IS THERE A RELATIONSHIP BETWEEN DENTAL CROWDING AND THE SIZE OF THE MAXILLARY OR MANDIBULAR APICAL BASE?

A Thesis

by

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ABSTRACT

OBJECTIVE: To investigate whether there is a relationship between maxillary and mandibular jaw size, measured at the level of the apical basal bone, and dental crowding, measured as tooth-size-to-arch-length-discrepancy (TSALD).

MATERIALS AND METHODS: 75 untreated Class I dental and skeletal adult patients were evaluated. Digital scans of dental casts were taken to measure maxillary and mandibular tooth size, dental arch perimeter, TSALD, intermolar width, and intercanine width. Cone beam computed tomography (CBCT) images were used to measure the overall basal cross-sectional area, 5 basal arch perimeters, and 5 basal arch widths of the maxilla and mandible. The maxillary apical base was measured in an axial plane at the level of the mesiobuccal root apex of the upper right first molar, parallel to the functional occlusal plane. The mandibular apical base was measured in an axial plane at the level of the superior border of the right mental foramen, also parallel to the functional occlusal plane. Due to the number of apical base variables, principal components factor analysis was performed to create multivariate factors, to more efficiently evaluate the associations.

RESULTS: The dental arch measures and maxillary apical base dimensions show that males are significantly larger than females. There are only limited sex differences in mandibular apical base dimensions. Maxillary and mandibular apical base dimensions are related. The dental arch measurements showed significant relationships with TSALD. No relationship was found between the size of the mandibular apical base and upper or lower TSALD. Low to moderate correlations were found between the size of the maxillary apical base and TSALD. Tooth size showed little to no relationship to TSALD.

CONCLUSIONS: While the size of the maxillary apical base is related to maxillary or mandibular crowding, the size of the mandibular apical base is not.

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NOMENCLATURE

ANB	A point to nasion to B point
CBCT	Cone beam computer tomography
Co-A	Condylion to A point
Co-Gn	Condylion to Gnathion
ICW	Intercanine width
IMW	Intermolar width
Md	Mandibular
mm	Millimeters
MPA	Mandibular plane angle
Mx	Maxillary
P	Perimeter
TSALD	Tooth size to arch length discrepancy
W	Width

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CHAPTER I

INTRODUCTION

The prevalence of Class I malocclusion, which is higher than any other type of malocclusion, exceeds the prevalence of normal occlusion.[1] The causes of crowding are multifactorial.[1] One long-held belief states that crowding is caused by maxillary and mandibular jaws that are too small relative to the sizes of the teeth.[2-4] In order to better define what constitutes jaw size, as it relates to the dentition, Lundström in 1923 coined the phrase "apical base" to describe the junction of basal and alveolar bones of the maxilla and mandible that house the root apices.[5] This definition has been used in many studies as the standard for jaw size.[6-12]

Many studies evaluating the relationship between jaw size and dental crowding have used dental measurements such as arch length, depth, and width as measures of jaw size. They found that subjects with dental crowding have smaller dental arch widths, perimeters, and areas than subjects with no crowding.[4, 13-16] However, this method of measuring arch size is problematic because when teeth are crowded, they move anteriorly into a narrower and shorter part of the dental arch. In other words, arch perimeter, length, and width measures will necessarily be reduced by the more mesial positions of the crowded teeth.[1]

Several other methods, independent of tooth position, have been developed to measure the jaw size. There have been studies that estimated jaw size based on 2-D cephalograms, as well as studies that used points on dental casts adjacent to the mucogingival junction (i.e. the WALA ridge), which are soft-tissue landmarks intended to estimate the underlying skeletal structure.[17] The findings from the cephalometric studies are controversial, with some reporting significant inverse relationships between maxillary (Co-A) and mandibular (Co-Gn) lengths and crowding, while others found no significant relationships.[18-20] Findings from the WALA ridge studies show significant correlations between dental and skeletal arch dimensions.[6-9] These methodologies are problematic as they do not directly measure the size of the apical basal bone, but are estimating it with soft tissue landmarks or simplified linear measurements of a 3-dimensional bony structure.

With the advent of cone beam computed tomography (CBCT), studies have investigated the relationship between jaw size and dental crowding utilizing 3-dimensional radiographic images of the basal bone of the mandible.[10-12, 21] Uysal et al found a significant inverse relationship between the size of the symphysis and lower incisor irregularity in females, but not in maless.[21] In a master's thesis, Bell found a low but significant relationship between the mandibular apical base and mandibular tooth-size-arch-length-discrepancy (TSALD) in adolescents.[10] In another master's thesis, Athar concluded that the apical base and dental arch perimeters were significantly different, and that no significant relationship exists between mandibular apical base perimeter, measured at the level of the inferior alveolar nerve canal, dental crowding, and dental arch perimeter.[12] An unpublished study performed at Texas A&M College of used CBCT images of untreated adults with class I malocclusion to show there was little or no relationship between the mandibular apical base size and mandibular crowding.

These CBCT studies had potential limitations and biases due to methodology, sample size, and lack of control for skeletal growth. To date, no study has analyzed the relationship between the maxillary apical basal bone and crowding.

The purpose of the current study is to investigate whether there is a relationship between maxillary and mandibular jaw size, measured at the level of the apical basal bone, and dental crowding, measured as TSALD.

CHAPTER II

LITERATURE REVIEW

It has long been assumed that dental crowding is caused by having maxillary and mandibular jaws that are too small relative to the size of the teeth. There is some evidence to show that larger teeth are associated with increases in dental crowding, but there is little evidence investigating the relationship between jaw size and crowding. The few studies that have investigated the relationship between crowding and jaw size have been based on dentoalveolar dimensions, rather than the basal bone aspects of the maxilla or mandible.

First, to better understand what crowding is and the severity of the problem, this literature review will investigate the methods used to quantify the amount of dental malalignment, followed by a review of the prevalence and etiology of dental crowding. Next, the definitions of what constitutes jaw size as it relates to the bony support of the dentition will be explored. Following this, to understand the available literature investigating the relationship between jaw size and crowding, the various methods used to measure and quantify jaw size and investigate the relationship between jaw size and malalignment or crowding will be reviewed. First, studies using the method of quantifying jaw size utilizing dental arch measurements will be reviewed, followed by studies utilizing the methods of analyzing the WALA ridge, lateral cephalograms, and cone-beam computed tomography. Finally, the objective and methodology of the current study will be summarized.

Methods for Measuring Crowding

Two basic methods exist for quantifying the amount of dental malalignment that characterizes Class I malocclusion: the irregularity index[22] and tooth-size-to-arch-length discrepancy (TSALD). In 1975, Little introduced the irregularity index, which scores the mandibular incisor alignment.[23] The alignment score is the sum of the linear distances between the anatomical contact points of the mandibular incisors. These 5 displacement measurements are summed to give the mandibular alignment score, ranging from 0 mm: perfect alignment, to 10+ mm: very severe irregularity. If spacing is present in addition to displacement or rotations, only the labiolingual displacements are recorded. This method provides a simple and consistent way to measure the mandibular anterior malalignment, but it has limitations. The posterior mandibular dentition and the entire maxillary dentition are not considered in this analysis. Spaces between the anterior teeth are not measured. This method simply quantifies the irregularity of the positions of the mandibular anterior teeth, without considering the space required to correct the alignment. Little stated: The Index is not an arch length assessment but, rather, a guide to quantifying mandibular anterior crowding. Also, the Index exaggerates malalignment in patients with significant rotations or labio-lingual displacements of the mandibular incisors, where the required space is maintained.[1, 23]

Performing a TSALD analysis quantifies the discrepancy between the amount of space available for the proper alignment of teeth and the amount of space required to place the teeth in their correct positions. To quantify the tooth size for the TSALD calculation, the mesio-distal widths of the teeth are measured from the distal to the mesial anatomical contact points of each tooth.[24] While both the Index and TSALD provide measures of anterior malalignment, the Index only explains 25-36% of the variation in TSALD, and vice versa, meaning the two indices measure different attributes.[1] Measuring TSALD provides a more accurate estimate of dental crowding.

Various methods exist for estimating space available, or arch perimeter. One method separates the dental arch into quadrants. It is based on linear measurements from the mesial of the first molar to the mesial of the canine to the mesial of the central incisor on each side of the arch. This method was recommended by Proffit and Fields[24] because it is more reliable than the manual calculation utilizing the brass wire method. If the sum of tooth widths exceeds the sum of the linear distance measurements in each of the four segments, an arch length discrepancy exists. This analysis assumes that the inclination of the incisors is neither excessively protrusive or retrusive. This method is commonly used in the literature for performing a space analysis to quantify dental crowding.[10, 14, 25]

In 1947 Nance[26] introduced the brass wire method to measure the "outside perimeter" of the dentition. Using plaster dental models, a brass ligature wire was contoured to fit on the middle third of the buccal surface of the mandibular teeth, from the mesial of the permanent first molar to the mesial of the opposite first molar. The wire was then straightened and measured to yield the arch length.

Huckaba built upon Nance's brass wire method, using a 0.025 inch brass wire centered over the contact points of the posterior mandibular dentition.[27] For the anterior dentition, the wire placement was dependent upon the inclination of the anterior teeth. If the teeth were judged to be upright over basal bone, the wire was positioned over the incisal edges. If the teeth were tipped labially, the wire was positioned lingually to allow uprighting of the teeth. If the teeth were tipped to the lingual, the wire was positioned to the labial to allow incisor proclination. The brass wire was then straightened and measured.[27]

Traditionally, crowding measurements have been performed on plaster dental casts. It is now possible to utilize 3-dimensional digital models and the associated analysis software for these calculations. In a systematic review of the literature, Fleming et al included 17 studies to evaluate the validity of the use of digital models to assess tooth size, arch length, irregularity index, arch width and crowding versus measurements generated on hand-held plaster models with digital callipers.[28] They concluded that digital models offer a high degree of validity when compared to direct measurement on plaster models, and differences between the approaches are likely to be clinically acceptable. This review confirms that digital models offer a valid alternative to plaster models.

Prevalence of Irregularity and Dental Crowding

Prevalence of Class I malocclusion is higher than any other type of malocclusion and exceeds the prevalence of normal occlusion.[1] According to Angle, individuals with Class I malocclusion are characterized as having normal molar relationships, but their teeth are not correctly positioned in the line of occlusion.[29, 30] The NHANES III estimated that approximately 22% of children ages 8-11 have clinically significant amounts (≥ 4 mm) of maxillary incisor irregularities; in the mandible, prevalence of clinically significant incisor irregularities is approximately 20.6%.[22] The prevalence of significant dental crowding increases with age. Clinically significant maxillary incisor irregularity increases to 31% among adolescents. Significant mandibular irregularity increases to 31% among adolescents, and then to 39% among adults.[22] Nearly 15% of adults and adolescents have severely crowded incisors, requiring extractions of teeth for proper alignment.[29] It has been estimated that approximately 40% of untreated persons in the US between 15 and 50 years of age have clinically significant incisor irregularity.[31]

Etiology of Crowding

The etiology of dental crowding is multifactorial. Many of these causes are well understood and documented, however there are suspected causes and relationships that have not been fully investigated. In 2014 Buschang attributed anterior crowding to slight tooth movements causing tooth contacts to slip and become displaced. After the contacts are broken, the teeth are freed and move out of alignment.[1] Teeth tend to move mesially until a new equilibrium is established, with usually more than one tooth compensating for the initial slipping. Increases in incisor irregularity and TSALD are caused by the displacements and rotations that occur while the teeth are compensating. Three general factors that contribute to crowding of the anterior teeth were described: 1) anterior-directed forces, 2) loss of posterior arch space during the mixed dentition, and 3) eruption of the anterior teeth associated with inferior growth displacement of the mandible during growth.[1] Greater amounts of growth require greater eruption to compensate for the vertical space created; eruption decreases the likelihood that the contacts between the anterior teeth will be maintained, which increases the risk of crowding. In 2013 Goldberg et al showed that greater vertical growth, greater incisor eruption, and especially increased facial divergences were all related to greater post-treatment mandibular crowding.[32] Historically, crowding was thought to be caused primarily by excesses in tooth size or deficiencies in jaw size.[2-4] The relationship between the mesiodistal width of teeth and dental crowding is controversial. Increases in tooth size have been shown to correlate with an increase in dental crowding.[13, 15, 16, 33] However, other studies have shown that tooth size is not related to crowding.[4, 10, 34] The current study will attempt to provide additional insight on this topic.

It has long been claimed in classic orthodontic literature and by orthodontic practitioners that jaw size can impact crowding of teeth, where jaws are too small relative to the size of the teeth. In Dr. Tweed's 1945 publication *A Philosophy of Orthodontic Treatment* he said: "I am convinced that at times there is too much tooth structure and too little basal bone to accommodate all the teeth in their correct relations."[2] In 1948 Salzmann stated: "the jaws... frequently do not achieve sufficient size to accommodate all of the teeth in an occlusal arrangement which falls within the range of normality. Lack of jaw growth, when it precedes tooth eruption, can produce... crowding of teeth."[3] Later, in 1983 Howe, McNamara, and O'Connor similarly said: "Three conditions which may predispose the dental arches to crowding are excessively large teeth, excessively small bony bases of the jaws, and a combination of large teeth and small jaws."[4]

Definition of Jaw Size

If crowding is related to jaw size, a question that follows is: what constitutes jaw size? Lundstrom in 1923 attempted to define jaw size when he coined the phrase "apical base" in reference to the maxillary and mandibular bony support near the root apices, which he thought cannot be altered with orthodontic treatment.[5] Tweed later expanded on this concept when he referred to the basal ridge of bone, which is that portion of the body of the mandible on which the alveolar process rests.[35] He argued that teeth are most stable when they are upright over this basal bone. In 1950, and later in 1966, Brodie defined the apical base as the zone between the maxillary and mandibular skeletal and alveolar bone that houses the root apices.[36, 37] More recently, Daskalogiannkis defined basal bone as the bone which supports and is continuous with the alveolar process.[38]

Methods to Measure Jaw Size and Correlations to Crowding

Dental Arch

In 1983 Howe et al. attempted to investigate the extent to which tooth size and jaw size each contribute to dental crowding.[4] They used dental models of 104 untreated subjects, separated into crowded (defined as having gross dental crowding judged without measurements) and non-crowded groups, to measure various arch measures, including arch widths, perimeter, and area. They found that subjects with dental crowding had smaller dental arch widths, perimeters, and areas compared to the non-crowded group. Subsequent studies have similarly found decreases in arch dimensions for subjects with increased dental crowding. Chang et al found the dental arch widths in the group with gross dental crowding (n= 75) were significantly smaller than those of the non-crowded group (n=89). [13] In 1989, Bishara et al compared 32 subjects with Class I occlusion at two stages of dental development: stage 1, when the permanent second molars initially erupted into occlusion (mean age of 13 years), and stage 2, at early adulthood (mean age of 26 years). They found a significantly greater reduction in available arch length in the group with the most TSALD at early adulthood. [14] In 2005, Bernabe et al separated 150 adolescent subjects into 3 groups based on dental crowding.[15] The significantly crowded group was defined as having a TSALD greater than 5.1 mm. The mild-to-moderate crowded group was defined by having a TSALD between 0.1 mm to 5 mm. The spaced group had a positive TSALD. They found significant differences between the 3 groups, showing a decrease in both arch length and intermolar width in groups with increased crowding. The variable with the highest explanatory capability was arch length. Poosti et al selected 60 adolescent and young adults with Class I malocclusion and separated them evenly into non-crowded and crowded groups (defined as having greater than 5 mm of crowing).[16] They showed significantly decreased maxillary intercanine and intermolar width in the crowded group.

The rationale of using dental measures to quantify jaw size is problematic because tooth orientation and position can significantly influence dental arch measurements. Additionally, TSALD and incisor irregularity increases in untreated subjects have been consistently associated with decreases in intercanine width and arch depth. Sinclair and Little showed a 0.7 mm increase in irregularity in the permanent dentition was associated with a 2 mm decrease in arch length and a 1.5 mm decrease of intercanine width.[39] Bishara et al. reported the greater the increases in malalignment, the greater the decreases in arch length.[14, 25] As anterior crowding increases, the posterior teeth move mesially into a narrower part of the dental arch, so measurements of arch perimeter, arch length, and arch width are expected to decrease.[1, 40, 41]

WALA Ridge

Studies have also attempted to quantify jaw size utilizing landmarks on dental models assumed to represent the apical base of bone. In 2000 Andrews et al. defined the WALA ridge as the band of keratinized soft tissue directly adjacent to the mucogingival junction.[17] This landmark was thought to serve as a clinically measurable structure representing the apical base. Various researchers have used digitized mandibular dental models to define each subject's dental facial axis (FA) points (defined as the midpoint of the facial axis of the clinical crown) to represent the dental arch form, and the WALA ridge, which they claimed served as a representation of the apical base and the basal arch form.[6-8] Each of these studies concluded that the WALA points proved to be a useful representation of the apical base basal arch form, and can be a useful predictor of individualized dental arch forms. Kim et al. in 2011 similarly investigated correlations between apical base, defined using WALA points, and dental arch forms, but found only moderate correlations between skeletal and dental inter-canine widths and concluded the basal arch may not be the principle factor in determining the dental arch form.[9] None of these studies analyzed the relationship of the WALA ridge to crowding. While the WALA ridge may provide a close approximation of the apical base form, it is made from points on the soft tissue, utilizing soft tissue landmarks, to represent an underlying bony structure.

Lateral Cephalograms

Other studies have used lateral cephalograms to quantify and define the bony tooth support, and investigated the relationship between the size of maxillary and mandibular basal bone to dental crowding. Turkkahraman et al. investigated the associations between dental crowding and dentofacial factors, measured from lateral cephalograms.[18] Lower incisor TSALD was measured from dental casts of 60 patients in the early mixed dentition stage separated equally into a crowded and non-crowded group. Crowding was calculated based on the anterior space available measured with two straight line segments between mesial surfaces of deciduous mandibular canines. Subjects with anterior crowding greater than 1.6 mm were included in the crowded group. Dentofacial measurements, including maxillary and mandibular lengths (Co-A, and Co-Gn respectively), were taken from lateral cephalograms. They found significant inverse correlations between lower incisor crowding and maxillary and mandibular lengths. Similarly, Janson et al. showed that increases in mandibular crowding were found among patients with decreased maxillary (Co-A) and mandibular lengths (Co-Gn), measured with lateral cephalograms.[19] Their study was based on 55 non-crowded (less than 3 mm mandibular TSALD) and 25 crowded (equal to or greater than 3 mm mandibular TSALD) Class II patients with full permanent dentitions. In contrast to these two studies, Montasser and Taha, who utilized lateral cephalograms and dental models for 15 non-crowded (less than 3mm of dental crowding) and 30 crowded (equal to or greater than 3mm of dental crowding) adolescent Class I subjects, found no relationships between maxillary (Co-A) and mandibular lengths (Co-Gn) and mandibular crowding.[20] Their findings suggest that dental crowding is independent of skeletal measures. Differences between these studies could be explained by the ages of the patients used and the types of malocclusion studied. More importantly, this method of defining the size of the maxillary and mandibular bone is problematic because the 3-dimensional size of the maxillary and mandibular apical bases was estimated utilizing a 2-dimensional radiograph to measure two straight lines representing only the maxillary and mandibular lengths.

CBCT

With the advent of cone-beam computed tomography (CBCT) it is now possible to accurately view and measure the underlying hard tissue in three-dimensions. Uysal et al. investigated the relationship between lower incisor crowding and the size of the mandibular symphysis.[21] CBCT images of 125 Class I patients ranging in age from 16-36 years (mean age of 21.6 years) were evaluated. For each subject, sagittal slices were taken through the central axes of the four lower incisors. Measurements included the height and thickness of the mandibular symphysis, cancellous bone height and thickness of the mandibular symphysis, and vestibular and lingual cancellous bone thickness. Little's irregularity index was calculated for the four lower incisors from the CBCT images. They found significant relationships between the measures of mandibular incisor crowding and basal bone dimensions in female subjects. For the female group, only 2 of the 6 skeletal measures showed significant differences. Though the inverse correlations were statistically significant, they were low (R= -.33—.44). There were no statistically significant differences or correlations for any of the measurements among the male subjects with different severities of incisor irregularity.

Bell completed a master's thesis investigating the relationship between dental crowding and the mandibular basal bone utilizing CBCT technology.[10] Thirty untreated 12-17 year-old patients from a private practice were included in the study. Dental models were used to measure mandibular total TSALD and the lower incisor irregularity index. Basal bone perimeter and cross-sectional area were obtained from two slices of the mandible taken parallel to the functional occlusal plane, passing through B-point, and also through the mental foramen. Each slice extended posteriorly to a perpendicular line passing through the mesial contact of the second molar. Estimates of basal bone perimeter were generated with elliptical formulas, using the outer cortical plate extending to the same posterior limit. Significant but low correlations (R=-.36-.41), with almost no predictive value, were found between mandibular basal bone perimeter, tooth size, and mandibular crowding. They concluded there is no strong relationship between tooth size, basal bone size, and crowding. While this was a good study, the sample size was relatively small, and the researchers did not control for growing patients, dental or skeletal classification of malocclusion, nor did they include the maxillary bone and teeth in their investigation. Additionally, the posterior limit for estimates of basal bone area and perimeter was defined by the position of the second molar. As previously discussed, with increased anterior crowding, the posterior teeth move mesially,[1, 40, 41] making it problematic to define basal bone with tooth landmarks.

In another master's thesis, Athar evaluated the relationships between mandibular crowding, dental arch perimeter, and the mandibular apical base perimeter at the level of the inferior alveolar nerve canal.[12] The inferior alveolar nerve canal was selected after a search of the literature showed that the inferior alveolar nerve has a strong association with development of the mandible, dental development, and development of the bone that surrounds the teeth. The perimeter of the canal was considered the perimeter of the mandibular apical base. Plaster models and CBCT images of 27 randomly-selected untreated individuals with full permanent dentitions were analyzed. Plaster models were used to quantify TSALD and incisor irregularity. Using CBCT images, the inferior alveolar canal was traced from the apex of the distal root of the second molar to the same landmark on the contra-lateral side. The inferior alveolar canal stops at the mental foramen, so the anterior segment was traced by joining the mental foramen of one side to the mental foramen of the contralateral side following the curvature of the anterior part of the mandible. This study concluded that the apical base and dental arch perimeters were significantly different, and that no significant relationship exists between mandibular apical base perimeter, measured at the level of the inferior alveolar nerve canal, dental crowding, and dental arch perimeter. Limitations of this study were similar to those previously identified, including a relatively small sample size, lack of control for growing patients and dental or skeletal malocclusion, defining the posterior limit of the basal bone by the mandibular second molar, and failing to consider the maxillary dentition and basal bone.

An unpublished study performed at Baylor College of Dentistry estimated mandibular apical base size using CBCT images of 51 adults with class I malocclusion. The apical base was defined based on the level of the mental foramen and the mesial root apex of the lower right second molar, extending posteriorly to a perpendicular line passing through the tip of the right coronoid process.[11] Apical base size was estimated based on 37 measurements, including the middle and outer skeletal arch perimeters, widths and cross-sectional areas at 5mm, 10 mm, 20 mm, 30 mm, 40mm, and a maximum depth from the most anterior point of the arch. Overall cross-sectional area, defined by the inner and outer cortical plates was also measured. Mandibular dental crowding (TSALD) was estimated from digitized photographs of plaster models. This study showed little or no significant relationship between the mandibular apical base size and mandibular crowding. This study did not evaluate the maxillary apical base and its relationship to maxillary or mandibular TSALD. To date, no studies have evaluated the relationship of the size of the maxillary apical base to crowding.

Purpose

The objective of the current study is to investigate whether a significant relationship exists between the area and perimeter of the maxillary and mandibular apical bases, measured utilizing CBCT images, and dental crowding, measured as TSALD from dental models in un-treated adult patients with Class I malocclusion.

CHAPTER III

MATERIALS AND METHODS

Subject Selection

Subjects for the current study were selected from two private-practice offices based on the following inclusion criteria: pretreatment CBCT radiographs and plaster dental models, 18 years or older, ANB angle within ±1 standard deviation of age- and gender-specific norms, Class I dental relationship (based on Angle molar classification), full permanent maxillary and mandibular dentitions (excluding third molars). Subjects were excluded based on the following criteria: previous orthodontics or orthognathic surgery, significant bone loss or periodontal disease, severely hyperdivergent patients (with a mandibular plane [MPA] greater than ±2 standard deviations of age- and gender-specific norms). A total of 75 consecutive patients were identified who met the selection criteria. There were 24 males (38.5 ±12.9 years of age) and 51 females (44.5 ±11.7 years of age).

Dental Model Analysis

Digital scans of the maxillary and mandibular dental casts were taken using an iOC iTero Scanner and uploaded into the OrthoCAD (Align Technology, San Jose, CA. version 5.2.1.290) diagnostics software for analyses of tooth size, arch perimeter, intercanine width, and intermolar width. Overall tooth size was calculated as the sum of the mesio-distal widths of all teeth, excluding second and third molars, from the mesial contact point to the distal contact point of each tooth (Figure 1). Replicate analyses of 15 cases showed no systematic measurement errors. Method errors ranged from ±0.43 to ±0.46 mm and intraclass correlations ranged from 0.983 to 0.989.

The maxillary and mandibular arch perimeters were estimated using the technique described by Huckaba.[27] A digital curve, extending to the mesial contacts of the first molars, was fit to lie over the incisal edges of the anterior teeth and the center of the contact points of the posterior teeth (Figure 2). If the anterior teeth were upright over basal bone, the curve was positioned over the incisal edges. If the teeth were tipped labially, the curve was positioned lingually to allow the uprighting of teeth. If the teeth were tipped lingually, the curve was positioned to the labial to allow for incisor proclination. The maxillary and mandibular tooth size arch length discrepancies (TSALD) were calculated by subtracting the overall maxillary and mandibular tooth widths from their respective arch perimeters. Analyses of 15 cases showed no systematic difference between replication measurement of TSALD, method errors ranging from ±0.35 to ±0.46 mm and intraclass correlations ranging from 0.918 to 0.969.

Maxillary and mandibular intercanine widths were measured by connecting a line from the midpoint of the cingulum at the lingual gingival border of each canine (Figure 3). The maxillary intermolar widths were measured by connecting a line from the lingual groove at the gingival margin of each maxillary first molar. The mandibular intermolar widths were measured by connecting a line from the midpoint of the mesio-distal crown width at the lingual gingival margin of each mandibular first molar. Replicate analyses of 15 cases showed no statistically significant systematic measurement errors. Method errors ranged from ±0.25 to ±0.60 mm, and intraclass correlations ranged from 0.986 to 0.996.

Apical Base Analysis: Orientation

CBCT images were uploaded into Dolphin Imaging 3D analysis software and oriented to standardized planes in all three dimensions. The axial plane, which was representative of the functional occlusal plane, was defined by bisecting the cusp tips of the right first mandibular molar and the right first mandibular premolar (Figure 4). The left side was checked to ensure a parallel plane. The sagittal plane was defined perpendicular to the axial plane, bisecting the incisive foramen.

Maxillary Apical Base Analysis

The measurements made on the maxillary apical base included an overall cross-sectional area, five arch widths, and five arch perimeters. The axial plane was defined perpendicular to the other two planes at the level of the mesiobuccal root apex of the upper right first molar (Figure 5). The posterior limit of the maxilla was defined by the most posterior aspects of the right and left maxillary tuberosities. All landmarks were digitized and measured using tools in the Digitize/Measure tab. First, the buccal and lingual cortical plates were traced and the total area was calculated (Figure 7). Using the 2D Path tool, a two-dimensional arch perimeter was then traced from the left most posterior limit, around the basal bone arch, to the right most posterior limit. The landmarks defining the perimeter were placed equidistant between the lingual and buccal cortical plates. Next, using the 2D Line tool and the symmetry caliper, five skeletal arch widths were created 5 mm (Mx 5W), 10 mm (Mx 10W), 20 mm (Mx 20W), and 30 mm (Mx 30W) from the most anterior aspect of the arch perimeter. In addition, a maximum posterior width (Mx MaxW) was digitized at the tuberosities. Finally, using the 2D Path tool, four additional arch perimeters were created extending 5 mm (Mx 5P), 10 mm (Mx 10P), 20 mm (Mx 20P), and 30 mm (Mx 30P) from the anterior aspect of overall arch perimeter. Replicate analyses of 15 cases showed no systematic measurement errors. Method errors ranged from ±0.83 to ±1.19 mm for perimeters and widths and ± 19.32 mm^2 for cross-sectional area. The intraclass correlations ranged from 0.976 to 0.990.

Mandibular Apical Base Analysis

The mandibular apical base was digitized and measured in the axial plane parallel to the functional occlusal plane at the level of the superior border of the right mental foramen, extending to a coronal plane passing through the most superior point of the right mandibular condyle (Figure 6). Unlike the maxillary analysis, the mandibular basal bone posterior limit was defined by the coronal plane. As described for the maxillary apical base analysis, corresponding landmarks in the mandible were digitized to quantify the mandibular apical base cross-sectional area, over-all skeletal arch perimeter, five arch widths, and four additional arch perimeters (Figure 8). Replicate analyses of 15 cases showed no systematic measurement errors, method errors ranging from ±0.59 to ±1.19 mm for perimeters/widths and ±17.70 mm^2 for cross-sectional area. The intraclass correlations ranged from 0.980 to 0.995.

Statistical Methods

The skewness and kurtosis statistics showed that the distributions of the measurements were all normal. Means and standard deviations were used to describe the variables. Independent sample t-test were used to evaluate sex differences. Pearson produce moment correlations were used to evaluate bivariated relationships. Due to the number of apical base variables, principal components factor analysis was performed to create multivariate factors, to more efficiently evaluate the associations. All the analyses were performed using IBM SPSS Statistic Version 23 (IBM Corp, Armonk, NY). The significant level was set to 0.05.

CHAPTER IV

RESULTS

Dental Arch Measurements

Females were older than males and had smaller tooth sizes and arch dimensions. Statistically significant sex differences were found for age, maxillary tooth size, maxillary arch perimeter, mandibular arch perimeter, and maxillary intermolar and intercanine widths (Table 1).

The bivariate correlations relating tooth size and TSALD showed a weak relationship (r=.257) between maxillary TSALD and mandibular tooth size (Table 2). Maxillary and mandibular TSALD were significantly related to both maxillary and mandibular arch perimeters, with correlations ranging from .392 to .625. Maxillary and mandibular TSALD were also positively related to maxillary and mandibular intermolar and intercanine widths. A significant relationship (r=.331, p=.004) was found between maxillary TSALD and mandibular TSALD.

Apical Base Measurements

The apical base measures showed that males were consistently larger than females. All of the maxillary basal bone measurements showed statistically significant sex differences (Table 3). The mandibular basal bone measurements showed significant sex differences for over-all area, perimeter, and maximum basal arch width.

Low to moderately low correlations were found between both maxillary and mandibular TSALD and the size of the maxillary apical base (Table 4). None of the relationships between maxillary or mandibular TSALD and the size of the mandibular apical base were statistically significant (Table 5).

Maxillary intermolar and intercanine widths were positively related to the size of the maxillary apical base (Table 6). Mandibular intermolar and intercanine widths were positively related with the mandibular apical base size, but only for a limited number of measures. Mandibular intermolar width was significantly related to the mandibular apical base arch perimeter and the mandibular maximum width. Mandibular intercanine width was significantly related to the mandibular apical base arch perimeter, 5 mm width, 10 mm width, and 20 mm width.

Multivariate Analyses

The factor analysis showed that there were two primary factors explaining over 88% of the variation in the 11 maxillary apical base measurements, and three factors explaining over 90% of the variation in the 11 mandibular apical base measurements. For the maxilla, factor 1 was defined as the maxillary anterior size factor, factor 2 was defined as the maxillary posterior and overall size factor (Table 7). In the mandible, factor 1 was defined as the mandibular anterior size factor, factor 2 was defined as a mandibular posterior size factor, and factor 3 was defined as a mandibular overall size (Table 8).

The two maxillary apical base factors were positively related with maxillary TSALD; the maxillary anterior factor was also positively related with mandibular TSALD (Table 9). The mandibular apical base factors showed a low positive relationship between mandibular anterior size and maxillary TSALD.

Controlling for maxillary TSALD, there were no relationships between mandibular TSALD and the size of the maxillary apical base. Similarly, when controlling for mandibular TSALD, no relationship was found between maxillary TSALD and the mandibular apical base.

The maxillary and mandibular apical base factors were significantly related. Maxillary anterior size showed low positive associations with mandibular anterior size and mandibular overall size (Table 10). The maxillary posterior and overall size factor showed a low positive association with anterior size and a moderately low correlation with mandibular overall size.

CHAPTER V

DISCUSSION

The size of the mandibular apical base is not related to maxillary or mandibular crowding. Most importantly, the current study found no significant relationship between the size of the mandibular apical base and mandibular crowding. There was weak relationship ($r = .228$) between the anterior mandibular apical base and maxillary TSALD. Uysal et al. found a significant relationship between the anterior mandibular bone and lower incisor irregularity in their female subjects.[21] However, incisor irregularity is not the same as crowding, which is better characterized by TSALD. Other studies have also found no statistically significant relationships between mandibular basal bone size, measured from CBCTs, and mandibular crowding, measured from dental models.[10-12] This suggests that the long-held assumption that lower jaw size contributes to crowding cannot be supported. Jaw size also does not explain the crowding that occurs in untreated cases with normal occlusion[1, 31, 41], or the post-retention irregularity and crowding that occurs in well treated cases.[42, 43] Two general factors contribute to crowding of the anterior teeth, including 1) early loss of space prior to the emergence of the permanent dentition and 2) slippage of interdental contacts.[1]

There is a relationship between the size of the maxillary apical base and upper and lower crowding. The current study showed modest associations (strongest correlation: $r=.503$ & $r^2 = 0.253$) between the maxillary apical base and maxillary and mandibular TSALD. These relationships have not been previously evaluated. This suggests that the smaller the size of maxillary basal arch, the greater the maxillary, and to a lesser extent, the mandibular crowding. This suggests that the maxillary is the primary arch constraining the amount of crowding that occurs. It also helps to explain why expansion of maxillary basal bone, without any other treatment being performed, results in decreased maxillary crowding[44]. Moreover, various studies have confirmed the compensating effects of the mandibular dentition following maxillary expansion in both the mixed- and permanent dentitions.[45-47] Maxillary expansion increases mandibular arch dimensions, which might be expected to decrease mandibular crowding. It is important to note that the size of the maxillary apical base explained less than one-quarter of the variation in crowding. This implies that three-quarters of the variation in dental crowding is explained by other factors.

Maxillary apical base size correlates to mandibular apical base size. The current study found a significant relationship between the size of the maxillary apical base and the size of the mandibular apical base. While this relationship has not been previously evaluated, there is indirect supporting evidence. Various studies that placed small metallic implants in maxillary and mandibular basal bone have reported significant width increases of both jaws, with maxillary width increasing more than mandibular width.[48] This suggests a coordination of the upper and lower jaws. It has also been shown the Bionator treatment alone increases the width of maxillary basal bone, and it appears to also increase the width of mandibular basal bone, although not significantly.[49] These findings point to maxillary and mandibular basal bone compensating to maintain jaw relationships.

There are significant sex differences for maxillary apical base dimensions, but only limited mandibular apical base dimensions. The current study found statistically significant sex differences in all maxillary apical base dimensions analyzed. The mandibular apical base showed significant sex differences only in the overall area, perimeter, and the maximum width. There is no available literature which has looked specifically at sexual dimorphism in the maxillary and mandibular basal bone directly. However, several studies utilizing CBCT images have shown significantly larger upper and lower jaw sizes in males.[50-53] These studies were largely measuring traditional cephalometric angles and planes, with some additional novel planes to define jaw size for various populations, but none of these planes specifically measures the apical base of the maxilla or mandible. Though these studies defined jaw size by traditional cephalometric measurements, they offer indirect evidence to confirm the current study's findings of larger maxillary apical basal bone, and larger overall mandibular apical basal bone in males.

The size of the dental arch is inversely related to crowding. The current study shows that upper and lower crowding increases as the sizes of the dental arch measurements, including intermolar and intercanine widths and arch perimeter, decrease. The literature largely supports this finding, showing negative correlations and significant differences in size between crowded and not crowded arches.[4, 13-16] However, a negative association might be expected because crowded teeth usually move mesially into a narrower and shorter portion of the dental arch as contacts between anterior teeth slip and become displaced.[1] By definition, the dental arch will always be too small to accommodate the teeth whenever there is crowding. This relationship between crowding and the size of the dental arch should be considered a spurious correlation.

The size of the teeth has little or no effect on crowding. In the current study, crowding was not related to upper or lower tooth size. Some studies have shown statistically significant relationships between tooth size and crowding,[13, 15, 16, 33] while others have not.[4, 10, 34] Studies showing relationships evaluated differences in tooth sizes between groups who are crowded and not crowded, with differences ranging from 1.7 - 6.2 mm for the sum of the teeth from first molar to first molar. No correlations were reported. The current study didn't find statistically significant correlations, but the methodology was different from those who found group differences. It is likely that the size of teeth plays a role, but only a minor role. Tooth size is not a primary contributor to crowding.

Clinical Implications

The results of this study do not justify expansion for all patients to prevent or minimize crowding. Considering the current study's findings, a justification for dental expansion may seem warranted. There was a significant relationship between the maxillary apical basal bone and crowding, but the strength of the relationship was low. The size of the maxillary apical base explained less than one-quarter of the variation in crowding, so from a practical standpoint, therapies aimed solely at widening the maxilla should not be expected to be sufficient in preventing crowding. Each case must be evaluated with all the dental and skeletal problems in mind. This study does indicate that patients with smaller maxillary apical bases are at greater risk of developing crowding so clinicians should consider that in treatment planning and in designing retention for those patients. From this study and the other studies reviewed, arch size and tooth size are not the primary factors causing dental crowding. A greater focus should be placed on analyzing other factors to continue in the pursuit of understanding this complicated and multifactorial problem.

CHAPTER VI

CONCLUSIONS

1. The size of the mandibular apical base is not related to maxillary or mandibular crowding.
2. There is a relationship between the size of the maxillary apical base and upper and lower crowding.
3. Maxillary apical base size correlates to mandibular apical base size.
4. There are significant sex differences for maxillary apical base dimensions, but only limited mandibular apical base dimensions.
5. The size of the dental arch is inversely related to crowding. This is likely a spurious correlation.
6. The size of the teeth has a minimal effect on crowding.

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APPENDIX A

FIGURES

Figure 1. Maxillary and mandibular tooth size (mesio-distal widths) analysis.

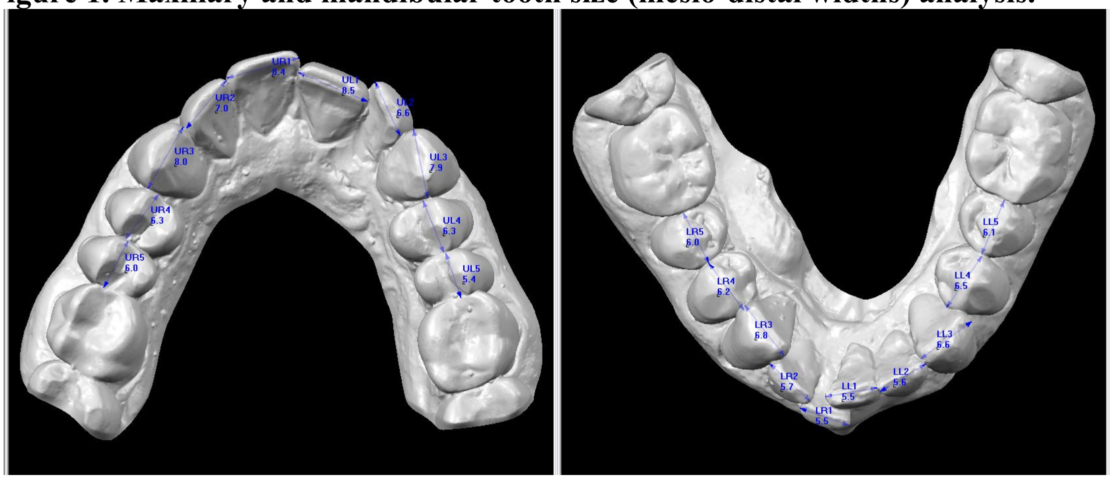


Figure 2. Maxillary and mandibular dental arch perimeter analysis.

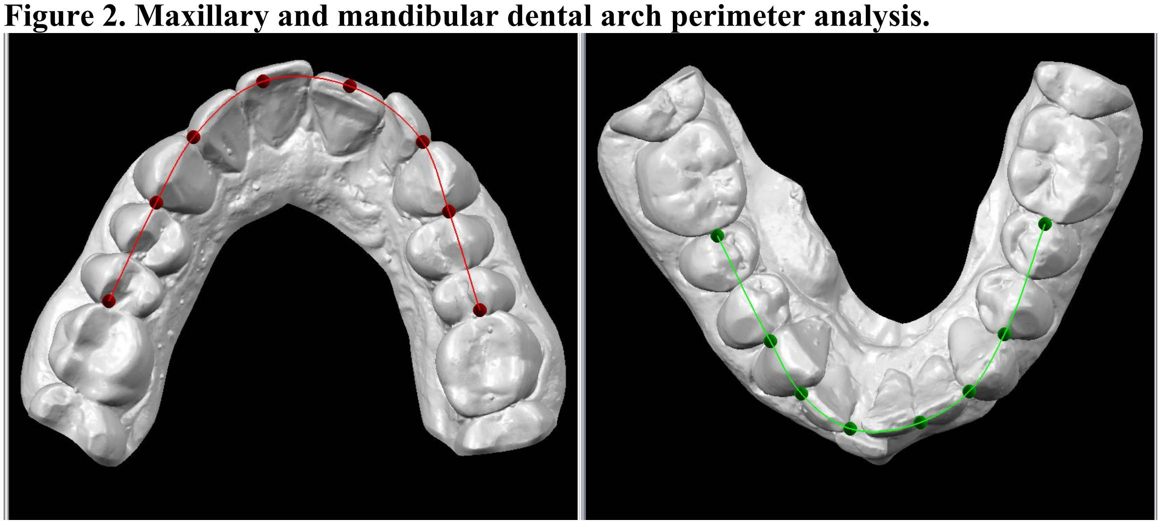


Figure 3. Maxillary and mandibular intermolar and intercanine widths.

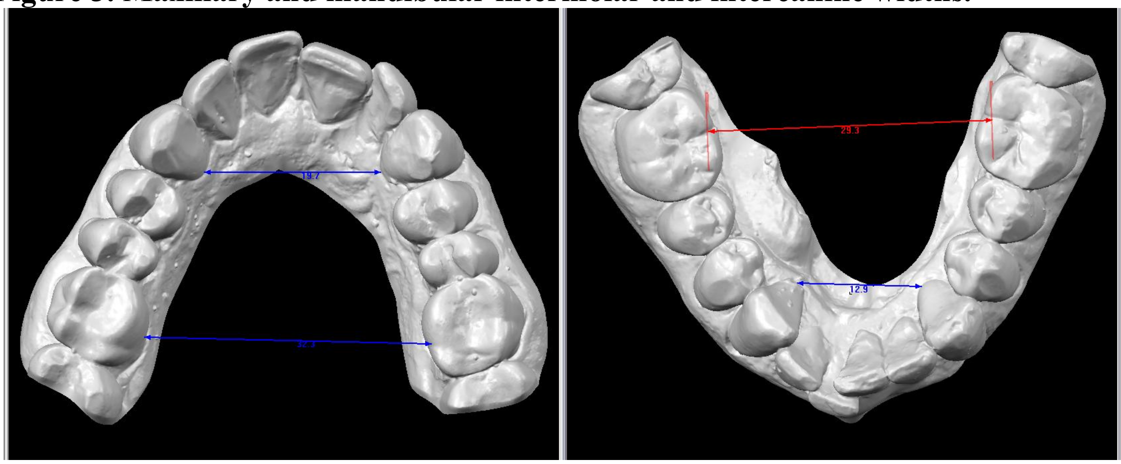


Figure 4. CBCT standardized orientation.

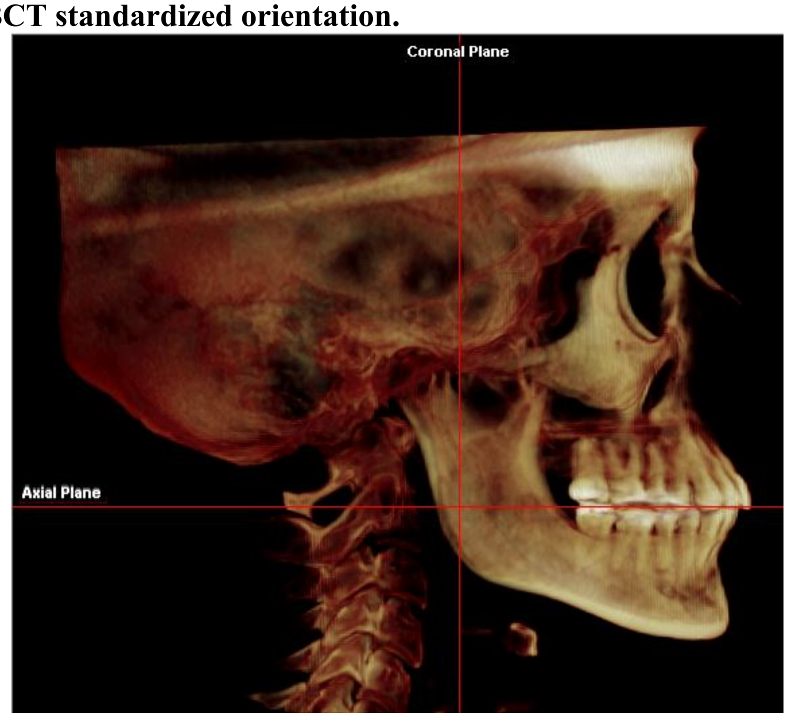


Figure 5. Maxillary apical base analysis orientation.

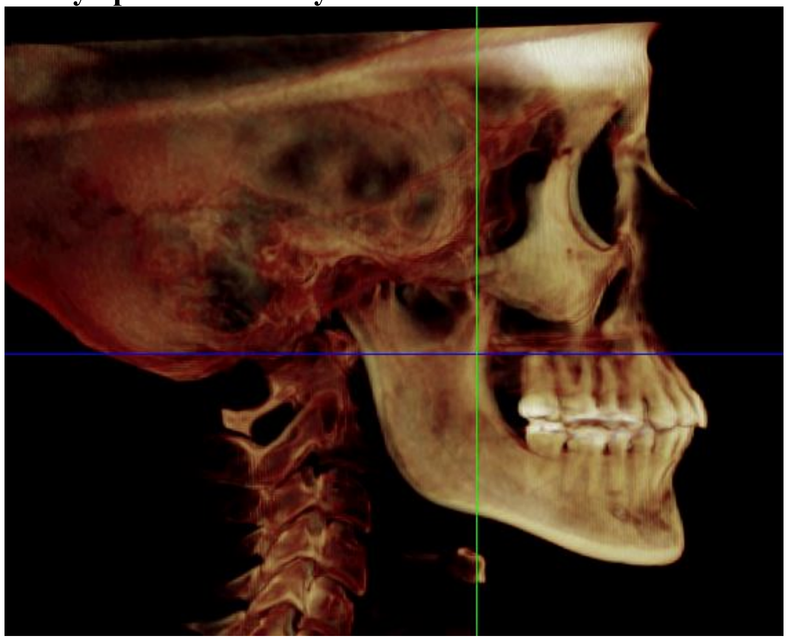


Figure 6. Mandibular apical base analysis orientation.

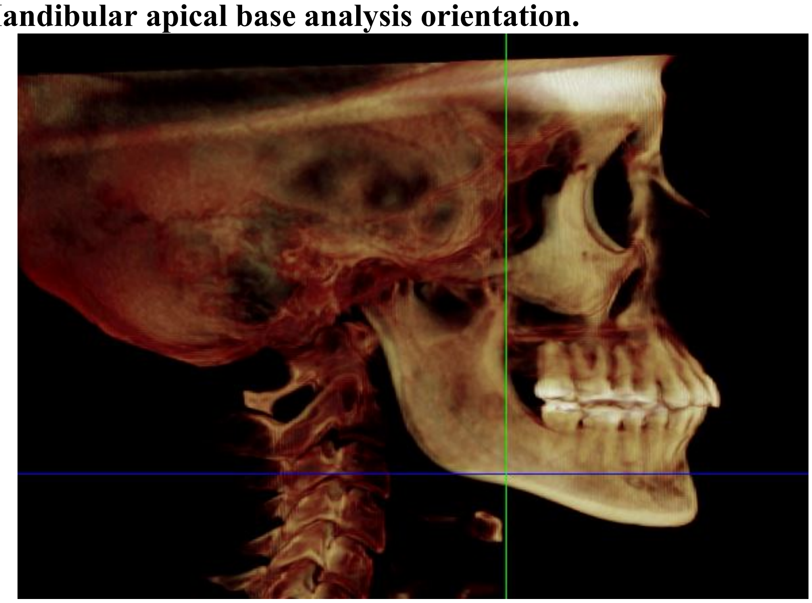


Figure 7. Maxillary apical base cross-sectional area (stippled area), arch perimeter, and arch widths at 5 mm (Mx 5W), 10 mm (Mx 10W), 20 mm (Mx 20W), 30 mm (Mx 30W), and a maximum posterior width (Mx MaxW).

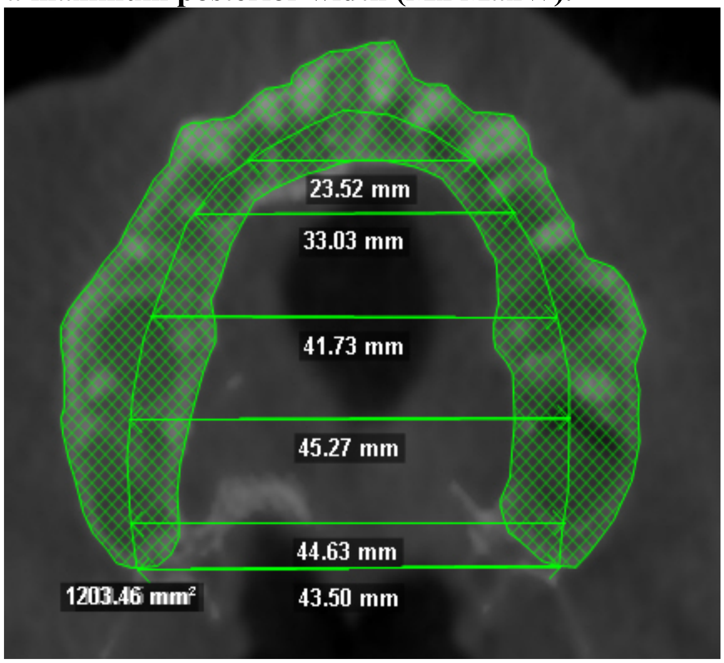
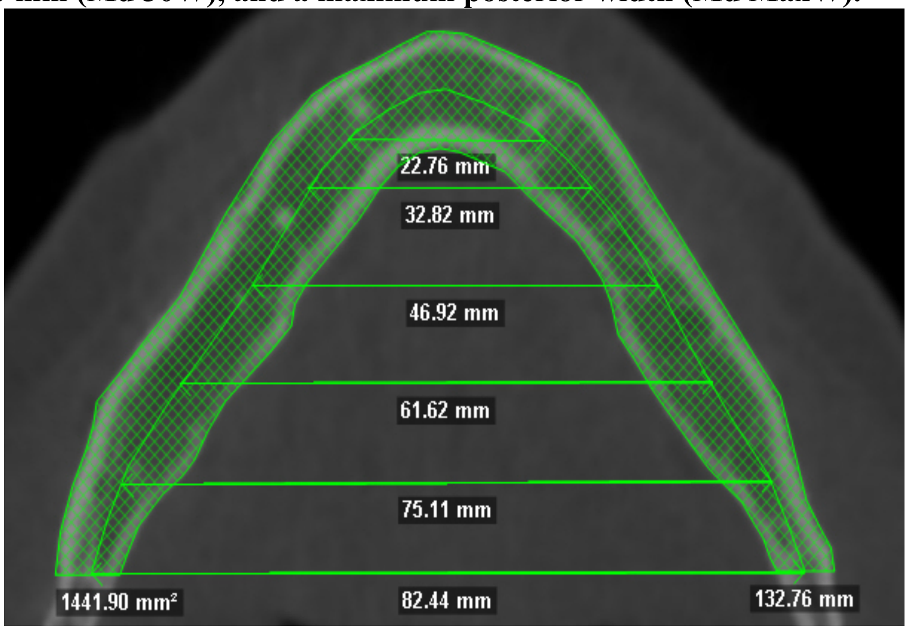


Figure 8. Mandibular apical base cross-sectional area (stippled area), arch perimeter, and arch widths at 5 mm (Md 5W), 10 mm (Md 10W), 20 mm (Md 20W), 30 mm (Md 30W), and a maximum posterior width (Md MaxW).



APPENDIX B

TABLES

Table 1. Sex differences in age, ANB, MPA, tooth size, dental arch measurements, and TSALD.

	Males		Females		Differences
	Mean	SD	Mean	SD	P-value
Age	38.52	12.95	44.55	11.68	.048*
ANB	2.69	1.38	3.04	1.53	.353
MPA	31.84	5.2	33.88	4.08	.069
Mx Tooth Size	75.33	3.35	73.45	3.86	.044*
Md Tooth Size	65.70	2.75	64.33	3.33	.083
Mx Arch Perimeter	76.28	4.13	73.16	4.19	.003**
Md Arch Perimeter	64.27	4.67	61.89	3.59	.018**
Mx TSALD	.95	2.81	-.292	2.57	.062
Md TSALD	-1.43	3.26	-2.44	2.52	.146
Mx IMW	36.71	3.38	34.51	2.84	.004**
Mx ICW	25.25	2.83	23.60	2.16	.007**
Md IMW	33.54	3.19	32.11	2.87	.055
Md ICW	19.60	2.63	18.52	1.98	.052

Table 2. Correlations between maxillary and mandibular TSALD and dental arch measurements.

		Mx Tooth Size	Md Tooth Size	Mx Arch Perimeter	Md Arch Perimeter	Mx IMW	Mx ICW	Md IMW	Md ICW
Mx TSALD	R	-.113	.257*	.515**	.427**	.489**	.549**	.208	.232*
	P	.334	.026	<.001	<.001	<.001	<.001	.074	.046
Md TSALD	R	.219	-.075	.392**	.625**	.426**	.533**	.447**	.568**
	P	.059	.520	.001	<.001	<.001	<.001	<.001	<.001

Table 3. Sex differences in maxillary and mandibular apical base measurements.

	Maxillary Apical Base					Mandibular Apical Base				
	Males		Females		Diff.	Males		Females		Diff.
	Mean	SD	Mean	SD	P-value	Mean	SD	Mean	SD	P-value
Overall Area (mm^2)	1518.53	221.67	1273.30	138.08	<.001*	1370.27	243.3	1204.47	170.78	.001**
Overall Perimeter (mm)	115.92	8.36	108.84	5.49	<.001*	127.90	9.30	120.64	8.14	.001**
5 mm Width (mm)	26.95	3.07	25.09	3.01	.015*	24.72	2.01	23.85	1.72	.057
10 mm Width (mm)	35.15	3.05	32.43	3.14	.001*	34.62	2.09	33.76	1.89	.081
20 mm Width (mm)	44.28	3.34	41.22	3.31	<.001*	49.16	3.05	48.66	2.70	.469
30 mm Width (mm)	47.89	3.22	44.62	3.06	<.001*	62.89	3.85	62.22	3.10	.419
Maximum Width (mm)	46.34	4.03	43.01	3.37	<.001*	79.30	5.40	75.30	4.38	.001**
5 mm Perimeter (mm)	29.21	2.97	27.50	2.84	.019*	27.08	1.94	26.38	1.88	.141
10 mm Perimeter (mm)	42.31	2.81	40.17	2.87	.003*	41.21	1.91	40.37	1.67	.056
20 mm Perimeter (mm)	64.23	2.91	61.88	2.84	.001*	65.86	2.26	65.31	2.02	.292
30 mm Perimeter (mm)	84.70	2.89	82.31	2.82	.001*	90.16	2.89	89.36	.31	.194

Table 4. Correlatioins between maxillary and mandibular TSALD to measures of the maxillary apical base.

		Mx Area	Mx Basal Perimeter	Mx 5W	Mx 10W	Mx 20W	Mx 30W	Mx Max W	Mx 5 P	Mx 10P	Mx 20P	Mx 30P
Mx TSALD	R	.360**	.309**	.443**	.474**	.494**	.445**	.029*	.440**	.468**	.503**	.472**
	P	.002	.007	<.001	<.001	<.001	<.001	.029	<.001	<.001	<.001	<.001
Md TSALD	R	.223*	.242*	.288*	.253*	.283*	.321**	.246*	.301**	.280*	.323**	.286*
	P	.044	.036	.012	.028	.014	.005	.033	.009	.015	.005	.013

Table 5. Correlations between maxillary and mandibular TSALD to measures of the mandibular apical base.

		Md Area	Md Basal Perimeter	Md 5W	Md 10W	Md 20W	Md 30W	Md MaxW	Md 5 P	Md 10P	Md 20P	Md 30P
Mx TSALD	R	.178	.111	.192	.202	.130	.091	.127	.254*	.212	.145	.122
	P	.127	.342	.098	.083	.266	.435	.279	.028	.068	.216	.299
Md TSALD	R	.072	.095	.127	.203	.149	.072	.077	.025	.156	.121	.107
	P	.537	.419	.278	.080	.204	.540	.512	.829	.183	.303	.363

Table 6. Correlations between maxillary and mandibular IMW/ ICW to their respective dental and apical base perimeters and widths of the apical base.

		Dental Arch Perimeter	Basal Perimeter	5 mm Width	10 mm Width	20 mm Width	30 mm Width	Maximum Width
Mx IMW	R	.550**	.640**	.718**	.757**	.798**	.774**	.523**
	P	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Mx ICW	R	.725**	.463**	.580**	.610**	.649**	.617**	.401**
	P	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Md IMW	R	.393**	.351**	.148	.204	.138	.110	.271*
	P	<.001	.002	.206	.079	.238	.347	.019
Md ICW	R	.686**	.081	.249*	.289*	.229*	.118	.068
	P	<.001	.490	.031	.012	.048	.313	.560

Table 7. Maxillary bone factor analysis showing eigenvalues (variation explained by each variable) and the factor loadings.

	Eigenvalues	**Factor 1 Mx Anterior Size**	**Factor 2 Mx Post. + Overall Size**
Mx Overall Area (mm^2)	.765	.201	.851
Mx Overall Perimeter (mm)	.669	.285	.767
Mx 5 Width (mm)	.963	.950	.245
Mx 10 Width (mm)	.968	.880	.440
Mx 20 Width (mm)	.916	.750	.595
Mx 30 Width (mm)	.908	.573	.761
Mx Max Width (mm)	.629	.319	.726
Mx 5 Perimeter (mm)	.945	.945	.231
Mx 10 Perimeter (mm)	.989	.919	.379
Mx 20 Perimeter (mm)	.983	.883	.450
Mx 30 Perimeter (mm)	.980	.847	.466
Percent of Total Variance		77.78%	10.53%

Table 8. Mandibular bone factor analysis showing eigenvalues (variation explained by each variable) and the factor loadings.

	Eigenvalues	Factor 1 Md Anterior Size	Factor 2 Md Posterior Size	Factor 3 Md Overall Size
Md Overall Area (mm^2)	.671	.036	-.174	.800
Md Overall Perimeter (mm)	.837	.034	-.001	.914
Md 5 Width (mm)	.940	.937	.233	.084
Md 10 Width (mm)	.939	.836	.490	.002
Md 20 Width (mm)	.938	.427	.868	-.053
Md 30 Width (mm)	.960	.261	.941	.077
Md Max Width (mm)	.933	.075	.467	.842
Md 5 Perimeter (mm)	.867	.889	.253	.112
Md 10 Perimeter (mm)	.957	.900	.383	.009
Md 20 Perimeter (mm)	.961	.649	.733	-.046
Md 30 Perimeter (mm)	.953	.474	.849	.077
Percent of Total Variance		60.44%	19.74%	10.32%

Table 9. Correlations between maxillary and mandibular TSALD to maxillary and mandibular basal bone factors.

		Mx Basal Bone Factors		**Md Basal Bone Factors**		
		Mx Ant Size	Mx Post + Overall size	Md Ant Size	Md Post Size	Md Overall Size
Mx TSALD	R	.406*	.270*	.228*	.014	.146
	P	<.001	.019	.049	.906	.212
Md TSALD	R	.227*	.225	.111	.073	.074
	P	.050	.053	.343	.536	.530

Table 10. Correlations between maxillary apical base and mandibular apical base.

		Md Ant Size	Md Post Size	Md Overall Size
Mx Ant Size	R	.284*	.271*	-.083
	P	.014	.019	.478
Mx Post + Overall Size	R	.241*	-.052	.583*
	P	.037	.660	<.001