improve care of some patients but not of others. They recommend that treatment must be tailored to the biologic variation presented by the individual patient.

Multiple factors, including anatomical and technical variables, have an influence on the bucco-lingual orientation of a tooth in the space. Even though the usage of prescription brackets has significantly improved the control of tooth positioning, the aforementioned variables could produce a wide range of tooth positioning expressions that may influence the treatment outcome. Being aware of all these variables in order to provide the best results to the patient becomes necessary. Most of the tools used to determine bucco-lingual angulations currently available are not practical from a clinical perspective. Sound clinical judgment and experience is still the most common, cost effective method used to assess bucco-lingual angulations.

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1.6.2 Panoramic Radiography

1.6.2.a Indications and contraindications

Panoramic radiography (also called pantomography), is a radiographic technique, taken with a specialized machine designed to present a view of the full circumferential length of both the maxillary and mandibular dental arches on a single film. The pantomograph was developed by Paatero in 1948 [25, 26]. The original technique used two films in one cassette positioned 6 mm apart[27]. The principal advantages of pantomography are that it images a broad area of the facial bones and teeth with a relatively low patient radiation dose and is easy and fast to execute[28]. The radiation dose to the patient is roughly ten times less than a full mouth survey but it is eight times more than a conventional cephalometric radiograph[29]. Other advantages are the simplicity and quickness of the procedure [30]. The major disadvantage of pantomography is that the result is not as anatomically detailed or dimensionally accurate as intraoral periapical radiographs[31]. Other problems include uneven magnification, geometric distortion, and over-lapped images of teeth. Furthermore objects whose recognition may be important for the interpretation of the radiograph may be located outside of the plane of focus resulting in their images being distorted or obscured.

During diagnosis, treatment planning and shortly before the end of orthodontic treatment the orthodontist makes x-rays to evaluate the overall mesio-distal root angulations of the teeth in the maxilla and mandible. Examination of the literature reveals that this evaluation is often performed by means of panoramic radiography. In a 2002 survey of orthodontic diagnosis and treatment procedures of American orthodontists, 57.9% and 79.1% of respondents reported taking progress and post-treatment panoramic radiographs respectively[32].

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The American Board of Orthodontics [2] (ABO) recommends using panoramic x-rays to asses root inclination and parallelism as a mean to evaluate the adequacy of the orthodontic finishing. The ABO has established a grading system to evaluate panoramic radiograph and dental casts. They recommend drawing an imaginary line on the film that would represent the correct position of the tooth long axis if the root was properly positioned followed by another line where the root apex is positioned. If a discrepancy of 2mm or less exists between these two lines no points are subtracted. More points are subtracted if the apices of the roots touch each other[2].

1.6.2.b Principles of image acquisition

When obtaining a panoramic radiograph, the cassette and x-ray tubehead move around multiple invisible rotational axes. The x-ray tube rotates in a horizontal plane around the patient's head as the film rotates in the same direction. The film and x-ray tubehead are connected and rotate simultaneously during the exposure[33, 34]. (Figure 1.4) Aluminium collimators in the shape of a slit, situated at the x-ray source and at the film, limit the central ray to a narrow vertical beam. If this narrow rotating beam were used to project the object on a stationary film the magnification in the horizontal dimension would be always greater than in the vertical dimension. By using a moving film the magnification in the horizontal dimension is equalized[30].

The axis around which the film and x-ray source rotate is called the rotation center. The vertical dimension of the image is the result of a conventional dental radiographic projection with the exception that there is a small negative angulation of the beam, so that the beam could pass under the occipital area of the cranium. This angle is between -4 and -7 degrees [32].

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During exposure the machine shifts to other rotation centers. Depending on the manufacturer the number and locations of the center of rotation differ. This rotational change allows the image layer to conform to the elliptical form of the dental arches.[33, 34] The most popular mechanical movement patterns are those that use a continuously moving rotation center (Figure 1.5). This sliding movement throughout the excursion is constantly shifts the rotation center along a defined path. The central beam is always tangential to a defined curved path and hence defines the projection geometry of each successive part of the jaws [30]. This center of rotation is initially near the lingual surface of the body of the mandible when the contra lateral temporomandibular joint is imaged. The center of rotation moves forward along an arc that ends just lingual to the symphisis of the mandible when the midline is imaged. The arc is inverted when the opposite side of the face is imaged.

1.6.2.c The focal trough

A panoramic image is made by creating a focal trough (also known as image layer) within a generic jaw form or size. The focal trough is a mathematical concept used to calculate the position of the dental arches in order to achieve the clearest image [33]. The focal trough is a three dimensional horseshoe shaped area in which anatomical structures are well defined on panoramic radiographs. Objects outside the focal through appear blurred, magnified and distorted, sometimes to the point that some structures are not identifiable [30].

In the central portion of the focal trough there is a curved plane in which the vertical and horizontal magnification factors are the same. This plane is called the central plane of the focal trough or image layer (Figure 1.6). It suggests that objects located in the central plane are free from distortion and unsharpness. However according to Welander et al. the aforementioned statement is only true in those systems having a stationary rotation center and a constant projection center. [35]

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In other systems distortion will arise since the beam is no longer perpendicular to the focal trough causing the image to be compressed horizontally.

Rather than one simple central plane, there are a number of curved planes within the image layer with different distortion and magnification characteristics[35]. It is important to make a distinction between the statement that an object lays at the central plane of the focal trough and the statement that an object lies within the central plane. When the central plane of the layer is not perpendicular to the beam, an object will appear distorted even though it lies entirely within the central plane[36].

The unsharpness in panoramic radiography is asymmetrical around the central plane of the focal trough, causing the layer to be wider toward the rotation center of the beam than toward the film. As a result the plane of maximum resolution is displaced toward the buccal area. Other variables will accentuate these effects: a screen film combination with high resolution, a small focal spot and a long projection radius[37].

Paiboon et al. [38] carried out a resolution test pattern to determine the size, position and centers of the focal troughs of different panoramic x-ray machines. It was observed that the centers of the focal troughs move bucally with decreasing border errors. This indicates that when a machine focal trough center is located and the operator attempts to place the object in the center, any buccolingual positioning error will show greater sharpness loss with lingual errors than with buccal errors. Structures on the opposite side of the patient, close to the x-ray source, appear out of focus and distorted because the x-ray beam sweeps through them in an opposite direction. These anatomical structures appear as ghost images. In general objects in the focal trough are magnified 20 to 30% [30].

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The location and number of rotational centers influence the size and shape of the focal trough. The closer the rotation center is to the teeth, the narrower the focal trough. This phenomenon is directly related to the distance from the center of rotation to the central plane of the image which is called the effective projection radius. The longer the projection radius the thicker the focal trough will be.

The degree of distortion is dependent upon the distance from the central plane of the focal trough. Distortion is less on the lateral segments of the jaws where the projection radius is longer[39]. On the other hand the layer thickness is inversely proportional to the width of the long narrow slit beam. The center of rotation and the speed that the x-ray beam sweeps through the objects constantly changes to modify the width of the focal trough. In the majority of panoramic machines the focal trough is wide in the posterior region and narrow in the anterior region[40].

Each manufacturer provides specific instructions to position the patient in order to place the teeth within the focal trough as close as possible. Nevertheless the focal trough is designed to accommodate an "average" jaw that might or might not conform to the patient's jaw. When the jaws are incorrectly centered on the focal trough due to anatomical differences or variations in patient positioning, the distortion effects are more pronounced and different magnifications of different regions of the jaws can be expected[41].

Welander et al. [42] described the average form and size of the mandible by using mathematical expressions to assess the impact of anatomical differences in applications of panoramic radiography. Three ethnic groups were included in their study: African Americans, Caucasians and Mexican-Americans. Differences in width of the dentition and the mandible were found between sexes and races but these differences were too small to be clinically significant. The individual width of the jaws varies considerably more within sexes and ethnic groups than the average among groups.

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Hassen et al. [43] compared the focal troughs of the Orthopantomograph5, Autopan and Panorex panoramic machines. It was observed that the focal trough of the three machines did not cover all tooth positions completely, particularly in the anterior region. As a consequence, slight anteroposterior or lateral malpositioning of the dental arch from correct position will place some teeth outside the focal trough. Furthermore they observed small differences between the right and left sides of three machines. They stated that these discrepancies could have resulted from methodological errors or from inherent machine asymmetry[43]

As the position of an object is moved within the focal through, its size and shape changes on the resultant image. The closer to the center of the focal trough a structure is positioned, the more clearly the image is represented on the resulting radiograph.[44] According to Paiboon et al., [38] the position of the sharpest plane within the focal trough may not be at the center of the focal trough. As a general rule when the object is displaced lingually of its optimal position in the focal trough, toward the x-ray source, the beam passes slower through the jaws than the speed at which the x-ray film moves. As a result the image of the structures in this region is elongated horizontally on the film. On the other hand when the object is displaced toward the buccal area of the focal trough, the beam passes at a faster rate relative to the film. Consequently the objects will be narrowed on the image. A circular object is reproduced as an ellipse when it is placed outside the focal trough due to different magnification in the horizontal dimension. When placed toward the rotation center the long axis of the ellipse is horizontal and when placed toward the film the long axis is vertical with little change in the vertical dimension. Additionally, due to the negative projection angle of the beam, buccal objects will be projected lower and lingual objects will be projected higher than objects in the focal trough central plane [30].

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Many factors can influence the shape and size of the focal trough and consequently the image definition. Some of the variables to be considered are the velocities of the film and x-ray tube head, and the alignment of the x-ray beam and the collimator width[45-47]. To obtain the finest image clarity it is crucial that the speed of the film passing the collimator slit be maintained equal to the speed at which the x-ray beam sweep through the objects of interest.

Acceleration of the panoramic film velocity shifts the focal trough away from the rotation center and a wider image layer results. By changing the speed the machine, the width of the focal trough can be changed as it goes from the anterior to the posterior regions of the jaws. The location of the focal trough can change with extensive usage, therefore recalibration is necessary.

1.6.2.d The Projection Angle

The movement pattern, including the angular changes of the scanning x-ray beam varies considerably from one manufacture to the other. These angular changes are usually greater in the anterior than the posterior region of the jaws, mainly due to the sharp curvature of the dental arch in the anterior region, thereby narrowing the sharpness zone in the incisor area[43].

In panoramic radiography the projection of the jaws is not truly orthogonal and the image distortion is also affected by the angulation between the image and the object.[48] Depending on the equipment the deviation from true orthogonally is usually between 20° to 30° in the premolar region. The direction of the beam is responsible for the perception of the object by the viewer[49]. Evident overlapping of the crown occurs normally, making interpretation of interproximal caries cumbersome.

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This radiographic phenomenon is associated with the deviation between the projection angle of the beam and the interproximal contacts between the teeth in the dental arch[50] (Figure 1.6). Although the form and shape of the dental arch has been the focus of interest in orthodontics for many years, little information exists regarding tooth position and it's relationship with the focal trough and the projection angle in panoramic radiography.

Scarfe et al. [50] determined the average angles of the interproximal tangent lines of different areas of the dentition, by studying axial radiographs taken on 160 subjects with different ethnical backgrounds. Coordinate references for interproximal tangents at 3154 contacts along an averaged dental arch form were digitized, and angulations between the arch form and midsagital plane were calculated. For the average arch form, the midsagital/interproximal angle rapidly increases from zero in the lateral and central incisor areas, to remain close to 70 degrees for most the dentition beyond the canine area. The average standard deviation of these angles is ±5.5 degrees for all posterior areas. A large variance exists in the canine region (82.5°±7.1), almost twice that in the premolar/ molar region. The data showed that optimal beam direction varies significantly from arch to arch. From the results of the study, it is evident that there are large discrepancies between the optimal and actual beam angulations, especially on the premolar region, ranging from 15 degrees to 45 degrees.

In an independent but similar study Scarfe et al. [50] designed an experiment to determine whether orthogonal panoramic projection could improve diagnostic accuracy over standard projections in the detection of interproximal caries. The orthogonal projection potentially improves the diagnostic value of the system by minimizing the deviation of the projection beam from the average arch form in the dentition. This concept assumes that a beam at right angles to the average arch form also bisects the proximal contact.

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The experiment demonstrated, however, that no significant difference in diagnostic accuracy was found between the standard and orthogonal panoramic projections [51].

Leite et al. [52]explored the use of off-axis projection geometry of the slit beam of radiation to reduce proximal overlap that exists in panoramic radiographs, and to displace the blurred image of the spinal column from important diagnostic areas. Even though the ideal rotational path directs the slit beam perpendicular to the dental arches, the limitations of existing designs of single projection geometry usually results in varying amounts of dental structures overlap.

It was determined that a multiple-beam panoramic system can reduce the number of proximal overlaps by using multiple off-axis projection angles rather than a conventional single-beam projection. Preliminary experiments demonstrated that off-axis angulations of 4, 6 and 10 degrees provided the most open contacts of proximal surfaces of the teeth in the anterior, premolar and molar regions. They concluded that the premolar region requires the highest deviation from the conventional projection in order to open its embrasures. The number of overlapped contacts was higher for the upper premolar area than the mandibular premolar area. The molar area was the second most problematic area. They also found that the total number of embrasures free of overlap was greater in the mandible than in the maxilla.

1.6.2.e Magnification and Distortion

All pantomographic images have some degree of distortion since a fixed beam-film relationship is utilized to project structures which vary greatly in the same individual and between individuals[53]. In periapical radiography, adjustments in film position and angulation are made to compensate for these differences, but in pantomography, adjustment is limited to positioning of the patient's head[53-56].

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Different percentages of distortion occur in different regions of the mouth. Angulation distortion on panoramic radiographs results from the combined distortion in the vertical and horizontal dimensions and at different locations and depths within the focal trough [3]. The resolution characteristics in panoramic radiography are different in the vertical and horizontal dimensions. While magnification is the same horizontally and vertically in the central plane of the focal trough, it varies from anterior to posterior regions and with object depth[56]. In the horizontal dimension there is a marked variation in magnification with the object depth.

A number of investigators have examined angular distortion in pantomography, specifically with regard to tooth position. It has been demonstrated that pantomographic films have some limitations to assess angular measurements of tooth inclinations[4, 7, 57-59]. Some investigators have found different degrees of error in the expression of the teeth long axis and elongation errors. The amount of distortion shown for different teeth was different depending on its location on the maxillary and mandibular arches. According to the conclusions drawn from most of these studies, statistically significant differences were noted for the majority of maxillary and mandibular image mesio-distal angulations as compared with the true mesio-distal angulations.

Although many studies have been conducted to evaluate distortion of mesio-distal root angulations, few studies found in the literature have assessed the relationship of buccal-lingual root angulation and dimensional distortion of panoramic x-ray projections. Samfors [54] was the first to study angle distortion with a mathematical model. They evaluated angular distortion in objects placed at various distances from the focal trough and concluded that objects placed buccal to the focal trough resulted in images with a more obtuse angle to the occlusal plane and objects placed lingual to the focal trough resulted in a decrease angle of inclination of the image. Their study restricted itself to a single panoramic unit and involved measurements of the anterior maxilla only.

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Lucchesi et al. [4] used a plexiglas mandibular phantom with steel pins representing tooth roots to investigate the suitability of both panoramic and plane-film radiography for the assessment of the mesio-distal angulation of teeth in the buccal segments of the mandible. Mesiodistal 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 bucco-lingual inclination ranging from 0 degrees to 25 degrees with the crown directed lingually. The Panoramic deviation was calculated by subtracting the correct angle of the pin from the angle measured on the panoramic radiograph. Results revealed that the degree of deviation from the actual angulation was greater with panoramic radiography than that of plane-film radiography.

They determined that deviations from normality were greater in the anterior regions of the jaws. Although the differences between actual and measured angulations with both techniques were accentuated with increased lingual inclination of the teeth, these errors occurred in both positive and negative directions. They suggested that the results might be different if using panoramic machines with different focal troughs and axis of rotation. Lucchesi stated that an explanation for this finding is difficult to deduce since it would be expected that machine errors should occur in either a positive or negative direction.[4]

Tronje found that vertical measurements on panoramic films may be reliable within certain definable limits [41]. On the other hand horizontal measurements were found to be very unreliable[60]. According to Tronje the distortion on panoramic image of the angle between inclined teeth would be the result of the combined distortion on the vertical and horizontal dimensions. He stated that previous studies had analyzed projected angles between objects situated in the same object plane and he considered that those calculations were incomplete since no consideration was given to inclinations in the depth dimension of the body, that is the bucco-lingual angulations of the teeth[7].

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He performed an analysis by means of mathematical calculations which were confirmed by experimental tests in order to determine the effect on the angle distortion of the combined inclination in all three planes of space. These calculations were performed using only one panoramic machine (The Siemens Orthopantomograph 3) and the test films were exposed in the region corresponding to the anterior part of the panoramic film where the sharply depicted layer is nearly cylindrical. Tronje found that the mesiodistal inclination angle distortion was more marked when the object was mesio-distally inclined 45°, and that this distortion decreases successively as the angle is increased or decreased. They also found that when the mesio-distal inclination of the wire representing the tooth was 45°, with buccolingual angulations ranging from 30° to 160°, the angle of distortion didn't exceed +/- 5°. Tronje stated that alterations in bucco-lingual inclination did not contribute significantly to angulation errors in the panoramic image because compensation would occur in the relative magnification and diminution of various parts of the image.

This compensating phenomenon, according to Tronje, is neither general nor exact but an object that has a certain mesio-distal inclination may at the same time have a great inclination in the bucco-lingual dimension, and still causes limited angle distortion in the image [7]. Tronje [7] claimed that the angle of the beam to the horizontal plane affects the angle of distortion so that the tolerance limits decrease when the angle of the beam increases. Based on their study the average angle in the mandible of the central ray to the horizontal plane is 5°. The average angle in the upper jaw is 15°. As a result the tolerance limits against angle distortion are greater in the lower jaw than the upper jaw. Tronje stated that is not possible to present generally applicable tolerance limits since the tolerance varies greatly with the mesio-distal inclination and displacement of the object toward the film or the center of rotation. The tolerance limits are at the same time different in different parts of the film. It must be considered that his conclusions should be analyzed and applied prudently since mesiodistal angulations of 45° are not anatomically representative of the norms.

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It is important to clarify that the aforementioned statements were only valid for structures located in the anterior part of the lower jaw and with its center in the sharply depicted object plane. Lucchesi attributed the differences between both studies to the different panoramic units and settings used in the studies. They stated that deviations from normality were greater in the anterior regions of the jaw. [4]

McKee et al. [59] compared known typodont mesio-distal tooth angulations with the images of mesio-distal tooth angulations from four different contemporary panoramic units. True mesio-distal tooth angulations relative to an orthodontic arch wire were determined with a tridimensional coordinate measuring machine and custom-designed software. The typodont was repeatedly imaged in each panoramic unit and the images were scanned and digitized with custom software to determine the roots mesio-distal angulations. One sample t-tests were made for each tooth to detect the mean difference between the true mesio-distal angulation and each panoramic unit's image angulation. They found statistically significant differences for the majority (74 %) of maxillary and mandibular image mesio-distal angulations as compared with the true mesio-distal angulations.

Mckee et al. [59] reported that significant differences were reasonably evenly distributed among the 4 panoramic units. For the maxilla, the image angle typically underestimated the central, lateral and canine and overestimated the premolars and first molars on both sides. In the maxilla, the anterior teeth roots were projected more mesially and the posterior teeth roots more distally creating an illusion of divergence of the maxillary canine and first premolars roots. For the mandible almost all the image angles underestimated the true angles, with the canine and the first premolar more severely underestimated. All the roots were projected more mesially than they really were with the exception of the right central mandibular incisor. In the mandible, the largest angular discrepancy on adjacent teeth occurred between the lateral incisor and the canine, with relative root parallelism projected as root convergence.

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The discrepancies were larger for mandibular teeth than they were for maxillary teeth. Even though the different panoramic units have varying focal trough dimensions and beam projection angles, all the machines seemed to systematically overestimate and underestimate true angles in the same way. According to McKee et al. when clinically significant tolerance limits of ± 2.5° in the mesio-distal angulation of teeth to the reference arch wire are applied, the majority (61%) of the maxillary and mandibular image angles were still significantly different from the true angle measurements.

In a similar but independent study McKee et al. [61] examined the effect of potentially common patient positioning errors in panoramic radiography on imaged mesio-distal angulations using a typodont/skull testing device. The skull was repeatedly imaged and repositioned five times at each of the following head positions: ideal head position, 5° right, 5° left, 5° up and 5° down. Subsequently the images were scanned and the angulations determined with custom software. The results of this study revealed that most of the image mesio-distal angulations from the different atypical head positions were statistically significantly different from the mesio-distal angulations at the ideal head position. If applying clinically significant tolerance limits of +/- 2.5° in the mesiodistal angulation between a tooth and an established reference plane, 53% of the image angles from the aberrant head positions were still significantly different from the images at ideal head position.

They also found that the maxillary tooth angulations were particularly sensitive to up/down skull rotations and that in contrast mandibular tooth angulations were particularly sensitive for right and left rotations. According to McKee et al. these results are difficult to explain[61].

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Stramotas et al. [8] investigated the accuracy of panoramic radiographs with regard to mesiodistal tooth angulations and the effect of different head position techniques on the assessment of linear and angular measurements. They used an acrylic framework and stainless steel wires representing the dentition and a functional occlusal plane. All exposures were taken using a Siemens Orthophos panoramic imaging system with a constant 25% vertical magnification. The phantom was built using 10 stainless steel pins at angulations selected using computer generated random numbers in a range of 15 degrees (buccolingually and mesiodistally) relative to the vertical plane. The model was positioned in the panoramic machine using focal trough guides. Four different positions were used:

a) Occlusal plane tilted 8 degrees anteriorly downwards.
b) The right side of the model tilted down 10 degrees.
c) The left side of the model tilted down ten degrees.
d) The occlusal plane tilted up 8 degrees anteriorly parallel to the horizontal plane.

Stramotas et al. [8] found that the linear measurements were not significantly affected for inclined objects in the sharply depicted image layer. They reported that parallel displacement of objects in the anterior region, toward the rotation center or toward the film affected the image of an angle between inclined objects less than ± 5°. These differences according to Tronje [7] are clinically insignificant.

Welander et al. [49] used acrylic test models with wires positioned to represent the positions and angulations of teeth. They expanded Tronje's [7] concept by applying it to non-cylindrical image layers. They found that an object with buccolingual angulations of between 30° to 160° could have a clinically insignificant angle distortion of ± 5°. The tolerance limits were lower for the posterior regions and the maxilla due to the angulation of the x-ray film.

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Stramotas et al. [62]evaluated the reliability of crown and root length, crown root ratio and angular measurements of teeth relative to constructed reference lines and adjacent dentition in the same region on repeated panoramic radiographs. They studied twenty cases. Half of the subjects had five implants in each jaw and the other half a full permanent dentition. The consecutive pairs of radiographs ranged from 6 months and three years apart. The results revealed that differences in angular measurements between the two time points occurred in 40% of the paired radiographs in dentate patients and 20% of the implant cases. Nevertheless the changes were less than 5°, and according to the authors that can be considered clinically insignificant. Stramotas et al. [62] suggest that a slight error in the construction of the reference lines might explain these results. On the other hand angles measured between teeth or implants in the same sextant showed no significant differences. They concluded that angular measurements can be used reliably in a clinical situation to show dental angular changes during orthodontic treatment such as evaluating root parallelism or opening of spaces for future implant placement. [62]

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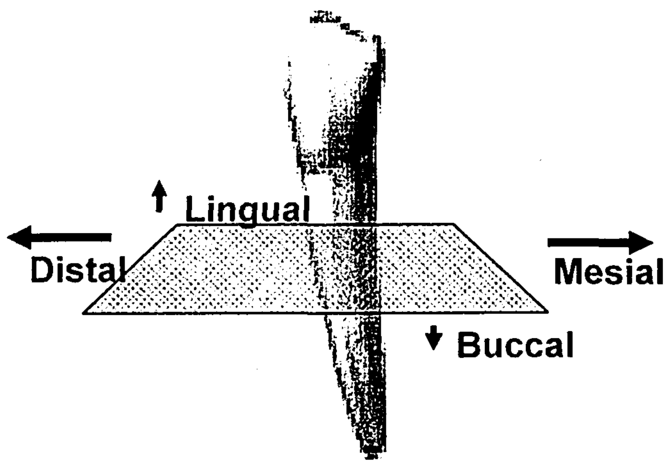
1.8 Figures

Figure 1.1 Terminology of tooth orientations



Frontal view of a tooth. Orientations or directions that a tooth can assume in the space:

1. Distal: A direction oriented along the dental arch away from the dental midline. Lingual: Of or pertaining to the tongue. A term used to describe directions toward the tongue.
2. Buccal: Toward the cheeks or lips.
3. Mesial: Toward or facing the midline, following the dental arch.

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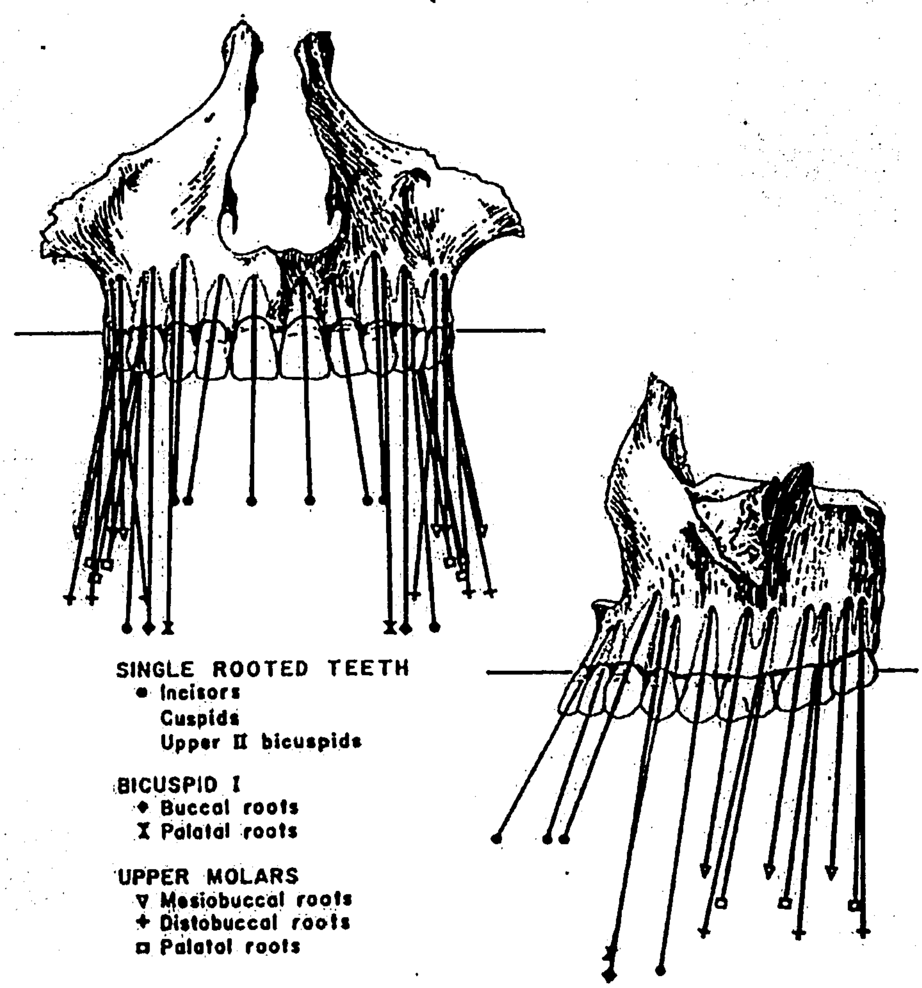
Figure 1.2 Root angulations for maxillary teeth



Taken from Dempster W. et al., JADA, Volume 7, December 1963. pg 792.

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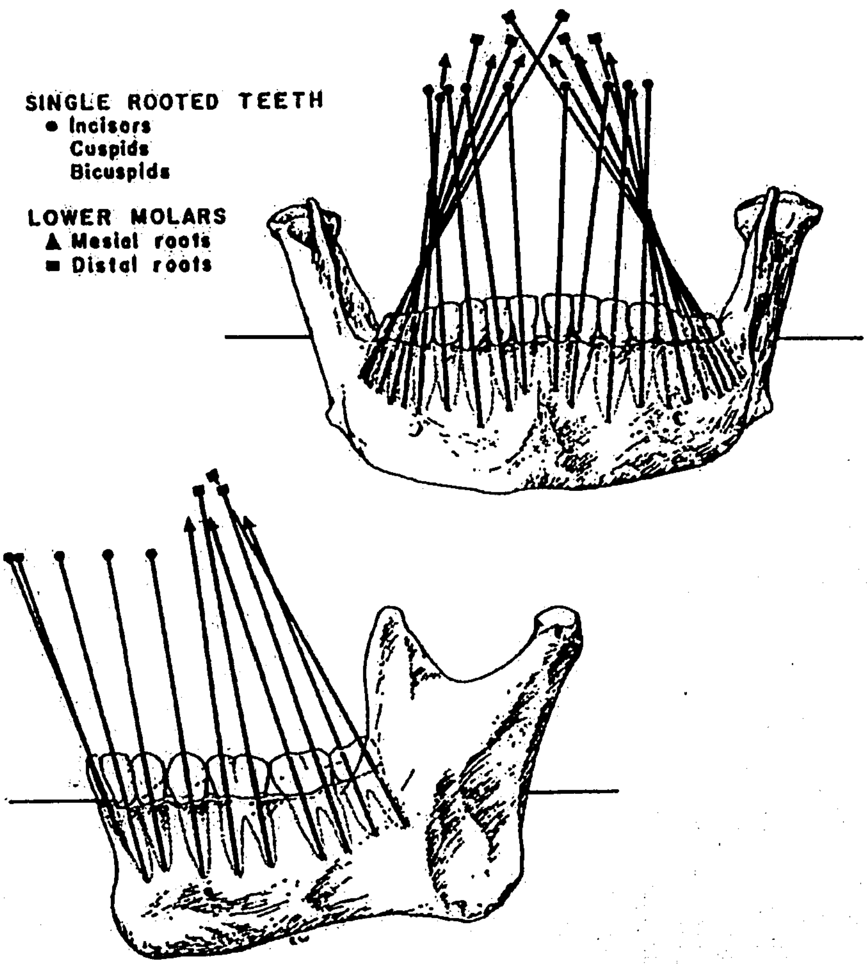
Figure 1.3 Root angulations for mandibular teeth



Taken from Dempster W. et al., JADA, Volume 7, December 1963. pg 793.

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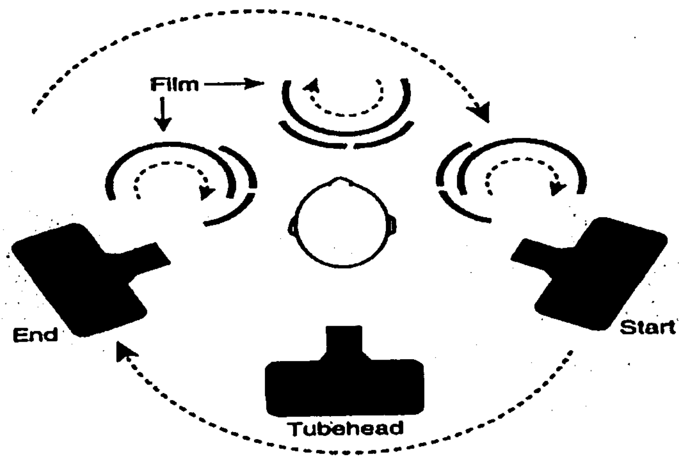
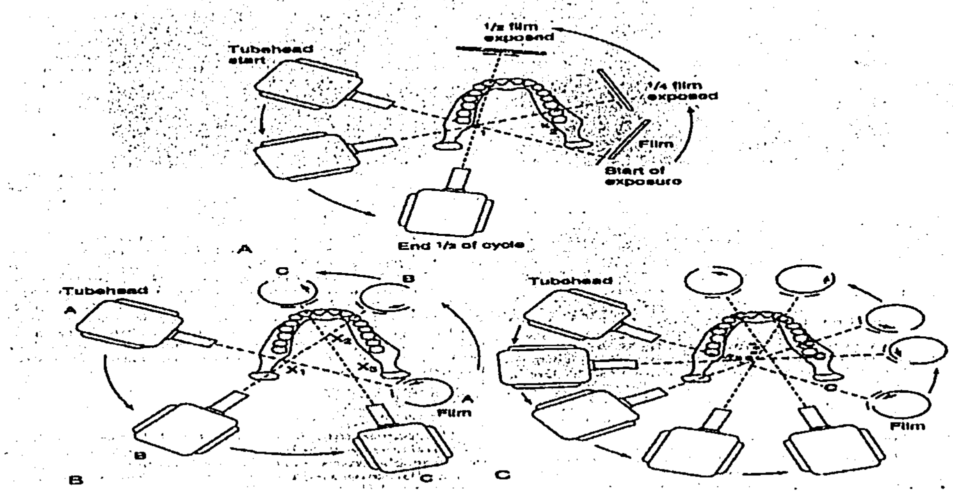
Figure 1.4



In Panoramic radiography the film and x-ray source move around the head of the patient.. (From Haring JI et al.: Dental radiography: principles and techniques, WB Saunders, 2000)

Figure 1.5



Types of Panoramic machines. A- A double center of rotation machines have two rotational centers one on the right one on the left side. B- Triple center of rotation machines have three centers of rotation and create an uninterrupted image of the jaws. C- Moving-center rotation machines rotate continuously around a moving center that is similar to the arches, creating an uninterrupted image of the jaws. (From Olson : Dental Radiography Laboratory Manual. Philadelphia, WB Saunders, 1995)

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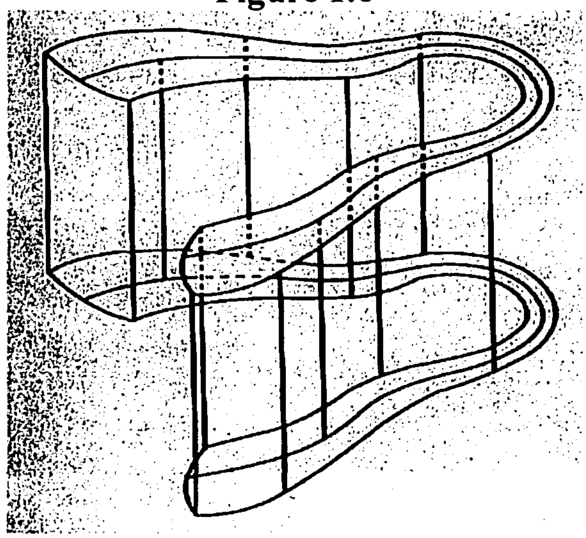
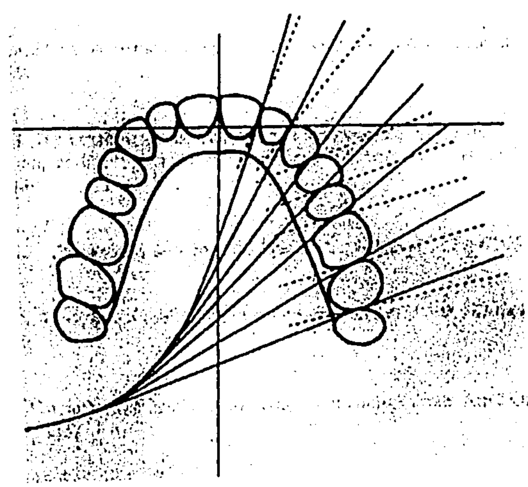
Figure 1.6



An example of an "image layer" or "focal trough". The line in the middle of the focal trough represents the central plane. (From Haring JI et al.: Dental radiography: principles and techniques, WB Saunders, 2000)

Figure 1.7



Typical beam direction in rotational panoramic radiography compared with interproximal contacts along the average arch form. (Taken from Scarfe et al. Journal of Oral Surgery, Oral Medicine and Oral Pathology, Volume 76, November 1993)

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Chapter 2

The Effect of Buccolingual Root Angulation on the Image Mesiodistal Angulation for Panoramic Radiographs

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2.1 Introduction

Panoramic radiography, in addition to clinical judgment, is the most commonly used method in orthodontics to assess mesiodistal root angulation and parallelism before, during and after orthodontic treatment. Accomplishing good root parallelism is crucial if one wishes to obtain a correct alignment of the teeth within their respective apical skeletal bases and a normal occlusion of the upper and lower teeth. At the same time, it could be an important factor in maintaining a stable result [1-3].

Correct bucco-lingual inclinations (torque) are also considered necessary to provide proper occlusal relationships and stability[4]. Correct torque positions the roots to best withstand the forces of occlusion. Torque of the maxillary incisors is particularly crucial in establishing proper anterior guidance and an esthetic smile line. Furthermore inadequately inclined teeth can create arch length discrepancies in the anterior segment and constriction and/or inappropriate cusp to fossa relationships in the posterior segments [5].

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A number of investigators have examined angular distortion in pantomography, specifically with regard to tooth position. It has been demonstrated that pantomographic images have limitations to assess angular measurements of tooth inclinations [6-13]. The distortion between inclined teeth (angular distortion) is the result of the combined distortion in the vertical and horizontal dimensions [6]. According to their results, statistically significant differences were noted from the majority of maxillary and mandibular image mesio-distal angulations as compared with the true mesiodistal angulations[11-13]. The amount of distortion shown for different teeth was different depending on location in the maxillary and mandibular arches.

Although many studies have been done to evaluate image distortion of mesiodistal root angulations, few studies found in the literature have assessed the relationship of buccal-lingual root angulation and angular distortion of panoramic projections. Samfors and Welander were the first researchers to study angular distortion of the anterior maxilla by means of a mathematical model [14]. They evaluated angular distortion of objects placed at various distances from the image layer and concluded that objects placed buccal to the focal trough resulted in images with a more obtuse angle to the occlusal plane and objects placed lingual to the focal trough resulted in a more acute inclination angle.

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Tronje et al. [10] also performed an analysis by means of mathematical calculations, which were confirmed by experimental tests, to determine the effect on the angle distortion of the combined inclination in all three planes of space. They reported that when the mesio-distal inclination of the wire representing the tooth was 45°, with bucco-lingual angulations ranging from 30° to 160°, the angle of distortion didn't exceed ± 5°. It should be noted however, that mesio-distal angulations of 45° are not anatomically representative of the norms. Furthermore their findings were only for structures located in the anterior part of the lower jaw and with its center in the sharply depicted object plane. Tronje [10] et al. stated that alterations in bucco-lingual inclination did not contribute significantly to angulation errors in the panoramic image because compensation would occur in the relative magnification and diminution of various parts of the image.

Lucchesi et al. [7] used a plexiglass mandibular phantom with steel pins representing tooth roots to investigate the suitability of both panoramic and plane-film radiography for the assessment of the mesio-distal angulation of teeth in the buccal segments of the mandible. Although the differences between actual and measured angulations with both techniques were accentuated with increased lingual inclination of the teeth, these errors occurred in both positive and negative directions. An explanation for this finding is difficult to deduce since it would be expected that machine errors should occur in either a positive or negative direction. Lucchesi et al. [7]suggested that the results might be different if using panoramic machines with different focal troughs and axis of rotation.

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The purpose of the present study was to determine if buccal-lingual root angulations changes have an effect on the expression of mesio-distal root angulations and root parallelism on panoramic radiographs.

2.2 Materials and Methods

2.2.1 Phantom Design:

An anatomical apparatus was constructed that could give results applicable to clinical situations and could be easily modified to change the bucco-lingual angulations of the dental units. A clear anatomic maxillary and mandibular typodont (ORMCO corporation, USA.) with ideal occlusion from second molar to second molar was used as the testing apparatus. For each typodont tooth (14 upper teeth and 14 lower teeth), two chromium steel balls (Commercial Bearing, Edmonton, AB) measuring 1.58mm in diameter were fixed into position. The first was placed in the buccal-lingual and mesio-distal midpoint of the crown on the occlusal surface. Excluding maxillary and mandibular molars, the second ball was inlayed into the center of the root in the apical third and cemented.

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For maxillary and mandibular molars, the apical ball was placed at the furcation point. An imaginary line joining the center of these two steel balls represented the long axis of each typodont tooth. These balls served as radiopaque markers for imaging.
The maxillary and mandibular typodont teeth were bonded with clear orthodontic brackets (Clarity, 3M Corporation, Monrovia USA) and a .020 inch round stainless steel heat treated wire (Permachrome resilient, Unitek 3M, Monrovia USA) was ligated into the bracket slots with elastic modules. The arch wire was heat treated in order to increase its stiffness and avoid archwire distortion during its manipulation. A portion of the typodont bases were removed exposing the apical markers for access for later angular measurement. (Appendix A)

The same typodont modified for nine different bucco-lingual root angulation settings was used throughout the study. The bases of the typodont were partially sectioned in eight different locations corresponding to eight different individual teeth so that the tooth bucco-lingual orientation could be easily modified and still be attached to the typodont. Tooth selection was based on an attempt to represent as many teeth as possible without compromising the integrity and stability of the typodont. The teeth chosen were the maxillary right lateral incisor (1.2), the maxillary right central incisor (1.1) , the maxillary left canine (2.3), the maxillary left first premolar (2.4), the left mandibular incisors (3.2 & 3.1), the mandibular right canine (4.3) and mandibular right first premolar (4.4). Each section and its corresponding tooth remained attached to the typodont via the archwire which preserved the original mesio-distal angulations.

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Subsequently the bucco-lingual angulations were modified using the arch wire as the center of bucco-lingual rotation for that particular tooth. An additional chromium steel ball was placed apical to the tooth on the fixed portion of the base, in order to maintain a reference point for the assessment of the bucco-lingual angulations changes. The gaps between the segments of the bases were stabilized with pink denture baseplate wax. (Dentalwax) (Appendix B)

In total, three different buccolingual angulations were used for each tooth. A decision was made to modify the neutral or original buccolingual angulation of each tooth by rotating the root toward the buccal 10° (buccal root torque) and toward the lingual 10° (lingual root torque). Nine different buccolingual angulations settings were necessary to analyze all the possible buccolingual orientations combinations between adjacent teeth. (Table 2.1)

The natural dentition and supporting alveolar/basal bone of a skull were removed to allow placement of the maxillary and mandibular typodont. Placement of this typodont was precisely focused to represent cephalometric normalcy in all three planes of space. In the transverse plane, the dental midline of the typodont was coordinated with the skulls skeletal midline and confirmed with posterior-anterior cephalogram. In the antero-posterior plane, a steel ball was placed at a defined A-point and a confirming lateral cephalogram image was taken. McNamara's cephalometric norms[15] for maxillary skeletal position (ie. Frankfurt horizontal to A-point perpendicular) were used to idealize the maxillary skeletal antero-posterior position.

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The mandibular typodont anterior-posterior position was determined by its centric occlusion articulation with the maxillary typodont. The dental relation of the typodont teeth was Class I molar and canine with 2mm overjet and 2mm overbite. The vertical positioning was dictated by the pre-existing distance from nasion to upper incisor incisal edge and the cant of the occlusal plane was based on cephalometric norms for the angular measurement of Frankfurt horizontal to occlusal plane[16]. Once the objectives of the positioning of the typodont within the skull were accomplished, the typodont was rigidly fixed into place over the remaining basal bone with pink denture baseplate wax and wires. (Appendix A).

2.2.2. Actual Angle Determination

A Coordinate Measuring Machine (C.M.M) (Starrett Corporation, Athol U.S.A.) at the Northern Alberta Institute of Technology was used along with a custom designed excel spread sheet to determine the actual (or true) mesio-distal and bucco-lingual angulation of the typodont teeth relative to the reference archwire. (Appendix C) Following initial calibration and set-up of the C.M.M., the steel markers and reference arch wire were digitized using varying orientations of external probes with a ruby ball measuring 1.00mm in diameter. The C.M.M. provided X, Y, and Z coordinate values (in millimeters) for each digitized point. The CMM is precise within 0.025 mm according to the manufacturer.

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Each tooth measurement consisted of six digitization points:

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.

T^r (tooth root)-contact of the C.M.M. probe with the most inferior surface of the steel ball at the apical end or furcation point of the typodont tooth.

W^d (wire distal)-contact of the C.M.M. probe on the superior surface of the reference archwire parallel to the distal contact of the typodont tooth with its neighboring tooth

W^m (wire mesial)-contact of the C.M.M. probe on the superior surface of the reference archwire parallel to the mesial contact of the typodont tooth with its neighboring tooth.

A (apical base)-contact of the C.M.M probe on the labial surface of the steel ball on the apical base of those teeth where the bucco-lingual angulation was modified.

B (bracket center)- contact of the C.M.M. probe on the anterior and central surface of the bracket which corresponds to the center of rotation of the typodont tooth around the wire (hinge axis).

T^c,T^r , **W^d** and **W^m** were used to calculate the mesio-distal angulations of the teeth. **T^c,T^r** , **A** and **B** points were used to compute the bucco-lingual angulations of the teeth.

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The X, Y and Z coordinate values for each point were entered in Excel spreadsheet format for generation of the actual or "real" mesio-distal and bucco-lingual angulation of the six different settings. (Appendix D)

The mesio-distal angle reported was the angle between the tooth long axis (represented by the steel balls) and reference arch wire. The reported bucco-lingual angle was the angle between the tooth long axis and the apical base-archwire reference line. Mesio-distal angulation greater than 90° represented distal root inclination and a value less than 90 indicated mesial inclination. Each tooth was measured five times to calculate the original mesio-distal and bucco-lingual angulation. Every time the bucco-lingual angulation was changed in the nine experimental settings, the bucco-lingual angulation determination for each tooth was repeated eight times.

2.2.3. Panoramic Imaging

For the panoramic projections the PM 2002 EC Panoramic unit (Planmeca; Helsinski, Finland) was used due to its more favorable beam angulation, as opposed to other panoramic units [12, 17]. The skull was placed, according to the manufacturer's instructions into the pantomographic unit (i.e. centered to the midsagital plane with FH parallel to the floor and the upper and lower incisors biting into the bite tab). Landmarks were predetermined and marked on the skull and panoramic unit to allow for the alignment with the machine positioning guides.

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Vertical and horizontal head positioning techniques were standardized as much as possible. Several radiographs were made to determine the best exposure setting in order to achieve the best contrast and least blurring. Two films were used in the cassette on each exposure to compensate for the lack of soft tissue.

2.2.4. Image Angle Determination

Each pantomographic image was scanned into a computer using a flat bed scanner with a resolution of 400 d.p.i and magnification of 200% (Epson Expression 1680). Determination of the 'measured' mesio-distal angulation from the pantomographic images was carried out using custom computer software. (Panoramic angulator, Crusher software, Edmonton Canada). The Software program was developed to allow digitization of the scanned images using four points for each tooth angle determination. These points corresponded to the locations used during 'actual' mesiodistal angle determination with the CMM. The order of landmark identification was standardized; however the sequence the teeth that were digitized on each film was randomized.

The digitization process was repeated sixteen times. At the end of the digitation process the program generated an excel spreadsheet of the image mesiodistal angulations. For the purpose of evaluating root parallelism expression the eight teeth were divided into four different pairs: Maxillary central and lateral incisor, maxillary canine and first premolar, mandibular central and lateral incisor and mandibular canine and first premolar. (Appendix E)

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In order to obtain a quantification of root parallelism two angles were used:

1. For the tooth closer to the midline, an angle between the tooth long axis and the distal segment of the archwire was calculated. The distal angle was the complementary angle of the angle calculated by the software.
2. For the tooth farther from the midline the angle between the long axis and the mesial segment of the archwire was calculated by the software.
3. The delta angle for each particular teeth pair was the summation of the aforementioned angles.

The delta angles were used to asses root divergence or convergence between the four adjacent tooth pairs (See Appendix D). As a result four angles were defined:

Δ1= Angle between the long axis of the upper central incisor (1.1) and the lateral incisor (1.2)

Δ2= Angle between the long axis of the upper canine (2.3) and the first premolar (2.4)

Δ3= Angle between the long axis of the lower central incisor (3.1) and the lateral incisor (3.2)

Δ4= Angle between the long axis of the lower canine (4.3) and the first premolar (4.4)

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2.3 Statistical Analysis

A pilot study was carried out to determine measurement error and intra-rater reliability of angle measurements in order to determine the sample size. Based on the results of this study, 16 replicates of each adjacent teeth angulation per setting were made. (48 replicates for each bucco-lingual root orientation per tooth) The sample size was calculated using PASS (NCSS, Kaysville, USA) with a multiple comparisons power analysis in order to detect differences among image angulations of one degree or above with a power of 90%. (Appendix F)

Descriptive statistics, including mean and standard deviations were calculated (SPSS software, Chicago, IL) for each set of angular measurements. Repeated measures ANOVA tests, using the Bonferroni test for pairwise comparisons were completed for each tooth to detect the mean differences among the image mesio-distal angulations when the tooth was in its neutral bucco-lingual angulation, 10° lingual root angulation and 10° buccal root angulation.

In addition, one sample t-tests were carried out to determine the differences between the true mesio-distal angulation for each tooth (calculated by the CMM) and the image mesio-distal angulations for each tooth with different bucco-lingual orientations.

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For statistical purposes the root parallelism angulations (deltas) were divided into four independent groups. It was decided to use the delta angle when both teeth were in their neutral bucco-lingual orientation as the reference angle to assess image root parallelism changes. The mean differences between delta angles where the bucco-lingual orientation was modified and the reference delta angle were calculated using repeated measures ANOVA tests, along with Contrast tests. The mean differences are represented in negative and positive values. Negative values correspond to root convergence and positive values are related to root divergence.

2.4 Results

The reproducibility for angles measurements with the CMM, shown by standard deviations, ranged from 0.10° to 0.65° for mesiodistal angulations and from 0.54° to 1.76° for bucco-lingual angulations (Table 2.2). Intra-rater correlation coefficient tests were completed with the purpose of evaluating intra-rater reliability for the digitization and calculation of the image mesio-distal angles. Based on the bucco-lingual orientations that were repeated on each selected tooth, from setting to setting, it was decided to randomly select and analyze values for image mesio-distal angulations for lingual, buccal and neutral orientations independently at day 1, 2 and 3. According to the results of five randomized tests the intra-rater correlation coefficient varied from 0.961 to 0.982 for buccal inclinations, 0.849 to 0.944 for lingual inclinations and 0.932 to 0.948 for neutral inclination (Appendix H).

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For the first part of the study all the mesio-distal image angles for each tooth were divided into three groups according to its bucco-lingual orientation (unmodified or neutral, 10° lingual root torque and 10° labial root torque). The means and standard deviations for the image mesio-distal angulations for all eight teeth are provided in Table 2.3. Repeated measurement ANOVAs and pairwise comparisons for each tooth, including mean difference and significance among the image mesio-distal angulations, are presented also in Table 2.3.

Almost all the image angles for each tooth had at least one angle measurement that was statistically different from the other mesio-distal angles with different bucco-lingual orientations. The only exception was the maxillary right central incisor. Figure 2.1 demonstrate a trend in the overestimation and underestimation of the mesio-distal tooth angulation dependent on bucco-lingual orientation for the canines and premolars. The panoramic image in general underestimated the mesio-distal angulations of teeth that had a lingual root angulation, while overestimating the ones that had a buccal root orientation. The roots with lingual root orientations were projected more mesially than they were in reality. On the other hand, roots bucally positioned were projected more distally. This phenomenon was particularly evident in the canine and premolar region, with the maxillary angulations being more affected than the mandible. For instance, the image angle difference between the 2.4 with lingual root orientation and the 2.4 with buccal root orientation was 18.5°. The trends observed on the premolar and canine region on both arches regarding the increase or decrease of the angle due to bucco-lingual angulations were not observed on the incisors.

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One sample t-tests revealed statistically significant differences between image mesio-distal angulations and true angulations for almost all the teeth selected, regardless of their bucco-lingual inclination. If analyzing only the image angulation values when the teeth were in their neutral bucco-lingual positions, statistically significant differences were noted on all the teeth selected in the mandible and the maxilla (Appendix I). Nonetheless, on the maxilla the angular differences for 1.1, 1.2 and 2.3 were less than one degree. The true angulation of 1.1 was slightly overestimated whereas the true angulations of 1.2 and 2.3 were slightly underestimated on the image. 2.4 image angulation was overestimated in the image by 3.5°. On the mandible the discrepancies were larger for the canine and premolar. The differences for the central and lateral incisor did not exceed 1.5°. The canine and premolar angulations were severely underestimated by 9.7° and 7.5°, respectively.

Root parallelism expression was also affected by bucco-lingual root angulations. Table 2.5 shows the mean differences between the delta angulations for modified bucco-lingual angulation settings and the reference delta angle. Negative values correspond to root convergence and positive values are related to root divergence. The parallelism angular distortion was more pronounced in the canine and premolar regions and was more pronounced on the maxilla than the mandible.

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For Δ2 (upper canine and first premolar) the maximum image root convergence was observed when the canine had a buccal root angulation and the premolar a lingual root angulation. There was a difference of 14° between this bucco-lingual setting and when both teeth were in their original bucco-lingual angulation. On the other hand the maximum root divergence was observed when the canine had a lingual root orientation and the premolar a buccal root orientation (Appendix G). The same distortion pattern but in less extent was observed in the lower canine and first premolar region (Figure 2.2). Δ3 (lower central and lateral incisor) was the least affected of all the Δs with no statistically significant differences(Appendix J).

Discussion

Previous investigations regarding the relationship of buccal-lingual root angulation and dimensional distortion of Panoramic x-ray images were conducted on non anatomical devices with non-realistic tooth orientations that do not represent accurately the human dentition. Most of these studies were based on wire meshes and pins representing the dentition and supporting structures [7, 9, 18]. The phantom used in the present study was designed to represent arch forms and dimensions that could resemble clinical situations. The anatomical tooth bearing apparatus had clinically reasonable root angulations (mesio-distal and bucco-lingual) that can be applied with confidence to clinical settings.

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Statistically significantly differences were found for the majority of the image angulations, among the three different bucco-lingual root orientations for each tooth. The mean differences for the anterior teeth on the maxilla and the mandible were within a range of 0.03° and 1.41°. Clinically significant tolerance limits should be applied to these results. It has been reported that mesiodistal variations of as much as 2.5° between a tooth and an established reference point do not represent a serious problem from a clinical perspective [9, 11, 12, 18, 19]. If this threshold is applied, only 50% of the measured mesio-distal image angles were clinically significantly different when the bucco-lingual orientation of the root was modified. These differences were only found in the canine and premolar regions of both arches. The vulnerability of mesio-distal image angular expression attributable to bucco-lingual angulation changes can be explained by different factors.

The focal trough (also known as image layer) is a three dimensional horseshoe shaped area in which anatomical structures are well defined on panoramic x-rays. The focal trough is calculated using mathematical models to position the dental arches in order to obtain the clearest image[20]. Objects outside the focal through appear blurred, magnified and distorted[21]. This distortion is different at different locations in the jaws. It varies from anterior to posterior and at different depths within the trough [22]. Errors in the expression of a tooth long axis result from the combined distortion in the vertical and horizontal dimensions[6].

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Bucco-lingual orientation changes alter the object film and source-object distances, resulting in varying degrees of horizontal and vertical magnification, and consequently might cause angular distortion[23]. The focal trough of certain panoramic machines do not cover all tooth positions completely, particularly in the anterior region[24]. As a consequence, slight anteroposterior or lateral malpositioning of the dental arch from correct position will place some teeth outside the focal trough causing the image angulation to be distorted.

It has been demonstrated by different researchers [14, 25 26] that when an object is positioned buccal to the focal trough, its image on the film is usually enlarged vertically and the object appears to be more mesially inclined or upright than in reality. On the other hand, objects that are placed lingual to the focal trough are elongated horizontally and depicted with a more distal inclination. If anteroposterior positioning of the object out or within the focal trough was the main factor responsible for angular distortion due to bucco-lingual orientation changes the results of this study would be different to what was found. As a result other causative factors should be considered.

During a panoramic radiograph exposure the machine shifts to various centers of rotation. Depending on the manufacturer, the number and locations of the center of rotation differ. The most popular mechanical movement patterns are those that use a continuously moving rotation center. This sliding movement throughout the excursion is constantly shifting along a defined path.

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The central ray of the beam is always tangential to a defined curved path and hence defines the projection of each successive part of the jaws. This rotational change allows the image layer to conform to the elliptical form of the dental arches[27, 28]. In order to follow the curvature of the dental arches, several angular changes of the scanning x-ray beam occur during the exposure.

When the central plane of the layer is not perpendicular to the beam, an object will appear distorted even though it lies entirely within the central plane. In panoramic radiography the projection of the jaws is not truly orthogonal and the distortion is also affected by the angulation between the x-ray beam and the object[29]. Depending on the equipment, the deviation from true orthogonally has been reported to be in a range of 15° to 45° in the premolar region[30]. This projection distortion may contribute to, and in fact be the major factor responsible for the panoramic image error for mesio-distal root angulation due to bucco-lingual angulation changes.

As a consequence of this optical phenomenon any increase in the buccal inclination of the root would be seen as an increase in the distal orientation of the tooth. Buccal orientation of the root would result in an overestimation of tooth angulations. The opposite is true for lingual root orientations, any changes toward that direction may result in underestimation of the tooth mesio-distal angulation.

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The anterior region is not very sensitive to changes in bucco-lingual root orientations due to the fact that the angular changes of x-ray beam allow for a more orthogonal projection of the jaws. The projection angle progressively deviates more from the true orthogonal toward the posterior regions, causing any bucco-lingual root angulation changes to be perceived as mesio-distal angulations changes.

Previous researchers have reported that the mandible presents less dental overlapping than the maxilla [31]. The projection angle deviation for the dentition in the mandible is perhaps more favorable than in the maxilla. As a result the tolerance limits against angle distortion are greater in the lower jaw than the upper jaw [10, 13]. These larger discrepancies between the optimal and actual beam direction could explain the increased susceptibility of the upper canine-premolar region over the same mandibular region.

The results of this study partially support the previous findings by McKee et al. According their findings, the maxillary incisors and canines true angulations are usually underestimated on the panoramic image, where as the posterior maxillary teeth angulations are usually overestimated. Nonetheless, on the maxilla the angular differences for 1.1, 1.2 and 2.3 were less than one degree. Based on the previous stated clinical tolerance limits, only the 2.4 image angulation can be considered clinically significantly different. Its angulation was overestimated in the image by 3.5° in accordance to the findings of McKee et al. For the mandible, based on their results, almost all image angles underestimate the true angles. The discrepancies were larger for the canine and premolar.

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The differences for the central and lateral incisor can be considered clinically insignificant since they didn't exceed 1.5°. The canine and premolar angulations were severely underestimated in accordance with, the results of McKee et al. [12].

If significant bucco-lingual orientation discrepancies exist between adjacent teeth, treating to the panoramic image expression may lead to root convergence or divergence depending on the teeth long axis orientations. The root parallelism distortion could be considered clinically insignificant for the anterior regions. Δ1 (upper central and lateral incisors) presented some statistically significant differences among the different bucco-lingual settings, but these differences were less than 2.5°, which can be considered clinically insignificant. The largest projected angular differences between adjacent teeth occurred between the upper canine and upper premolar.

When the canine had a buccal root orientation and the premolar a lingual root orientation, the root parallelism in the mesiodistal plane was projected on the film as root convergence. Treating to the panoramic radiograph would result in extreme root divergence. The opposite was found when the canine had a lingual root orientation and the premolar a buccal orientation. Treating to the panoramic radiograph would result in unnecessary root convergence This has special significance for orthodontically closed extraction sites, since they are more prone to open if the adjacent teeth are not parallel[32-36]. In the mandible, the canine and the first premolar parallelism discrepancies were much smaller than the maxilla.

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As stated by previous researchers, the usage of panoramic radiograph to assess root angulation and parallelism in the first premolar extraction area might be of poor clinical value[12]. It is important that the clinician be aware of the effect that orthodontic introduction of canine and/or premolar root torque will have on perceived mesio-distal root angulation based on the panoramic radiograph. If the buccolingual position of a canine is maintained constant, orthodontic buccal root torque of the premolar may be expressed as root divergence on the panoramic film. Lingual root torque of the premolar would be expressed as root convergence.

The decision to select 10° of buccal and lingual root angulations changes was based on an attempt to simplify but at the same time to make use of realistic angulation changes. These bucco-lingual orientations, from a clinical point of view, would likely represent reasonable ranges of normal bucco-lingual angulations that can be achieved by using fixed orthodontic appliances. Bucco-lingual root angulations greater than 10 degrees would be clinically noticeable and probably not desirable.

Axial positioning of teeth in the bucco-lingual plane is very orthodontically difficult to control. Multiple variables related to the properties of the orthodontic materials may have an influence on the bucco-lingual orientation of a tooth in the space. These variables include: inability to fill the slot, irregularities from the manufacturing of brackets, differences in the stiffness of wire alloys, variations between actual and reported bracket torque values and ligation modes [4].

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Moreover, anatomical variables such as facial surface contours and the angle formed by the coronal and radicular long axis, are extremely variable in the general population. These anatomic variations will result in varying torque expression with direct impact on bucco-lingual root angulations [5].

Cost effective low radiation dose three dimensional imaging is now available with the new volumetric image scanning devices [37, 38]. These imaging devices offer the clinician an opportunity to simultaneously evaluate mesiodistal and buccolingual root angulation without the inherent distortion of panoramic radiography. In the absence of three dimensional imaging, sound clinical judgment and experience is still the most common, cost effective method used to assess bucco-lingual angulations.

The results of this study are only directly applicable to the panoramic machine used in this study. The results might be different if using panoramic machines with different focal troughs and axis of rotation. Nevertheless, based on a previous study that compared the optimal beam angulations of four different panoramic units, all units had similar distortion for mesiodistal root angulations [12]. The PM 2002 CC, used in the present study, deviated the least from optimal angulation over most of the dental arch. [17] The effect of bucco-lingual root angulations identified in the current study may be more pronounced with other panoramic units.

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It is important to consider that differences in the arch form can also introduce different degrees of image angular distortion due to bucco-lingual angulations. Those arch forms that accommodate better to the panoramic machine average arch form and angulations changes will be less susceptible to angular distortion. The effect of bucco-lingual angulation changes less or greater than 10° on the mesio-distal image angulation were not contemplated in this study. Whether the discrepancies between the image angles and the true angles are proportional to amount of change is still to be analyzed.

Conclusions:

Within the limitations of this study the following conclusions can be made:

- The majority of the image mesio-distal angulations for each tooth were statistically significantly different when the bucco-lingual orientation of the tooth was modified. The only exception was the upper right central incisor.
- The image angle in general underestimated the mesiodistal angulations of the teeth that had a lingual root angulation, while overestimating the ones that had a buccal root orientation. The roots with lingual root orientations were projected more mesially than they are in reality and the roots bucally positioned were projected more distally.

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- The canine and premolar regions presented the largest mesiodistal angular discrepancies among the different buccolingual orientations. If applying clinically significant tolerance limits of ±2.5° in the mesiodistal angulation to the reference archwire, only the image angles of these teeth can be considered clinically significantly different from each other.

- The mesiodistal angle distortion due to buccolingual angulation changes seems to increase from anterior to posterior regions. The discrepancies among the image angles for each tooth were larger for maxillary teeth than for mandibular teeth.

- When changing the buccolingual angulation, the largest angular differences between adjacent teeth occurred in the upper canine/premolar area. The second largest discrepancy occurred in the mandibular canine/premolar area.

- An understanding of the buccolingual orientation effects on the image mesiodistal angulation expressions for panoramic images is extremely necessary, especially in the premolar extraction site.

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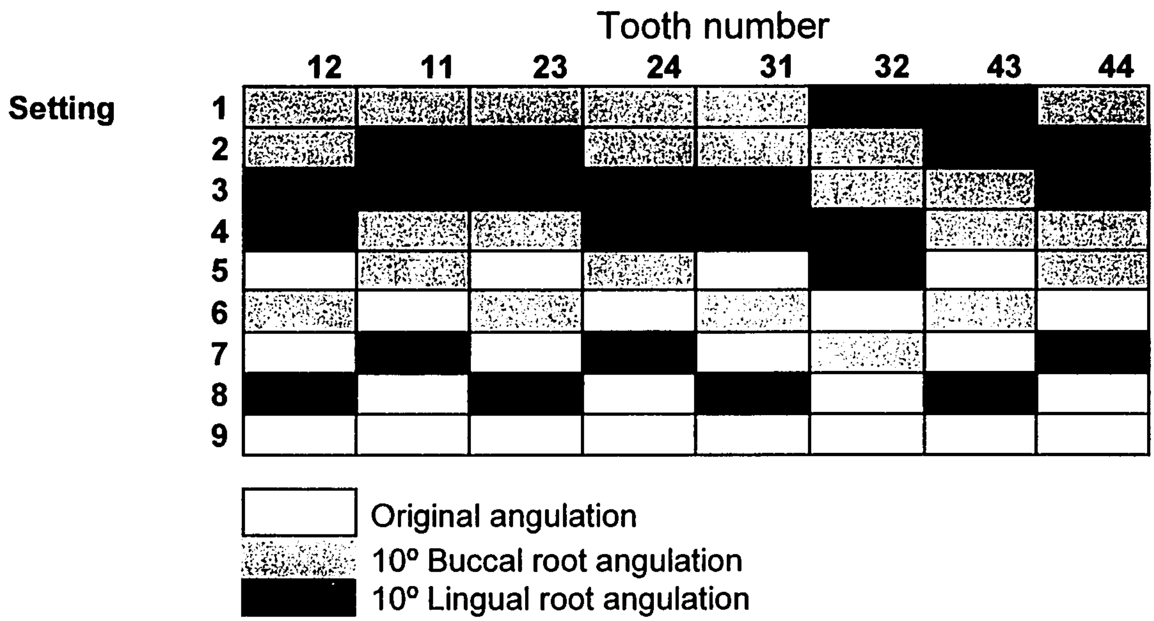
2.8 FIGURES AND TABLES

Table 2.1
Buccolingual angulations settings for the nine Panoramic image sequences



Each box color represents the bucco-lingual root orientation for each tooth on each particular setting.

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Table 2.2

Mean and standard deviation values for the mesiodistal and bucco-lingual angulation of the phantom. (in degrees) Displayed by tooth number determined with the C.M.M

tooth No.	Mesiodistal angles			Neutral Buccolingual angles		
	Mean	S.D	C.V*	Mean	S.D	C.V*
11	91.87	0.43	0.47	11.43	0.54	4.7
12	95.18	0.65	0.68	13.77	1.10	8.0
23	94.18	0.24	0.25	13.11	0.64	4.9
24	91.95	0.53	0.58	8.46	0.71	8.4
31	91.27	0.33	0.36	15.56	1.02	6.6
32	91.24	0.28	0.31	17.56	0.49	2.8
43	95.17	0.36	0.38	2.63	1.50	57.0
44	94.10	0.10	0.11	7.62	1.76	23.1

***CV (Coefficient of variation) Measurement of relative variation that express the standard deviation as a percentage of the mean.**

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Table 2.3

Mean and Standard deviations for the image mesiodistal angulation by tooth number and buccolingual orientation (in degrees) including mean differences for pairwise comparisons.

Tooth	Actual(CMM) Mean &SD	Root orientation	Image Mean & S.D	(I) Buccolingual Orientation	(J) Buccolingual Orientation	Mean Difference (I-J)	P-Value
11	91.87±0.43	Neutral	90.96 ± 1.17	10° Buccal	10° Lingual	0.03	1
		10 ° Buccal	90.76 ± 0.92	10° Buccal	Neutral	-0.20	0.998
		10° Lingual	90.72 ± 0.90	10° Lingual	Neutral	-0.23	0.601
12	95.18±0.65	Neutral	95.66 ± 0.89	10° Buccal	10° Lingual	-0.28	0.433
		10 ° Buccal	95.21 ± 1.02	10° Buccal	Neutral	-0.45	0.046*
		10° Lingual	95.49 ± 0.64	10° Lingual	Neutral	-0.17	1
23	94.18±0.24	Neutral	94.66 ± 0.99	10° Buccal	10° Lingual	8.61	0.000*
		10 ° Buccal	99.78 ± 0.95	10° Buccal	Neutral	5.12	0.000*
		10° Lingual	91.17 ± 1.61	10° Lingual	Neutral	-3.50	0.000*
24	91.95±0.53	Neutral	95.52 ± 0.90	10° Buccal	10° Lingual	18.42	0.000*
		10 ° Buccal	105.93 ± 1.32	10° Buccal	Neutral	10.41	0.000*
		10° Lingual	87.5 ± 1.87	10° Lingual	Neutral	-8.01	0.000*
31	91.27±0.33	Neutral	92.14 ± 1.13	10° Buccal	10° Lingual	1.37	0.000*
		10 ° Buccal	92.09 ± 0.84	10° Buccal	Neutral	-0.04	1
		10° Lingual	90.73 ± 1.41	10° Lingual	Neutral	-1.41	0.000*
32	91.24±0.28	Neutral	89.73 ± 1.17	10° Buccal	10° Lingual	0.21	1
		10 ° Buccal	88.96 ± 1.03	10° Buccal	Neutral	-0.77	0.007*
		10° Lingual	88.75 ± 1.77	10° Lingual	Neutral	-0.98	0.007*
43	95.17±0.36	Neutral	85.44 ± 1.02	10° Buccal	10° Lingual	6.45	0.000*
		10 ° Buccal	89.24 ± 1.14	10° Buccal	Neutral	3.80	0.000*
		10° Lingual	82.79 ± 1.40	10° Lingual	Neutral	-2.65	0.000*
44	94.1±0.10	Neutral	86.56 ± 1.56	10° Buccal	10° Lingual	8.83	0.000*
		10 ° Buccal	90.31± 1.62	10° Buccal	Neutral	3.75	0.000*
		10° Lingual	81.48 ± 1.08	10° Lingual	Neutral	-5.08	0.000*

- **A mesiodistal angulation greater than 90° indicates a distal inclination of the root. A mesiodistal angulation less than 90° indicates a mesial inclination of the root**
- **Based on 48 measurements for each tooth for each buccolingual orientation**
- *** A p-value of less than 0.050 is considered statistically significant**

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Figure 2.1
Image mesiodistal angulations according to buccolingual angulations by tooth number

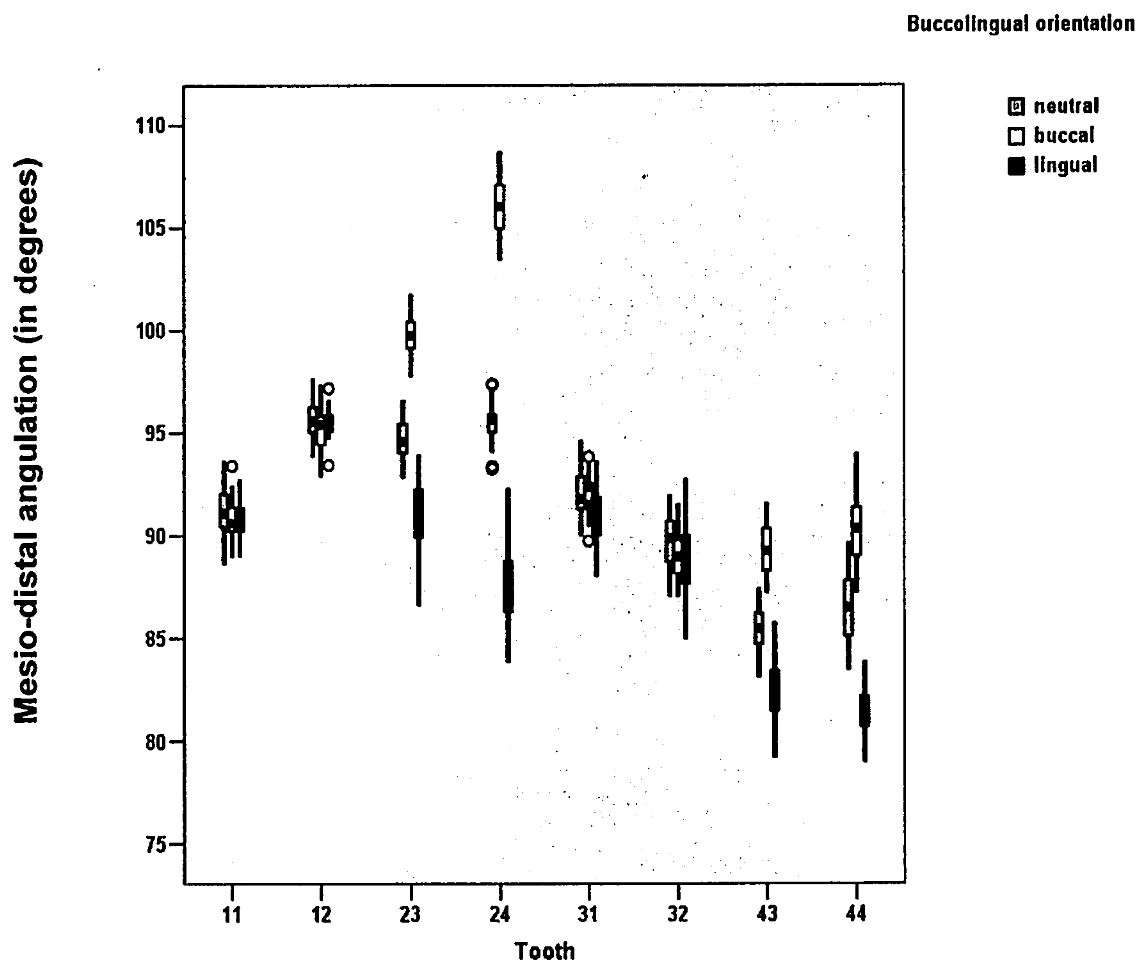

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Table 2.5

Mean angular differences (in degrees) between each delta angulation setting and the delta angle for neutral bucco-lingual orientation.

ROOT ORIENTATION	Δ 1 (11-12) mean difference	p value	Δ 2 (23-24) mean difference	p value	Δ3 (31-32) mean difference	p value	Δ4 (43-44) mean difference	p value
Buccal+Lingual	0.88	[illegible]	-14.23	[illegible]	-0.6	[illegible]	-9.53	[illegible]
Neutral+Lingual	1.6	0.008	-7.35	[illegible]	0.3	[illegible]	-5.08	[illegible]
Buccal+Neutral	-0.45	0.445	-5.75	[illegible]	-0.66	0.304	-3.78	[illegible]
Lingual+Lingual	-0.52	0.248	-1.35	0.057	-1.24	[illegible]	-3.01	[illegible]
Lingual+Neutral	0.45	0.376	3.79	0.000	-0.94	[illegible]	1.64	0.000
Buccal+Buccal	-0.02	0.965	6.01	0.000	-0.58	[illegible]	1.01	[illegible]
Neutral+Buccal	0.6	0.127	10.18	0.000	0.27	0.595	3.54	[illegible]
Lingual+Buccal	-0.45	[illegible]	13.53	0.000	-1.05	0.285	5.2	0.000

- **Negative values relate to root convergence and positive values relate to root divergence.**
- **The mean difference is significant at 0.05 level.**

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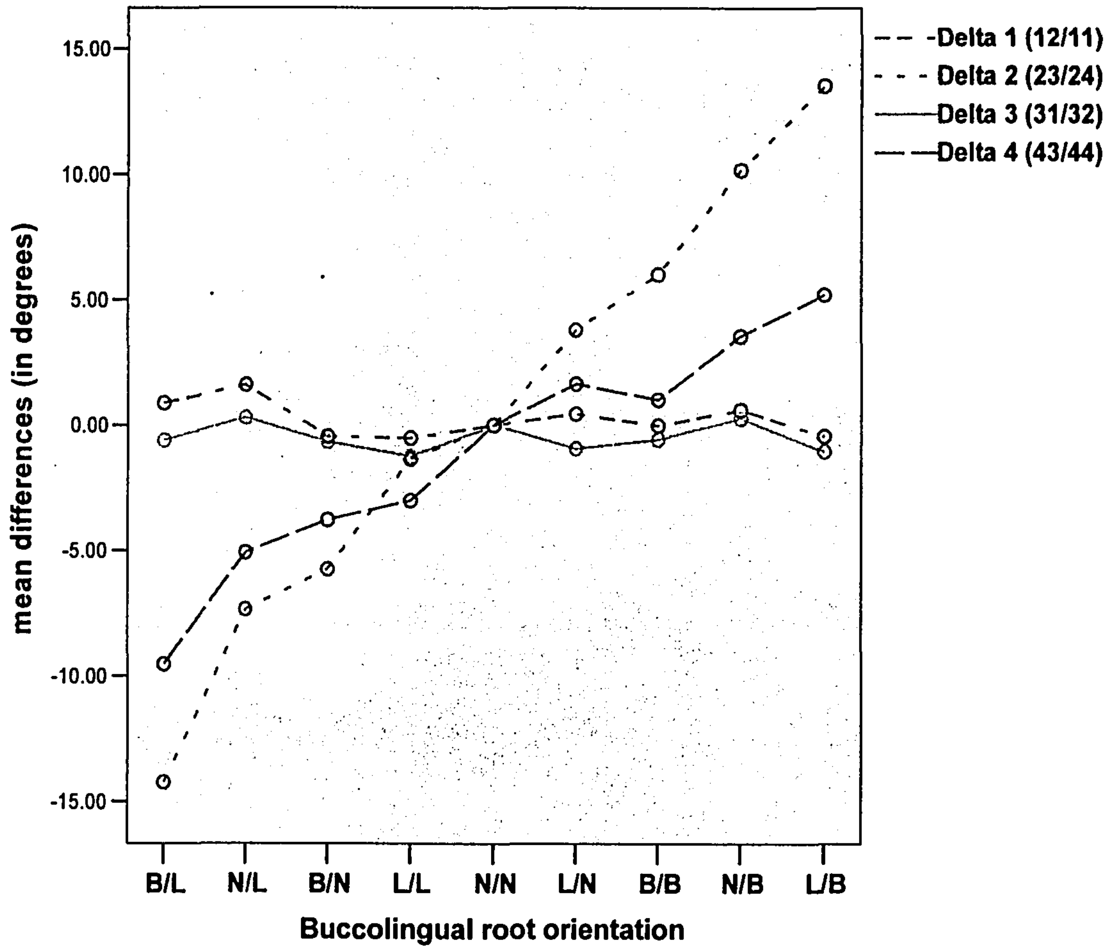
Figure 2.2

Mean delta angulations differences between different buccolingual angulation settings and the delta angle for neutral bucco-lingual orientations.



- **Mean angular Difference = (Delta angle for each setting per adjacent teeth pair) – (Delta angle for the setting where both teeth were in their neutral bucco-lingual orientation)**
- **The letters correspond to the bucco-lingual orientation for each tooth: Buccal root torque (B), Lingual root torque (L), Neutral Root Torque (N). The fist letter corresponds to tooth closer to the midline and the second one to tooth farther from the midline.**
- **Negative values relate to root convergence and positive values relate to root divergence)**

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Chapter 3

General Discussion

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3.1 Importance and control of buccolingual tooth angulations.

In orthodontics correct positioning of the teeth in the three planes of space is necessary to obtain correct occlusal relationships and a stable result. Correct alignment of the teeth, good occlusal function and dental esthetics are determined mainly by the proper orientation of the teeth within the alveolar processes. Most of the interest in the orthodontic literature regarding tooth orientation has been focused on mesio-distal tooth angulation. It is well known that root parallelism is an important factor in the distribution of occlusal forces with closed contact points[1]. If roots are well positioned, sufficient bone will be present between adjacent teeth. Orthodontically closed extraction sites are more susceptible to open again if adjacent teeth roots are not parallel[2-7].

The bucco-lingual orientations of teeth are also very important since they position the roots to best withstand the forces of occlusion. Torque of the maxillary incisors is particularly necessary in establishing correct anterior guidance and an esthetic smile line. Moreover, inadequately inclined teeth can create arch length discrepancies on the anterior segment and constriction and/or improper cusp to fossa relationships on the posterior segments[8, 9]. Given the importance of bucco-lingual angulation to the orthodontic result it is surprising that bucco-lingual tooth angulation has taken a secondary role to mesio-distal angulation.

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Bucco-lingual angulation is probably more difficult to control than mesio-distal angulation[9]. Bucco-lingual root angulation changes are in general more constrained by the anatomical envelope (alveolar process); at least more so than mesio-distal root angulation changes. The level of attached gingival can be dramatically affected by the bucco-lingual orientation of a tooth in the alveolar process. Areas with thin, delicate gingival tissue are more prone to exhibit gingival recession with buccal inclination of a tooth, especially in the incisor area. In areas where inflammation is present, loss of connective tissue attachment usually occurs. Critical evaluation of bucco-lingual angulations is in general more important from a periodontal perspective than mesio-distal tooth inclinations[10].

The straight wire appliance is designed to control tooth positions and inclinations in three mutually perpendicular planes of space. From a technical perspective axial positioning of teeth in the bucco-lingual plane is the most difficult to control. Anatomical factors can influence dramatically the bucco-lingual orientation of the teeth. The buccal contours of the teeth are not identical between patients. Any given torque placed in the bracket could result in the placement of the same types of teeth at different bucco-lingual orientations according to variations in the buccal surface contours. Even if the buccal surface contours were constant, variations between the long axis of the crown and the long axis of the root would result in different root orientations with constant crown positions [8].

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A second factor of torque variation in preadjusted brackets arises from the interaction of materials with dissimilar properties. Material properties such as hardness and elastic modules differ significantly among different archwire types and sizes, causing different degrees of torque expression. Other sources of variation in the expression of torque include the inability to fill the slot because of the size differences between archwire and bracket slot, irregularities from the manufacturing process of brackets and ligation modes. All these factors could account for increased third order clearance or bracket archwire play that might result in incomplete torque expression [9].

3.2 Panoramic radiography and buccolingual angulation

During diagnosis, treatment planning and shortly before the end of orthodontic treatment the orthodontist takes radiographs to evaluate the overall mesio-distal root angulations of the teeth in the maxilla and mandible. Examination of the literature reveals that panoramic radiography is the most common diagnostic tool to assess root inclination and parallelism. In a 2002 survey of orthodontic diagnosis and treatment procedures of American orthodontists, 57.9% and 79.1% of respondents reported taking progress and post-treatment panoramic radiographs respectively [11].

Panoramic radiography is the American Board of Orthodontics recommended tool to assess root inclination and parallelism. This is done to evaluate the adequacy of the orthodontic finishing[12].

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Given the popularity and the importance of panoramic radiographs in orthodontic diagnosis and treatment, it is important to remember that a panoramic radiograph is a two dimensional representation of three-dimensional anatomical structures. The ideal imaging modality in orthodontics is the one that enables the clinician to determine anatomic truth in terms of the accurate depiction of spatial orientation, size, form and relationships of desired structures. This requires assessment of the anatomy in three planes of the space because craniofacial form is defined three dimensionally and substantial and important information is lost when a three dimensional structure is represented in a two-dimensional format. The diagnostic imaging methods used nowadays in most orthodontic practices are not intended to assess bucco-lingual tooth inclinations. In the hope of eliminating expression errors, methods have been developed to provide three-dimensional representations of the craniofacial complex. Three-dimensional techniques such as computer assisted tomography can be extremely useful in assessing bucco-lingual tooth angulations and the effects of orthodontic treatment upon tooth orientation and supporting periodontal structures. Even though the popularity of these diagnostic tools is increasing, they are still far from being a widely used diagnostic tool in orthodontics. There is still insufficient information on appropriate or "normal" tooth positions, especially bucco-lingual angulation. It's controversial if normalcy is different among different facial types [13, 14]. This information could be valuable to the clinician toward the objective of obtaining a stable and predictable result.

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Artifacts on the panoramic radiograph are due to the projection of a volume on to a plane surface. These artifacts are not seen on the computed tomographic techniques. Reformatted CT has been used in recent years for cross-sectional imaging of the jaws[15]. Through the use of this method, multiple thin axial slices obtained through the jaws are directly acquired as the x-ray tube rotates around the patient. The data are then reformatted to produce cross-sectional and curved "panoramic images." Software allows for reformatting and viewing the image data from any point of view. Using these software tools the anatomy can be peeled away layer by layer to view the desired anatomy.

One computed tomographic technique, cone beam computed tomography is very promising due to its inherent speed in volumetric acquisition. Moreover it permits intrinsically the manufacture of less expensive CT machines. The advantages of CT systems are uniform magnification, generation of a high-contrast image with a well-defined image layer free of blurring, multiplanar views, 3-D reconstruction, and the availability of image evaluation software. According to Mah [15] tri-dimensional imaging can resolve many of the shortcomings of traditional methods, particularly those associated with projection and perspective.

Despite its anticipated superiority with regards to the accuracy of cone beam CT to asses root angulation and parallelism over regular radiographic techniques, no study has been published yet. Disadvantages of CT include expense, and higher doses of radiation than those received during conventional panoramic radiographic techniques.

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Mozzo et al. [16] studied the geometrical distortion and the radiation dose absorbed by patients using specific mandibular type phantoms on Newtom (CBCT) scans. On average the radiation dose absorbed is between 4 to 9 mSv and approximately one sixth that of traditional spiral CT. Radiation dosimetry studies conducted by Mah [15] et al. have placed the effective absorbed dose at 50.3 μSv. A Panoramic image is in the range Of 2.9-9.6 μSv and a full mouth series ranges from 33 to 84 μSv.

Panoramic radiography has many shortcomings related to the accuracy of size, location and form of the image created [17]. These discrepancies occur for the reason that the panoramic image is made by creating an image layer or focal trough within a generic jaw form or size. Any deviation from this generic jaw form will result in a structure that is not centered within the image layer causing some degree of distortion[18].

Different percentages of distortion occur in different regions of the mouth. A number of investigators have examined the angular distortion in panoramic radiography, specifically with regard to tooth position. It has been demonstrated that panoramic films have some limitations to assess angular measurements of tooth inclinations[19-26]. Angulation distortion on panoramic radiographs results from the combined distortion in the vertical and horizontal dimensions and at different locations and depths within the focal trough [19].

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Even though several studies have been done to asses angular distortion in panoramic radiographs; in the majority of these studies no consideration was given to inclinations in the depth dimension of the body. [24, 25]

The effect on the angle distortion, of the combined inclination in all the three planes in the space, has not been extensively studied. Placing an inclined object uniformly across the focal trough results in differential magnification due to its inclination. It could be hypothesized that changes in the tooth orientation in the bucco-lingual plane might have a bearing on the image expression of tooth angulation since distortion can be affected by changes in the object depth within the focal trough.

The purpose of this study was two-fold. The first objective was to determine if the image mesio-distal tooth angulations from a panoramic radiograph of a typodont/skull apparatus are significantly different when the bucco-lingual angulations are altered and the mesio-distal angulations are fixed.

The second purpose was to examine if the root parallelism image expression from adjacent teeth of a typodont/skull apparatus significantly differs when the bucco-lingual angulations are altered and the mesio-distal angulations are fixed. It was expected that the results of this study could offer clinical guidelines to the practitioner as to what extend and it what locations bucco-lingual angulations should be taken into consideration when assessing root angulations on panoramic images.

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Several researchers have looked at the effects of buccolingual angulations on the mesiodistal image perception for panoramic radiographs. [20, 23, 26] All the previous studies have basically the same limitations:

1. The studies restricted themselves to either the maxilla or the mandible and to specific areas of the jaws such as the anterior segments. Consequently the results of these studies were only applicable to the locations where the test films were exposed.
2. Previous investigations were conducted on non anatomical devices with non-realistic tooth orientations that do not represent accurately the human dentition. Most of these studies were based on wire meshes and pins representing the dentition and supporting structures.
3. Some studies used a cylindrical layer and a fixed rotation center of the beam instead of a standard panoramic machine. These approximations are only valid within a limited section of the curved layer in panoramic radiography.

The present study has the advantage of using an anatomical tooth bearing device with realistic bucco-lingual and mesio-distal tooth angulations. The testing device was constructed based on anatomical and cephalometric principles of the dentition. The skull/typodont testing device was designed to represent arch forms and dimensions that could resemble clinical situations.

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Using the archwire as a reference for angular measurement and bucco-lingual orientation changes offered a convenient method of angular quantification that is also representative of a clinical situation. Bucco-lingual tooth angulation changes in orthodontics are produced by the force applied by the wire through the bracket. The bucco-lingual angulation will always change around an axis with its center in the slot of the bracket.

The results of this study revealed that bucco-lingual tooth angulations changes can in fact change the perception of mesio-distal angulation on panoramic images, especially in the canine/premolar region. When the panoramic machine rotates around the head of the patient, the x-ray beam continuously moves along side of the jaws projecting the contralateral side on the film. The center of rotation is initially near the lingual surface of the right body of the mandible when left side is imaged. The rotation center moves forward along the arc that ends just lingual to the symphisis of the mandible when the midline is imaged. The arc is reversed as the opposite side of the jaws is imaged.

The x-ray beam passes through the dental arches from the lingual to buccal and to some degree from distal to mesial. While the panoramic image is a continuous image of the jaws, the successive shifts to changing centers of rotation and angulations of the x-ray beam introduce erroneous expressions of the true mesiodistal tooth angulations on the film.

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The direction of the x-ray beam is responsible for the two-dimensional perception of the three-dimensional object by the viewer. Evident overlapping of the teeth occurs normally, making interpretation of dental pathologies cumbersome[27-29]. This radiographic phenomenon is associated with the deviation between the projection angle of the beam and the interproximal surfaces between the teeth in the dental arch.

The x-ray beam is not perpendicular to the buccal surfaces of the teeth along each and every tooth on the dental arch but is rather tangential to the buccolingual plane. The projection/dental arch discrepancies increase toward the posterior areas of the jaws. As a result the deviation in the premolar region is more significant than any other areas and this deviation varies among different panoramic machines [29].

What is depicted as a mesio-distal angulation of a tooth on the film in fact corresponds to the combined expression of its bucco-lingual and mesio-distal angulations. Any lingual inclination changes of a tooth located in the canine/premolar region is expressed as a mesial orientation of the root. Conversely, when the root apex seen in the film appears to have moved to the distal, the root in question has in fact moved buccally. These results support the findings of Samfors and Welander[30]. They concluded that objects placed buccal to the focal trough resulted in images with a more mesially inclined angle and objects placed lingual to the focal trough resulted in a distally inclined angle of inclination of the image. Their study restricted itself to a single panoramic unit and involved measurements of the anterior maxilla only.

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In the anterior region the deviation from orthogonal is minimal. As a result any bucco-lingual orientation changes are less likely to produce an angular image distortion. On the other hand the deviation in the canine/premolar region is significant enough to be clinically noticeable. The angular discrepancies on the canine/premolar area were larger for the maxilla than the mandible. The fact that the deviation from the orthogonal projection is less pronounced in the mandible than the maxilla might explain why the mesio-distal angular distortion was more marked in the upper jaw.

The most common teeth to be extracted for orthodontic purposes are the mandibular and maxillary premolar [10]. This radiographic phenomenon takes special importance in the extraction sites since any bucco-lingual angulation discrepancies between the premolar and the canine, or the premolar and the molar could be expressed on the image as excessive convergence and/or divergence of the roots. If the premolar had a lingual root orientation and the canine a buccal orientation then the roots would look to convergent on the radiograph. If the opposite was true; if the canine had a lingual root orientation and the premolar a buccal angulation, then the roots would look to divergent on the film. Treating to the panoramic representation could result in excessive convergence or divergence of the roots if the buccolingual orientation discrepancies are not corrected.

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Paiboon et al. [31] observed that the centers of the focal troughs are positioned toward the buccal. According to them this phenomenon indicates that when a machine focal trough center is located and the operator attempts to place the object in the center, any buccolingual positioning error will show greater sharpness loss with lingual errors than with buccal errors. The image angulation mean differences between neutral and lingual root orientation were less than the difference between the neutral and buccal root orientations. The only exception was the lower right first premolar where the buccal orientation differed more than the lingual. Paiboon et al [31] study findings could make us assume that mesiodistal angular distortion is more pronounced for the same tooth when its root is positioned lingually since lingual root orientations might position the root outside the focal trough where some image definition is lost. As a result more unsharpness and distortion, especially horizontal, might be expected for lingually positioned roots. Nonetheless, the results of our study do not support this assumption; they in fact contradict this hypothesis.

It could be hypothesized that buccolingual orientation changes might position the roots outside the focal trough and consequently result in image angular distortion. It could also be expected that minor changes in the object depth within the focal trough would result in some degree of horizontal and angular distortion. Previous investigators have reported [32] that the focal trough is narrower in the anterior segments than the posterior segments.

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If the mesio-distal angular expression errors were caused mainly by positioning of the objects outside, or at different depths within the focal true, it would be obvious to assume that this phenomenon would be greater in the anterior regions than the posterior regions. Nevertheless the results of this study do not support this hypothesis. Perhaps the conclusions of previous studies that limited angle distortions occur as a result of buccolingual angulation changes are correct.[23] These deductions are correct provided that the object is positioned in the anterior regions of the jaws where the projection angle is more orthogonal.

3.3 Recommendations and limitations

An anatomical device was created with the purpose to represent the jaws and the dentition as anatomically reasonable as possible. Yet, it is important to make clear that the results of this study are only applicable to the typodont/skull device and tooth angulations used in this study.

Variations in the size and shape of the jaws may also influence the expression of the root angulations and might provide different results. Even though the mesio-distal and bucco-lingual angulations used in this study were intended to emulate realistic tooth angulation it was not possible to represent the wide range of what can be considered "normal" in general population. As stated before, a definition of normality, as far as root orientation is concerned, is at this point nonexistent in the orthodontic literature.

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Root angulation changes of 10° to the buccal or the lingual are, in our opinion, realistic changes that can be achieved with fixed orthodontic appliances. There is still limited information regarding to what extent orthodontic treatment affects buccolingual orientations. Variations of as much of 10° might be anatomically normal among the general population. Since only one lingual and one buccal root orientation changes were used in this study it is impossible to provide evidence that the amount of angular distortion is proportional to the degree of angular changes. This investigation could be expanded to include more varied degrees of lingual and buccal root orientation changes.

The results of this study are only applicable to the Planmeca 2002. Scarfe et al. [33] demonstrated that the Planmeca 2002 deviates the least from optimal interproximal angulation over most of the dental arch. It is important to consider that Scarfe et al. study compared only a few panoramic units. Perhaps other panoramic units, with different focal troughs and rotational patterns, are less susceptible to angular distortion due to bucco-lingual orientation changes. It can be expected that the findings of this study might be expressed in varying degrees among different panoramic units. The focus of this investigation could be expanded to include more panoramic units. This would clarify whether the same trends could also occur with different panoramic units.

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The results of this study can be compared to the image angulations from plane-film techniques. Plane-film radiography might be less susceptible to angular distortion caused by bucco-lingual angulation changes since the radiographic projection is more orthogonal to the dental arch. However, in the clinical situation more than two intraoral films should be used to more accurately record root angulations and parallelism on a curved arch.

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APPENDICES

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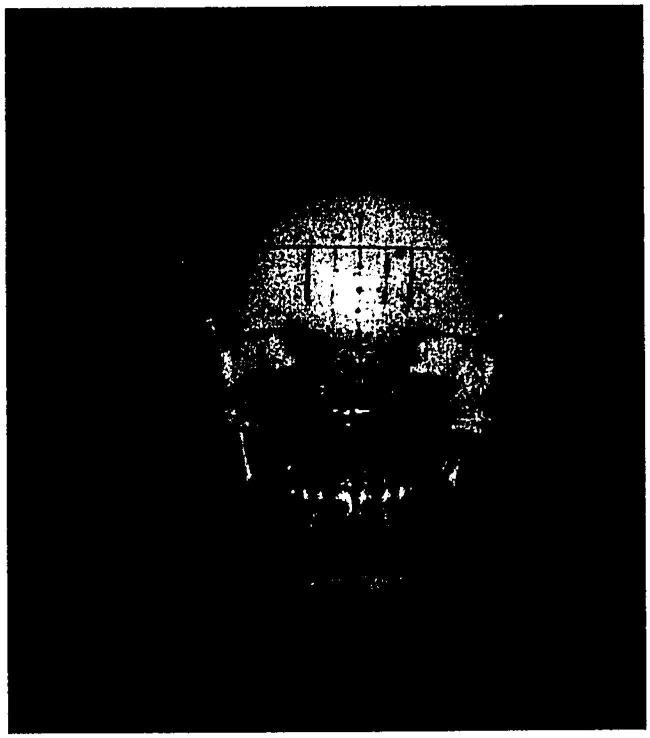
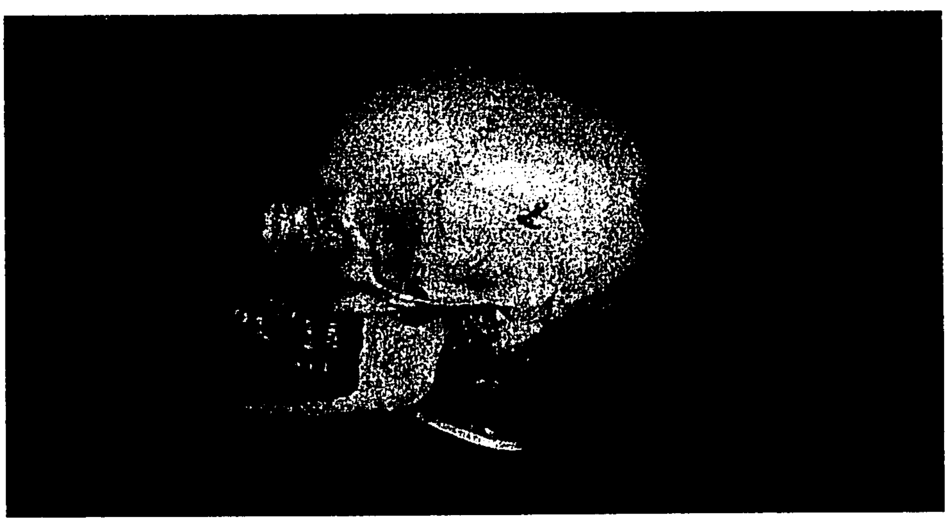
Appendix A
Typodont/Skull Testing Device





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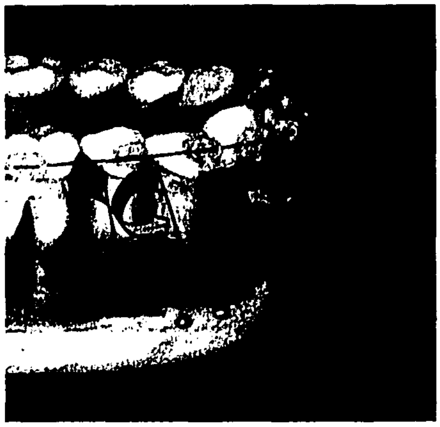
Appendix B
Typodont buccolingual angulations changes



In the picture above tooth 4.4 has 10 degrees of buccal root inclination and tooth 4.3 has 10 degrees of lingual root angulation. In the picture below tooth 4.4 is in its original or neutral buccolingual angulation and 4.3 root is still lingually positioned.

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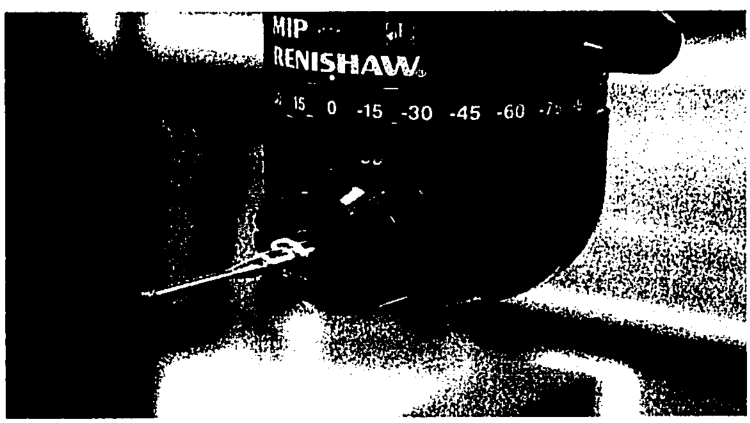
Appendix C
Coordinate Measuring Machine

Probe



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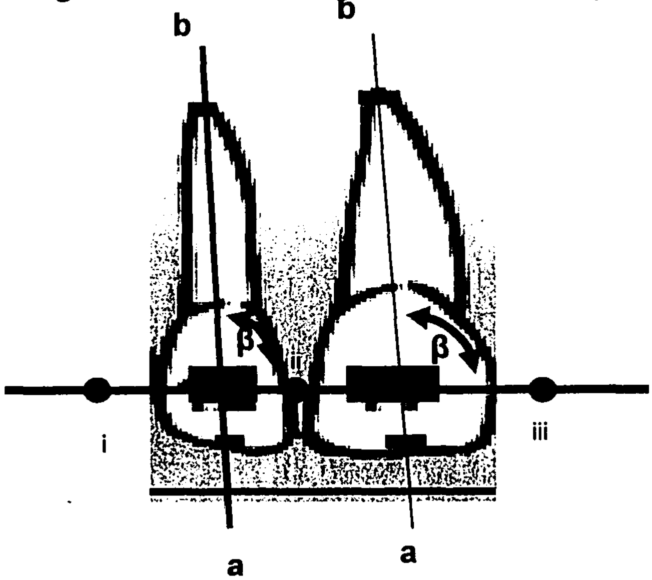
Appendix D
Mathematical Models

1. Mesiodistal true and image angle determinations

A mathematical model was designed to determine the angle formed by two lines in three dimensional space and at the same time to compare this angle to the same angle measured when the two lines are projected onto the radiographic film. Figure 1 shows two teeth and an archwire that are projected onto a radiograph (image angle determination) β angle is formed by the tooth long axis (represented by a line that connects point a & b) and a archwire approximation line that is formed by joining computer generated midpoints between adjacent teeth (points i, ii, iii) The angle is determined using simple geometry.

Figure1 Mesio-distal angulation landmarks (frontal view)



In order to define the β angle for a three-dimensional model Figure 1 and 2 should be contemplated. Figure 1 shows the front view of the teeth long axis points and the archwire and Figure 2 illustrates the side of one of the teeth. For Figure 2 the tooth long axis is also formed by a line that connects points 21a and 21b, which is inclined at an angle θ with respect to the vertical plane.

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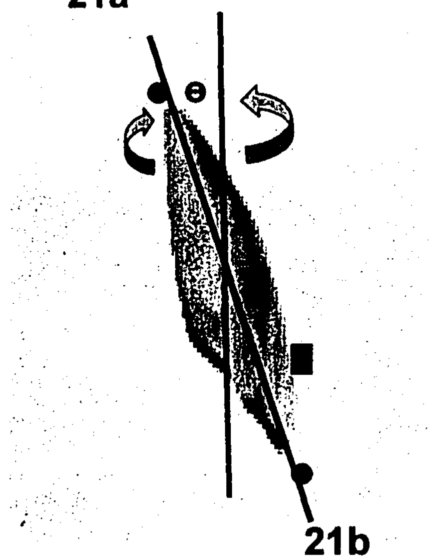
Figure 2 Mesio-distal angulation landmarks (sagittal view)



The β angle is projected onto a plane representing the face of the tooth on figure 1. Two lines can be used to define a plane. The tooth long axis line and the archwire line were used to define a face plane. If the tooth axis line lies on a plane and the archwire line is parallel to that plane, then a new plane is formed. The constructed plane includes the tooth long axis line (which is assumed to be parallel to an edge of the tooth bracket) and is parallel to the archwire line at the point contact between the archwire and the bracket. The β angle is defined as the line angle between the long axis line and the archwire line when is projected back onto the constructed plane. This angle can be measured using the dot product.

The dot product calculates the amount that one vector overlie another when the two vectors are placed tail to tail. Figure 3 shows a bidimensional example of the dot product of two vectors, where the quantity length is equal to:

$$A \bullet B = Ax \times Bx + Ay \times By + Az \times Bz$$

of vectors A and B. The vector A is translated in space to location A' so that its tail is coincident with the tail of B. The dot product is the amount that A' projects onto B in this configuration. The angle between the two vectors can be written by:

$$\beta = COS^{-1}\left(\frac{A \bullet B}{\|A\| \times \|B\|}\right)$$

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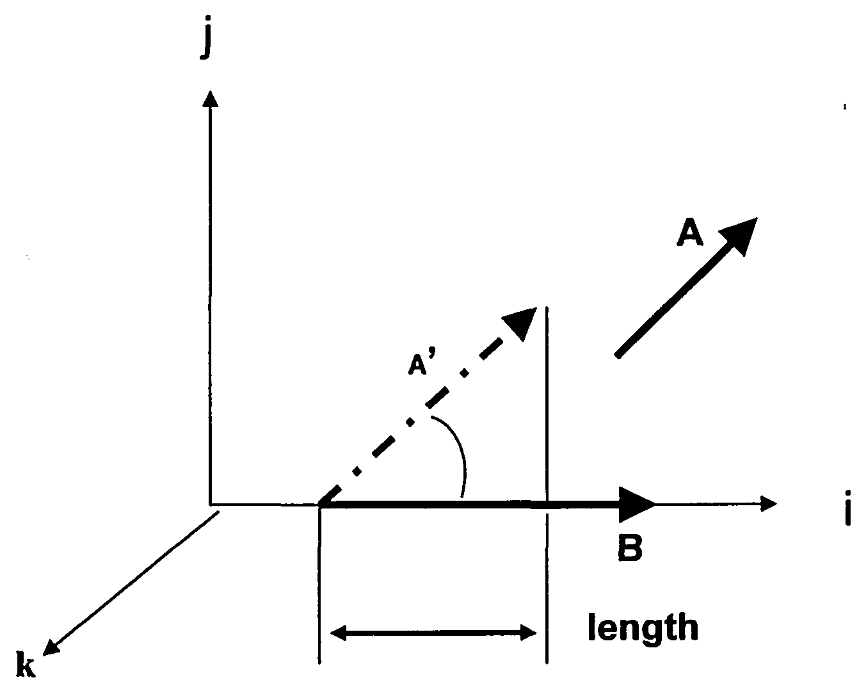
FIGURE 3



For the true angle determination the end points of *a* (tooth long axis) and *b* (the archwire approximation line) are fully specified using the Coordinate measuring machine. For the image angle determination (bi-dimensional plane) the end points are digitized in the radiograph and the *z* components of the points have a zero value.

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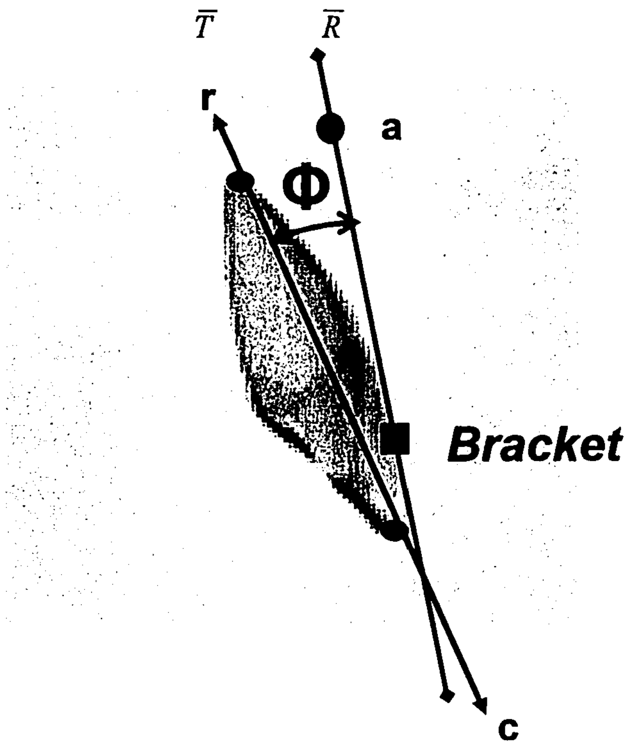
2. Buccolingual angle determination

The buccolingual orientation can be determined by computing the angle formed by two lines in three dimensional space. Figure 4 shows the side of one tooth and an bracket attached to it. The Φ angle is formed by the tooth long axis (represented by a line that connects point c & r) and an imaginary line that connects point a (apical base) to a point on the facial surface of the bracket (point b). As a result two vectors with magnitudes a and b are defined: tooth long axis ($\overline{T}$) and reference line ($\overline{R}$)



. The vectors magnitudes are calculated with the x, y and z coordinates obtained with the Coordinate Measuring Machine. The T and R vectors are computed using the following equations:

$$\overline{R} = \overline{r}_{B/A} = (x_B - x_A)i + (y_B - y_A)j + (z_B - z_A)k$$

$$\overline{T} = \overline{r}_{R/C} = (x_R - x_C)i + (y_R - y_C)j + (z_R - z_C)k$$

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Based on these two vectors, magnitudes an angle can be calculated using the dot product or scalar product. This angle will be the smallest non negative angle between them. The length of both vectors is equal to:

$$\ell_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$$

Using the dot product the vector T is translated in space to location A' so that its tail is coincident with the tail of vector R. The dot product is the amount that T' projects onto R in this configuration. The angle between the two vectors can be calculated from:

$$\cos\phi = \frac{\overline{T} \bullet \overline{R}}{\ell_T \bullet \ell_R}$$

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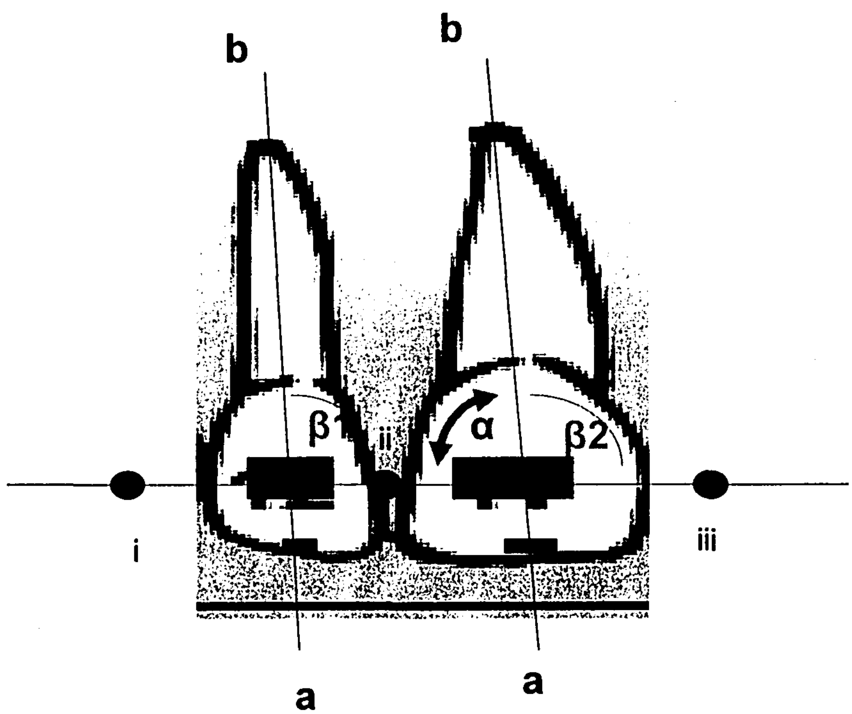
3. Root parallelism determination

Figure 5 shows two teeth and an archwire that are projected onto a radiograph. As stated before the β angle is formed by the tooth long axis (represented by a line that connects point a & b) and an archwire approximation line that is formed by joining computer generated midpoints between adjacent teeth (points i, ii, iii). The root parallelism (convergence and divergence) between adjacent teeth can be established by adding two separate angles. These two angles can be computed based on the mesiodistal image angles of an adjacent tooth pair. The first angle is the mesiodistal image angle of the tooth that is distal to the adjacent teeth (β1). If it is assumed that the archwire approximation line is straight from point ii to point iii, then α angle is the complementary angle of β2. This angle is equal to: 180- β2.



As a result the parallelism angle (Δ) can be computed using the following equation:

$$\Delta = \beta 1 + \alpha$$

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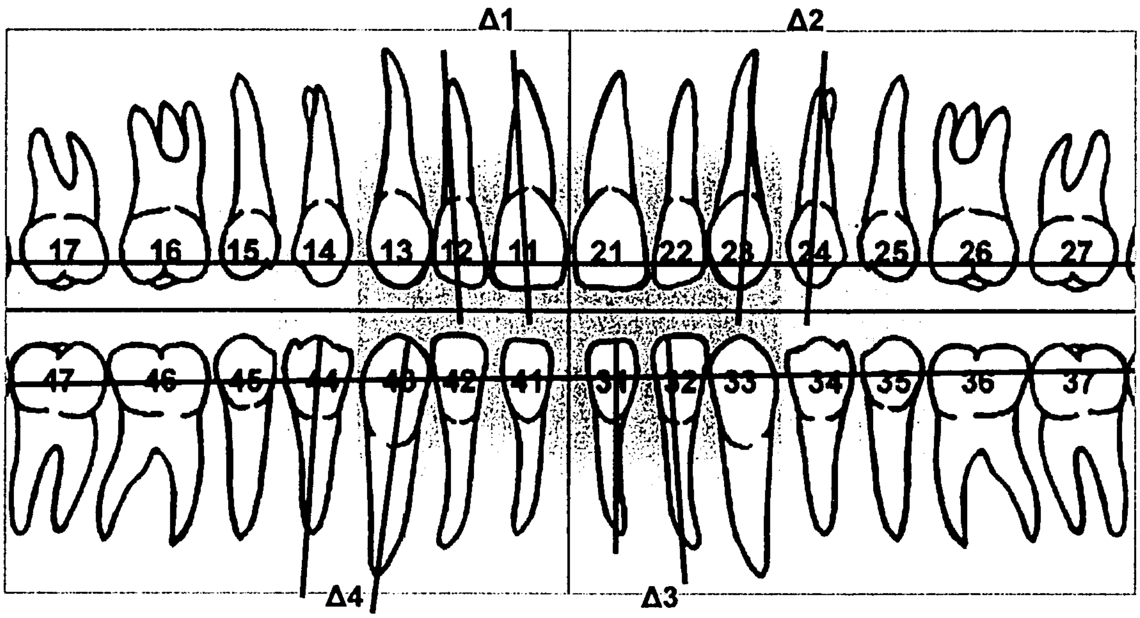
Appendix E

Delta angles



Appendix F
Sample size Calculation

Calculation Summary of Multiple Comparisons Power Analysis obtained with PASS software.

Sample sizes of 47 per group are obtained from the three groups whose means are to be compared. The total sample of 141 subjects achieves a 90.39% power to detect a difference of at least 1.00 degree using pairwise multiple comparisons test at a 0.05 significance level. The common standard deviation within a group is assumed to be 0.93.

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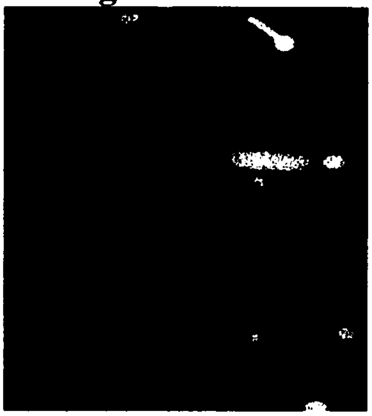
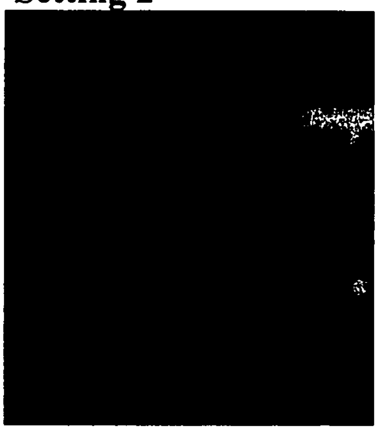
Appendix G
Mesiodistal image expressions at different buccolingual settings.

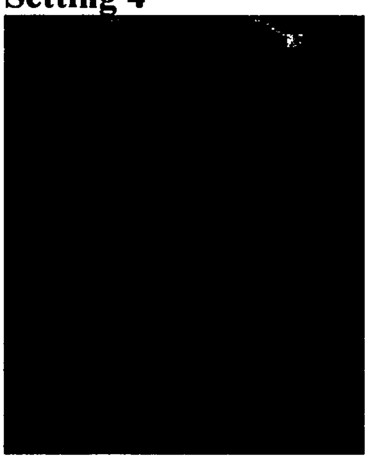
Setting 9



Setting 2



Setting 4



The lines represent the tooth long axis of tooth 2.3 and 2.4. In **setting 9** both teeth are positioned in their original buccolingual orientations. Good root parallelism is observed. In **setting 2**, 2.3 root is positioned lingually and 2.4 root is positioned buccally. The root angulation is expressed as root divergence on the film. **Setting 4** Root convergence is observed on the film when 2.3 root is oriented buccally and 2.4 root is oriented lingually.

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Appendix H

Intraclass coefficient (ICC) for determination of intrarater reliability according to bucco-lingual angulation.

	Randomization sequence number				
Orientation	1	2	3	4	5
buccal	0.967	0.982	0.967	0.975	0.961
lingual	0.849	0.944	0.901	0.909	0.913
neutral	0.933	0.948	0.937	0.941	0.932

Random numbers were selected for all teeth for T1, T2 and T3 in order to calculate a general ICC for each buccal angulation.

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Appendix I
One sample t-tests between image angulations and true angulation determined with the CMM. Maxillary teeth
(Mean differences in degrees)

Tooth 11

Test Value = 91.87						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	-5.42	47	0.000*	-0.91	-1.25	-0.57
buccal	-8.38	47	0.000*	-1.11	-1.38	-0.85
lingual	-8.82	47	0.000*	-1.15	-1.41	-0.88

Tooth 12

Test Value = 95.18						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	3.77	47	0.000	0.48	0.23	0.74
buccal	0.21	47	0.836	0.03	-0.26	0.33
lingual	3.41	47	0.001	0.31	0.13	0.50

Tooth 23

Test Value = 94.18						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	3.37	47	0.002	0.48	0.19	0.77
buccal	41.03	47	0.000	5.60	5.33	5.87
lingual	-12.95	47	0.000	-3.01	-3.48	-2.54

Tooth 24

Test Value = 91.95						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	27.30	47	0.000	3.57	3.30	3.83
buccal	73.10	47	0.000	13.98	13.59	14.36
lingual	-16.44	47	0.000	-4.45	-4.99	-3.90

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One sample t-tests between image angulations and true angulation determined with the CMM. Mandibular teeth (Mean differences in degrees)

Tooth 31

Test Value = 91.27						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	5.31	47	0.000	0.87	0.54	1.20
buccal	6.83	47	0.000	0.82	0.58	1.07
lingual	-2.67	47	0.010	-0.54	-0.95	-0.13

Tooth 32

Test Value = 91.23						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	-8.85	47	0.000	-1.50	-1.84	-1.16
buccal	-15.31	47	0.000	-2.27	-2.57	-1.97
lingual	-9.70	47	0.000	-2.48	-2.99	-1.96

Tooth 43

Test Value = 95.17						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	-66.16	47	0.000	-9.73	-10.03	-9.43
buccal	-35.96	47	0.000	-5.93	-6.26	-5.60
lingual	-61.32	47	0.000	-12.38	-12.78	-11.97

Tooth 43

Test Value = 94.11						
	t	df	p-value	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
neutral	-33.62	47	0.000	-7.55	-8.00	-7.10
buccal	-16.25	47	0.000	-3.80	-4.27	-3.33
lingual	-81.02	47	0.000	-12.63	-12.94	-12.32

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Appendix J

Mean and standard deviation values of Δ1 for the nine different buccolingual settings.

Settings[1](1.2-1.1)	Mean	S.D	C.V*
1 (B-B)	184.39	1.11	0.60
2 (B-L)	183.89	0.63	0.34
3 (L-L)	185.29	1	0.54
4 (L-B)	185.02	0.92	0.50
5 (N-B)	183.96	1.31	0.71
6 (B-N)	183.96	1.66	0.90
7 (N-L)	186	1.36	0.73
8 (L-N)	184.87	0.98	0.53
9 (N-N)	184.41	1.74	0.94

1- The letters next to each setting corresponds to the bucco-lingual orientation for each tooth: Buccal root torque (B), Lingual root torque (L), Neutral Root Torque. The fist letter corresponds to tooth 12 and the second one to tooth 11.

*CV (Coefficient of variation) Measurement of relative variation that express the standard deviation as a percentage of the mean.

Mean and standard deviation values of Δ2 for the nine different buccolingual settings.

Settings[1] (23-24)	Mean	S.D	C.V*
1 (B-B)	186.59	1.23	0.66
2 (L-B)	194.1	1.97	1.01
3 (L-L)	179.22	2.63	1.47
4 (B-L)	166.34	1.05	0.63
5 (N-B)	190.75	1.78	0.93
6 (B-N)	174.83	0.69	0.39
7 (N-L)	173.23	1.05	0.61
8 (L-N)	184.37	1.66	0.90
9 (N-N)	180.57	1.13	0.63

1- The letters next to each setting corresponds to the bucco-lingual orientation for each tooth: Buccal root torque (B), Lingual root torque (L), Neutral Root Torque. The fist letter corresponds to tooth 23 and the second one to tooth 24.

*CV (Coefficient of variation) Measurement of relative variation that express the standard deviation as a percentage of the mean.

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Mean and standard deviation values of Δ3 for the nine different buccolingual settings

Settings[1] (31-32)	Mean	S.D	C.V*
1 (B-L)	182.27	1.29	0.71
2 (B-B)	182.3	1.45	0.80
3 (L-B)	181.83	1.98	1.09
4 (L-L)	182.75	1.05	0.57
5 (N-L)	183.18	1.76	0.96
6 (B-N)	182.21	0.62	0.34
7 (N-B)	183.17	1.8	0.98
8 (L-N)	181.94	1.58	0.87
9 (N-N)	182.88	2.08	1.14

1- The letters next to each setting corresponds to the bucco-lingual orientation for each tooth: Buccal root torque (B), Lingual root torque (L), Neutral Root Torque. The fist letter corresponds to tooth 31 and the second one to tooth 32.

*CV (Coefficient of variation) Measurement of relative variation that express the standard deviation as a percentage of the mean.

Mean and standard deviation values of Δ4 for the nine different buccolingual settings

Settings[1] (43-44)	Mean	S.D	C.V*
1 (L-B)	186.6	1.36	0.73
2 (L-L)	178.39	1.32	0.74
3 (B-L)	171.87	1.03	0.60
4 (B-B)	182.41	1.3	0.71
5 (N-B)	184.95	2.26	1.22
6 (B-N)	177.63	2.35	1.32
7 (N-L)	176.32	2.16	1.23
8 (L-N)	183.04	2.57	1.40
9 (N-N)	181.4	1.19	0.66

1- The letters next to each setting corresponds to the bucco-lingual orientation for each tooth: Buccal root torque (B), Lingual root torque (L), Neutral Root Torque. The fist letter corresponds to tooth 43 and the second one to tooth 44.

*CV (Coefficient of variation) Measurement of relative variation that express the standard deviation as a percentage of the mean.

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