University of Alberta

Relationship of human tongue volume with inter-dental maxillary and mandibular arch width, palatal axial cross-sectional perimeter, palatal index and root axial inclination

by

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Dédicace

À mes parents que j’aime par-dessus tout et qui m’ont encouragé tout au long de mes études et ont suivi mon progrès avec attention et dévouement à mon succès. Je les remercie du fond de mon cœur et leur dédie ma thèse, l’aboutissement de toutes mes années d’étude, de mes efforts et de ma poursuite vers l’excellence.

Abstract

Objective : To determine the relationship of tongue volume as determined from Cone Beam Computed Tomography (CBCT) scan reconstructions with maxillary and mandibular arch width, axial cross-sectional palatal perimeter, palatal index and axial inclination of upper and lower first premolars and molars.

Method: Thirty subjects without prior orthodontic treatment swished barium sulfate to coat the tongue prior to CBCT imaging. The scan reconstructions were analyzed with three after-market softwares and intra-examiner reliability was assessed.

Results: Absolute agreement intra-class correlation coefficients were used to determine reliability of the measurements. Pearson correlation coefficients and regression analysis were used to determine relationships.

Conclusions: Tongue volume was strongly correlated with upper inter-molar width and palatal perimeter at the molar level, and least correlated with lower inter-molar width and axial inclination of the upper and lower first premolars and molars. The differences in measurements obtained from the three softwares were not statistically significant.

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Chapter I: Introduction and Literature Review

1. Introduction

The relationship between oral soft tissues, in particular the tongue, and craniofacial skeletal growth has been debated in the scientific literature.[1-8] The extent of the role of the tongue in contributing to development and morphology of maxillary and mandibular arch forms and the precise positioning of the teeth is still under investigation as further studies expand our knowledge and refine the current beliefs and theories.[1,7] Imbalances between the outward forces from the tongue and inward forces from the cheeks and lips may contribute to the development of malocclusions and dental arch constrictions.[6] Knowing the size and volume of the tongue and its relationship with potential development of malocclusions would aid clinicians in diagnosis. Direct measurements of the tongue have been attempted previously, [1,7,9] as have tongue volume measurements from magnetic resonance imaging, [10-13] and computerized tomography[14,15]. Recently, with the introduction and gain in popularity of Cone Beam Computed Tomography three-dimensional radiography in dental and orthodontic offices, the possibility of assessing tongue volume for patients becomes interesting as an aid in the diagnostic process.

This study investigated tongue volume measurement from Cone Beam Computed Tomography scan reconstructions using three after-market medical imaging softwares, namely Anatomage inVivo 5 (InVivo 5 Anatomy Imaging Sciences, San Jose, USA), Avizo 6.0 (VSG Visualization Sciences Group, Inc.), Mimics 13.1 (Materialise NV). Tongue volume measurements were related to findings of the maxillary and mandibular inter-dental arch width dimensions, the palatal perimeter and ratio between palatal height to palatal width, and axial inclination of the upper and lower first molar and premolar teeth.

2. Literature Review

a. Theories of Craniofacial Growth

Multiple factors influence the size and shape of the jaws, and it is the equilibrium of these factors that determine the normal and pathologic responses of the skeleton.[6] The proportion of each of these factors and their interplay is not clearly understood. However, it is known that although genetic factors can not be changed, the environmental factors also play an important role and can be modified.[6] Larger tongues sizes in children, abnormal tongue positions, tongue habits and other factors influence the jaw growth.[6]

Theories have been proposed to explain skeletal growth and growth stimulus. Without a doubt, strong genetic, as well as environmental, influences contribute to growth direction and, to a certain extent, quantity.[6] Factors such as inadequate nutrition, level of physical activity, or state of health have all been shown to contribute to growth stunting.[6] Three theories have emerged concerning craniofacial growth: bone as its primary determinant of growth, cartilage as the primary determinant with secondary skeletal growth response, and soft tissue in which the skeleton is embedded as the primary determinant with secondary growth response from cartilage and bone. This third theory is otherwise known as the functional matrix theory.[6]

The first theory presented by Brodie in 1941 implied that genetic control acted on growth centers within the bone and that the skeleton responded by symmetric increase in size of all bony surfaces.[16] Therefore growth centers within the bone were the primary determinants of the growth amount as per genetic control. This theory was replaced when it became evident that growth at the level of cranial sutures, distant from the growth centers, responded to external environmental influences and reacted to these stimuli, as well as transplanted bone elsewhere in the body showed no innate growth properties.[6]

The second theory emerged from this knowledge and presented cartilage growth as the determinant of skeletal growth.[16] Certain cartilage segments displayed innate growth properties when transplanted in the body, such as the epiphyseal plate of long bones, the cartilage from the nasal septum and the cartilage from the cranial base spheno-occipital synchondrosis. However not all cartilages showed such properties, such as the condylar cartilage originally believed to be the source of the ramus and mandibular bone remodelling. It became evident that although certain cartilages may present genetically controlled independent growth potential, most other bodily cartilage growth is simply reactive to surrounding soft tissue changes.[6,16]

The functional matrix theory of growth proposed by Moss in the 1960's and revisited in the 1990's, outlines the major determinant of growth of the maxilla and the mandible as a response to the functional needs of the growing soft tissues of the face, oral and nasal cavities.[17,18] To adapt to changing functional needs and environmental factors, the soft tissues react and grow, which creates a response within bone and cartilage. Thus, it is clear that growth, as well as the attachment location of the muscles of the oral cavity creating pressure and tension areas, play a large role in determining the adaptation and shape of the maxillary and mandibular jaws. An equilibrium is reached between the forces from the inner and outer oral cavity which ultimately affects jaw size and shape.[6] If abnormal forces, attachment location, or pathologic conditions arise, it may result in an adaptive pathologic growth of the skeletal response. Certainly, the equilibrium forces from tongue, lips and cheeks influence the vertical and horizontal tooth position as well as its position in the dental arch.[6,16]

b. Anatomy of the tongue muscles, floor of the mouth

The tongue is a striated muscle formed of intrinsic and extrinsic muscular components in an oral or movable part, and a pharyngeal or non-movable part.

The intrinsic muscular fibers allow for change in the tongue's shape, whereas the extrinsic muscles allow for movement of the tongue. The intrinsic muscles that form the tongue are the superior longitudinal, inferior longitudinal, transverse and vertical muscular fibers. The extrinsic muscles of the tongue are the genioglossus muscle, responsible for protraction and depression, the hyoglossus muscle, responsible for depression, the styloglossus muscle, allowing retraction and elevation, and the palatoglossus muscle, which elevates and narrows the oropharynx during swallowing.[19]

Growth of the human tongue has been studied by Temple *et al*.[20] in 2002 and Cohen *et al*.[21] in 1976. Although tongue growth is not fully understood, it appears that the tongue follows a similar growth pattern to muscle tissue of the body.[20] At birth, the tongue is a small and broad muscle filling the oral cavity as its primary role is in suckling and feeding of the infant. Gradually, around 1 year of age post-natally, the posterior third of the tongue starts its descent.[22] It is not until around 4 years of age that the posterior third has completely descended into the pharyngeal region with the transition in feeding and diet change. By this time, the tongue begins to form part of the anterior pharyngeal boundary.[22] The infantile tongue-thrust type swallow is partly explained by this proportionately larger tongue in a smaller mouth, and the transition to an adult pattern swallow is enabled by the later growth in size of the tongue. Temple *et al*.[20] demonstrated that the human tongue grew in two parts regardless of gender. From infancy to adolescence, the growth of the tongue doubles in length, width and thickness, with the anterior portion of the tongue reaching its adult size by 8 to 10 years of age. There was no significant growth of the anterior portion beyond 10 years of age. The posterior portion of the tongue continued with over 70% further growth until its adult size by 15 to 16 years of age at which time growth is essentially complete.[20,23]

c. Specific role of the tongue in craniofacial growth

As an important and sizable muscle in the oral cavity, the tongue muscle influence on craniofacial growth is considerable. To better understand tongue influence on skeletal growth, animal studies have been conducted.

Liu *et al*.[4,24-26] have studied extensively the effects of tongue volume reduction and its consequence on muscle activity, mastication, and the resultant response on craniofacial growth. After a reduction in the size and volume of the tongue of young fast-growing pigs, they measured the effect on functional loading of the tongue, masticatory activity and efficiency, bony effects and growth influence. They found that masticatory activity and efficiency were diminished, although daily food consumption and body weight were not affected. The volume reduction of the tongue decreased the functional load along the mandibular lingual surfaces, and the anterior mouth, and to a lesser extent the maxillary and premaxillary palatal surfaces.[24] This resulted in a negative effect on linear expansion development of the craniofacial skeletons of the sham pigs. More particularly, they noted that craniofacial skeletal and inter-dental arch size were significantly less developed, with a marked reduction in the development and expansion of the mandibular anterior length, ramus height, anterior dental arch and midface width of the sham pigs. Overall, the symphysis area and the anterior dental arch were the most affected marked by reduced bone mineral density.[4]

In a four article series, [2,3,5,27] the Anatomischer Anzeiger Journal shed light on the multi-factorial role of the tongue on craniofacial growth. The above results are corroborated in the earlier study by Becker *et al*.[2] who found an important relationship in orofacial growth of the tongue and reduced lower jaw width development in a miniature pig animal model after half the sample received partial glossectomy surgery. In a further study using the same miniature pig animal model, the alveolar bone height development and overall mandibular length showed markedly less development in the partial glossectomy group.[27] Hubner *et al*.[3] found that the tongue and peri-oral muscles, however, did not play a significant role in the vertical component of mandibular growth nor in maxillary and skull growth. Finally, Pommerenke *et al*.[5] outline the key role and effect of the tongue on craniofacial growth at specific times in the development of the miniature pigs. Their study demonstrated that a reduction in the length of the tongue in the accelerated postnatal growth phase lead to delays in growth of mandibular length and width. When partial glossectomy was done on the sham pigs at 12 weeks old, there was a marked delayed growth in length and width of the mandible, whereas the same intervention on sham pigs at 6 weeks old showed no detectible influence on growth in mandibular length. In contrast, the mandibular length growth of 16-week old sham pigs was less affected. Craniofacial growth potential decreases with maturity, but the reduction is locally and periodically accentuated with differential intensity. The authors were amazed how little effect the partial glossectomies had on the maxilla in all groups. They hypothesize that growth of the maxillary complex is controlled more by genetics than epigenetic factors. The authors concluded that their study confirmed the importance of the tongue as a quantitative stimulator of the orofacial complex in sham pigs. However, the authors were amazed by the complexity of the epigenetic factors that affected mandibular growth, of which none appeared to have a lasting, dominant effect in the mandibular growth process. Balance and interactions between genetic and environmental factors, as well as between structural and functional entities lead to a multitude of adaptive growth processes.

Although a similar model has not been published in humans and can not be confirmed, it is likely that a similar effect and pattern does occur during human craniofacial growth. It is unclear to what extent the tongue grows in spurts or phases and when these may occur during human growth and development.

d. Palatal vault shape

Another influence of the soft tissues and neuromuscular balance is the palatal vault shape. Difficult to characterize, the palatal vault has been studied in terms of volume size, cross-sectional thickness and area available to accommodate the tongue volume.[9,28-31] Tongue posture and habits, such as tongue thrusts, mouth breathing, lowered tongue postures, have been examined in the literature to determine their influence in palatal vault shape and development.[15] Other studies have shown that palatal vault volume is correlated to the amount of space available for the tongue.[9,32] One might consider the axial cross-sectional perimeter of the palate as a component of the palatal volume. However, no study has assessed the correlation between palatal vault cross-sectional perimeter and the tongue volume.

e. Axial inclination of the dentition

As much as the tongue plays a role in jaw skeletal development, especially the alveolar bone development and inter-dental width, it is logical to consider the effect of the tongue on the inclination of teeth buccal-lingually. Andrews[33,34] studied the axial inclination of all teeth at the level of the crowns and noted an increasing lingual inclination of the mandibular teeth from anterior to posterior, and an increasing lingual inclination of the maxillary teeth from anterior to posterior. This allowed for the proper occlusal inter-digitation as well as alignment of contacts and marginal ridges. Dewel[35] in 1949 and Ferrario[36] in 2001 studied the crown axial inclination and found similar results.

f. Measurement of Tongue Volume

i. Physical measurement

Direct measurements of the tongue volume had been attempted till the 1990's as explained below.

Bandy *et al*.[1] in 1969 studied the relationship between tongue volume and the mandibular dentition (lower inter-molar width, inter-canine width, mandibular arch perimeter, inter-incisal angle) in 39 adult men and attempted to devise a method of measuring tongue volume. The authors reported that measuring tongue size with callipers is unpredictable because of the mobile and shifting tongue size. Furthermore, alginate impressions of the tongue were unsuccessful since the tongue does not remain immobile during the material setting. However, the authors innovated a fluid-displacement system into which the tongue could be extended, with a measurement error between 0.8% to 4.0% once the subjects were standardized with a ruler, determining the protruding tongue length for 17 subjects measured twice with a week interval. The measurements for the 39 subjects were repeated 8 times and averaged, and a mean tongue volume of 31.4cc with a standard deviation of ± 4.9cc was reported. The authors concluded that "with [their] method of measurement, the volume and length of the tongue seem to have little, if any, influence on the width and length of the lower dental arch, on the degree of inter-incisal relationship, and on the angle of the lower incisor teeth to the mandibular plane.   A statistically significant correlation of 0.4 exists between measurable tongue volume and arch perimeter." These conclusions came to disprove the previously held beliefs regarding the influence of the tongue volume and pressure on the size of the mandibular arch.

Oliver *et al*.[9] in 1986 followed with a study on the relationship between tongue volume, oral cavity size and speech in 35 adults using a plaster model from tongue impressions and then determining water displacement as the tongue volume. Measurements were repeated a second time for 12 randomly selected subjects after a three week interval by two examiners and inter-rater reliability was low. The authors concluded that there were individual limitations that influenced the impression technique and volume measurements obtained; therefore, they found varying levels of correlation between tongue volume, oral cavity size, and speech and articulatory defects.

Tamari *et al*.[7] in 1991 studied the relationship between tongue volume and lower dental arch size in 74 Japanese adults using plaster models from tongue impressions. The mean tongue volume was 22.6 cm^3 for women and 25.3 cm^3 for men. The authors concluded that "the mean tongue volume and mean lower dental arch sizes were significantly larger in men than in women; the tongue volume and the lower dental arch sizes were significantly correlated; and these correlations tended to be higher at the more posterior part of the dental arch."

ii. Magnetic Resonance Imaging

The tongue is more clearly visualized on magnetic resonance images (MRI) as a muscle of the oral cavity and can be relatively easily delineated from the muscles that form the floor of the mouth. Five articles were retrieved which attempted to segment the tongue muscle and determine its volume from MRI images taken. However, they could not be compared directly as their inclusion of muscles, as per the definition of the muscles constituting the tongue, differed. Some included only the intrinsic muscles with the genioglossus and hyoglossus; others the styloglossus muscle, or additionally, the palatoglossus.

Ludescher *et al.*[10] studied the correlation between the tongue volume from MRI images taken on 20 subjects and the height of the mouth cavity. They determined tongue volume from combined coronal and sagittal views by partial volume effect to decrease artifacts, and defined the height of the mouth cavity from the geniohyoid muscle of the floor of the mouth to the highest point of the palatal vault. To determine accuracy of the measurements and technique, the tongue volume was determined in the same manner on two pigs. Although the accuracy results were not reported in the article, the authors did find that there was no difference in the volume measurements obtained whether 5mm or 8mm slice thickness was chosen. There is no mention in the article regarding repeated measures to test for reliability of the tongue volume and oral cavity height. The authors reported mean tongue volume for females of 95.7 ± 4.5 cm^3 and for males of 110.7 ± 8.9 cm^3.   The correlation coefficient of tongue volume to height of the oral cavity was r=0.93 and a linear relationship between tongue volume and height with the following regression equation:

TongueVolume = 1.57**HeightOralCavity* – 3.7.

Lauder *et al*.[11] determined tongue volume, as well as oropharynx and oral cavity volumes. The tongue volume was correlated to body weight. To determine reliability of the data, measures were repeated twice for all 19 adult subjects from the same images at two time points. Tongue volume was measured from the coronal view (mean tongue volume of 71.2cc) and the sagittal view (mean tongue volume of 79.3cc) in human subjects. They then determined the accuracy of their findings by repeating the study in 10 rabbits and comparing it to the true rabbit wet tongue volume, and found the estimated tongue volumes from MRI images to be comparable to the actual tongue volume, although the error between the two repeated measure trials in humans was greater than with rabbits. The correlations obtained between the volumes of the tongue, oropharynx and oral cavity were 0.92, 0.79 and 0.90, respectively, and the correlations obtained between tongue volume and body weight were 0.86 from the coronal orientation measurement and 0.82 from the sagittal orientation measurement. The authors recognized the difficulty in locating the inferior and lateral borders of the tongue even on MRI images which may have resulted in some error in measurement.

Humbert *et al.*[12] determined tongue volume and its fat fraction on MRI IDEAL-FSE (iterative decomposition of water and fat with echo asymmetry and least squares estimation – fast spin echo) images from 10 subjects. Intra-rater reliability was determined by repeating the measurement a second time on 51 randomly selected slices. The authors reported a mean tongue volume of 64.1 cm^3 (range of 52-76.6 cm^3, and standard deviation of ± 8.1 cm^3) with an average fat fraction of 26.5% (range 21%-31.5%, standard deviation of ± 3.5%).

Ajaj *et al.*[13] determined tongue volumes of 10 patients affected by acromegaly compared with 50 healthy patients using real time MRI TrueFISP images (fast imaging with steady-state precession sequences). The authors then re-determined tongue volumes of the acromegaly subjects following somatostatin analogue therapy. Measurement reliability was not assessed. The average tongue volume for the healthy subjects was 77 mL for the women, 117 mL for the men, and for patients with acromegaly, it was 145 mL for women and 180 mL for men. After therapy, the mean tongue volumes were reported to be 125 mL for women, 154 mL for men, approximately 15% volume reduction. The study reported that "patients with acromegaly have a greater tongue volume than healthy subjects do."

In a study by Yoo *et al.*[8] determination of a relationship between tongue volume and mandibular prognathism in 10 female adults was sought. The mean tongue volume was 64.6 cm^3 (standard deviation of ± 11.8 cm^3) from MRI scans.

Reliability was determined by repeating the measures three times at a time interval. The authors concluded that the tongue volume was not associated with dental arch size, nor that female adults with mandibular prognathism had larger tongues. They did, however, find a correlation between tongue volume and a backward and downward rotation of the mandible.

iii. Computerized Tomography and Cone Beam Computerized Tomography

Only two studies have been carried out measuring tongue volume on Computerized Tomography (CT) and no studies to date have measured tongue volume from Cone Beam Computerized Tomography (CBCT).

Roehm[14] measured tongue and oral cavity volume from 32 subjects in relationship to anterior open-bite. Twenty-seven subjects had no open-bite and five subjects were diagnosed as having an open-bite. All subjects were placed in a supine position and CT scans were taken to assess three-dimensional size of the tongue and oral cavity from perpendicular planes constructed from the anterior nasal spine to the hyoid bone level. The mean tongue volume obtained was $59.12cm^3$ with a range of 42.63 to $84.50cm^3$. For subjects without anterior open-bite, the tongue volume to oral cavity ratio was 0.86, whereas it was a 0.91 ratio for subjects with open-bite. Measures were validated using human cadaver CT scans and dissected tongues with a fluid displacement technique, and found strong accuracy of the CT method regardless of potential errors form head positioning. Although CT delivers high level of radiation, it was concluded that CT was a reliable and effective method to view and compare tongue and oral cavity sizes.

Lowe *et al*.[15] related tongue to airway volumes from CT reconstructions in 25 male adult subjects with obstructive sleep apnea. No control group was used to compare the results. Subjects were placed in a supine position and CT scans were taken. The mean tongue volume obtained was 71.96cm^3±13.41cm^3 with a range of 44.03 to 99.67cm^3 and the mean airway volume obtained was 13.89cm^3±5.33cm^3. The authors found that the subjects presenting more severe obstructive sleep apnea symptoms also had larger tongue sizes and smaller airway volumes, however the constrictions were mostly in the oropharynx area, with one subject presenting constriction of the hypopharynx area.

Three-dimensional imaging technology started in the 1970's with the first CT scanner invented by Sir Godfrey Hounsfield and Alan McLeod McCormick commercially available in 1972, and have become more widespread in the medical field in the 1980's.[37,38] With the advent at the beginning of this century of a sole 360-degree rotation around the patient cone-shaped x-ray beam, the Cone Beam Computed Tomography imaging technology has made huge strides in improved accuracy, image quality, computer evolvement, mathematical complexity, software analyses, and reduced radiation doses.[39] The magnetic resonance imaging MRI has followed a similar trend since the 1980's and 1990's, but has not been incorporated as readily into the field of dentistry as the CBCT technology, because the MRI is still reserved for more specific and focused imaging.[37,38,40,41]

With its high quality radiographic image, its accuracy as a three-dimensional image reconstruction of the patient, its superior resolution with decreased patient radiation exposure and capture time, and its alluring lower financial cost than the more expensive MRI machines, the CBCT machines are fast replacing the digital panoramic and cephalometric two-dimensional radiographic machines in many orthodontic offices of North-America.[38,40,41] The NewTom (Aperio Services), i-Cat (Imaging Sciences International), 3D Accuitomo (J. Morita), CB MercuRay (Hitachi), are some of the few companies amongst others which offer CBCT machines in North America and world wide.[41]

3. Statement of Problem

Multiple factors influence the size and shape of the jaws, as was discussed previously, and it is the combined effect of genetics and environmental soft tissue factors that determine craniofacial growth and facial bone and teeth final size and position.[6] Previous studies have attempted to quantify the relationship between tongue size with the oral cavity available space and mandibular arch dimensions from direct *in vivo* measurements, CT radiographic and MRI images.[1,7-9,11-15] CT radiographic technology have the draw back of exposing patients to large radiation doses (average range dose for maxillary jaw of 1,031-1,420 microSiverts and for mandibular jaw of 1,320-3,324 microSiverts[41]), have increased capture time with the potential of increased image unsharpness and distortion from patient movement, as well as not being readily accessible in dental practices.[39,42] On the other hand, CBCT radiographic technology have lower radiation doses (average range dose of 36.9-50.3 microSiverts[41]), rapid scan time minimizing image distortion from patient movement, isotropic voxel resolution, and are gaining in popularity and accessibility in dental offices.[39,42] To date, no study has yet reported tongue volume relationship with maxillary and mandibular dentition position in combination with the dento-alveolar measurements. This would allow to better understand the impact of tongue volume on craniofacial development.

4. Research Objectives

The aim of this study was to determine the relationship of tongue volume as determined from Cone Beam Computed Tomography (CBCT) scan reconstructions with maxillary and mandibular arch width, axial cross-sectional palatal perimeter, palatal index (ratio of palatal height to palatal width) and axial inclination of upper and lower first premolars and molars.

5. Specific Hypothesis

Six hypotheses were pursued in this study:

1. a. Tongue volume is positively correlated with maxillary intra-arch width

   b. Tongue volume is negatively correlated with maxillary intra-arch width

2. a. Tongue volume is positively correlated with mandibular intra-arch width

   b. Tongue volume is negatively correlated with mandibular intra-arch width

3. a. Tongue volume is positively correlated with cross-sectional palatal vault perimeter

   b. Tongue volume is negatively correlated with cross-sectional palatal vault perimeter

4. a. Tongue volume is positively correlated with palatal index

   b. Tongue volume is negatively correlated with palatal index

5. a. Tongue volume is positively correlated with axial inclination of the dentition

   b. Tongue volume is negatively correlated with axial inclination of the dentition

6. There is no difference in the measurements obtained between the three after-market analysis softwares

The following null hypotheses were posed:

1. There is no correlation between tongue volume and maxillary intra-arch width as measured at the molar and premolar level

2. There is no correlation between tongue volume and mandibular intra-arch width as measured at the molar and premolar level

3. There is no correlation between tongue volume and axial cross-sectional palatal vault perimeter as measured at the maxillary molar and premolar level

4. There is no correlation between tongue volume and palatal index as measured at the molar and premolar level

5. There is no correlation between the axial inclination of the maxillary and mandibular first molar and first premolar and the tongue volume

6. There is no difference in the measurements obtained between the three after-market analysis softwares

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Chapter II – Software Application for Analysis of Tongue Volume using CBCT imaging

1. Introduction

Multiple factors, both genetic and environmental, influence the size and shape of the jaws. Three theories have been brought forth to explain growth of the craniofacial skeleton: bone as its primary determinant of growth, cartilage as the primary determinant with secondary skeletal growth response, and soft tissue in which the skeleton is embedded as the primary determinant with secondary growth response from cartilage and bone.[1] According to the last theory, the neuromuscular balances found in the soft tissues of the oral cavity are one of the most important determinants in influencing growth direction and development. The tongue plays an important role in this neuromuscular balance of the jaw skeletal structures.[1]

To date studies have been carried out from magnetic resonance imaging (MRI) to assess tongue volume and its possible correlations to oral cavity size, oropharynx size, and in one study jaw skeletal development as per mandibular prognathism correlation, as well as early detection of tongue pathologies.[2-5] Two studies explored the relationship between tongue volume to oral cavity size of subjects with anterior openbite, and tongue volume to airway volume in subjects with obstructive sleep apnea on computed tomography (CT).[6,7] Much remains to be understood in terms of the influence of neuromuscular balance and its role in craniofacial skeletal growth. It is of particular interest to the orthodontic community, who strive to understand growth and control its direction, to further our knowledge in the different components that comprise this neuromuscular balance. MRIs are not routinely taken before commencing orthodontic treatment nor during treatment, although such information offered by this 3-dimensional imaging technology could be invaluable to orthodontists during the diagnostic phase.[8] Three-dimensional radiography, such as the Cone Beam Computed Tomography (CBCT), is becoming increasingly available to the orthodontic community.[9,10] Furthermore, the accuracy of the CBCT technology is improving while decreasing the amount of x-rays emitted.[11,12]

The capacity for the CBCT to generate radiographic images which are anatomically representative of the original model with a 1:1 size magnitude - isotropic, and the ability to obtain slices from any angle of the virtual craniofacial structure, allows calculations and analyses to be carried out more easily and precisely. Presently, clinicians find CBCT radiographic images and volumetric representations useful for hard tissue, teeth and craniofacial structure visualization and diagnoses. It is still challenging to visualize soft tissues on these radiographic images even with the accuracy and detail comparable to the images and reconstructions obtained from MRI.[10,13,14]

One of the simple ways radiologists have found to outline soft tissue structures on radiographs and images is by using barium sulfate solutions of varying viscosity which can be coated on the area of interest to be visualized. Barium sulfate (chemical formula $BaSO_4$) is a white crystalline solid. It is a water insoluble radiocontrast agent administered orally or by enema, for radiographic imaging and other diagnostic procedures most often used in the upper and lower gastrointestinal tract. The extremely low solubility of this heavy metal prevents absorption of harmful toxic amounts of barium sulfate. Barium sulfate has a relatively high density on radiographs and appears as a white demarcation or outline on the image.[15-18]

The aim of this study was to visualize and segment tongue volume from three-dimensional radiographic data obtained from Cone Beam Computed Tomography (CBCT) scan reconstructions on three different after-market softwares and outline some of these software challenges.

2. Methods

The study was approved by the Health Research Ethics Board (HREB) at the University of Alberta. (Appendix 1)

a. Sample

This study encompassed 15 women and 15 men ages 12-years 9-months to 36-years 3-months. Previous studies on tongue volume measurement from Magnetic Resonance Imaging (MRI) [4,5,19-21] have included similar sample sizes between 10 subjects to 50 subjects.

b. Methodology

Patients who required a CBCT radiograph as part of their initial records appointment workup were selected from the University of Alberta graduate orthodontic clinic and the private orthodontic practice of Dr. K. King in Medicine Hat, Alberta. Instruction sheets were offered and informed consent signatures were obtained prior to participation in the study. CBCTs for these patients would have been taken at their usual records appointment as a part of the necessary radiographs; therefore, they were not being unnecessarily subjected to additional radiation. (Appendix 1)

Disposable vials containing 15mL barium sulfate powder were mixed with 5mL water and then given to the patient. After swishing in the mouth for 15 seconds to coat the dorsal and lateral aspects of the tongue, the patient would spit the solution out into a disposable cup and then be seated in the i-CAT machine (Imaging Sciences International, Hatfield, PA). CBCT radiographic images were then taken immediately with a collimation height scan of 13 centimetres, scan time of 20 seconds and resolution of 0.3 millimetre voxel size.

Once CBCT scan reconstructions were obtained from patients and the tongue was visible with the use of contrast medium, the tongue muscle needed to be segmented from the images using an available after-market software. First, the retrieved CBCT radiographic images were rotated using the i-CAT software, as explained below. This allowed easier and reliable segmentation of the lower aspect or ventral aspect of the tongue. Secondly, the exported DICOM files were viewed and segmentation was carried out by using three after-market analysis softwares: Avizo 6.0 Standard (VSG, Visualization Sciences Group, Inc.), Mimics 13.1 (Materialise NV), and Anatomage inVivo 5 (InVivo 5 Anatomy Imaging Software, San Jose, USA). The volume measurements were then compared. Other softwares are available but were not tested in this study, such as Geomagic (Geomagic Inc. NC, USA) and Amira (Visage Imaging). Dolphin 11.5 (Dolphin Imaging Systems, LLC, a Patterson Technology) was explored but not retained for this study due to its challenges as explained below.

c. Application of software options to measure tongue volume

i. I-CAT

Once the radiographic CBCT images were taken on a patient, the i-CAT software converted the image into DICOM files. The i-CAT software enables viewing of the images and modifying its output prior to exporting for analysis with other compatible software. The i-CAT software itself does not offer segmention and volume calculation algorithms, although it is possible to make simple linear and angular measurements.

To modify the images, it was possible to rotate each axial, coronal and sagittal view to facilitate orientation of perpendicular planes for the tongue segmentation. Easily identifiable landmarks were chosen to form artificial borders.

The cemento-enamel junction (CEJ) of the lower first molars and premolars were rotated to be on the same plane on the sagittal and axial views, such that this plane was parallel to the x-axis plane. This formed the lower aspect or ventral aspect of the tongues for segmentation. (Figures 2-1, 2-2, 2-3)

Figure 2-1 Representative subject, Rotation of the image with CEJ of molars parallel to x-axis on the i-CAT interface

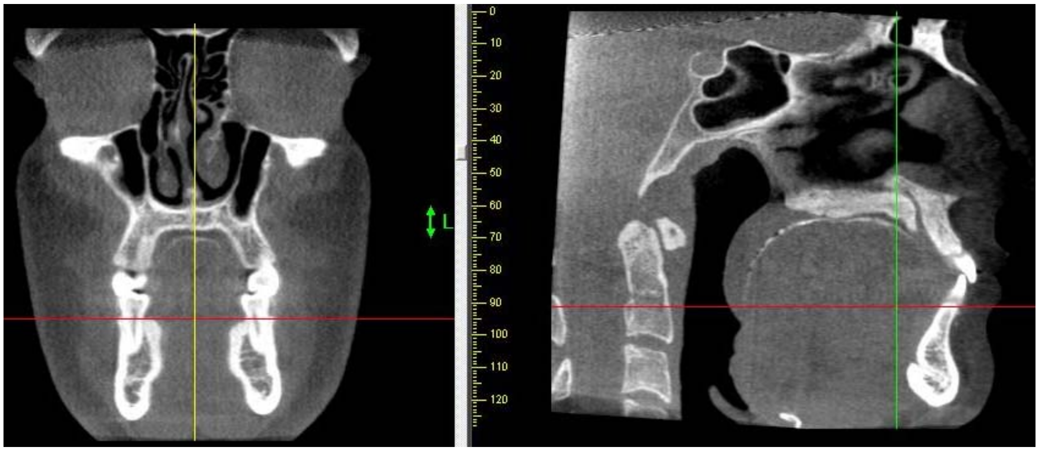

Figure 2-2 Representative subject, Rotation of the image with CEJ of premolars parallel to x-axis

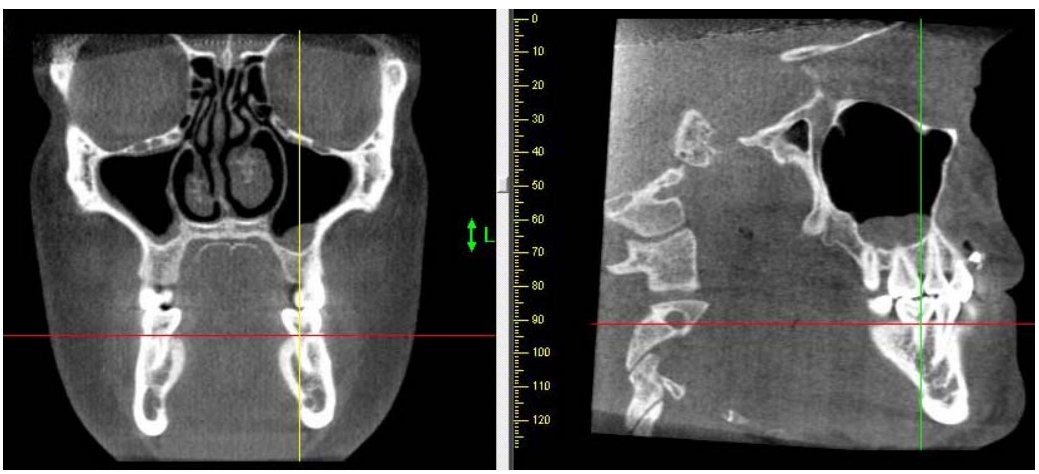

Figure 2-3 Representative subject, Confirmation of CEJ plane parallel to x-axis

A perpendicular plane descending from the posterior nasal spine (PNS) from the axial orientation was chosen to form the posterior aspect of the tongue for segmentation on the axial view. (Figure 2-4)

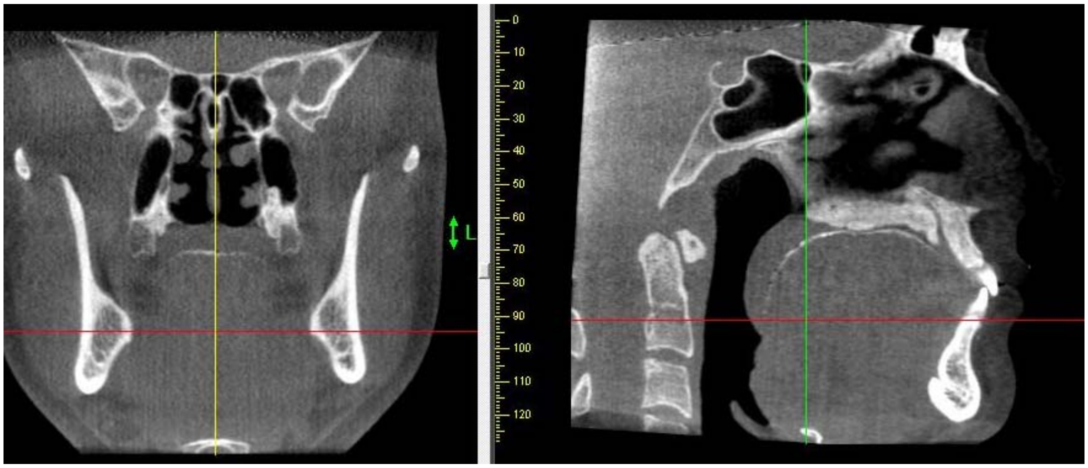

Figure 2-4 Representative subject, Posterior cut-off from perpendicular plane on axial orientation

The dorsal and lateral aspects of the tongue were identifiable from the contrast provided by the barium sulfate coating. (Figure 2-5)

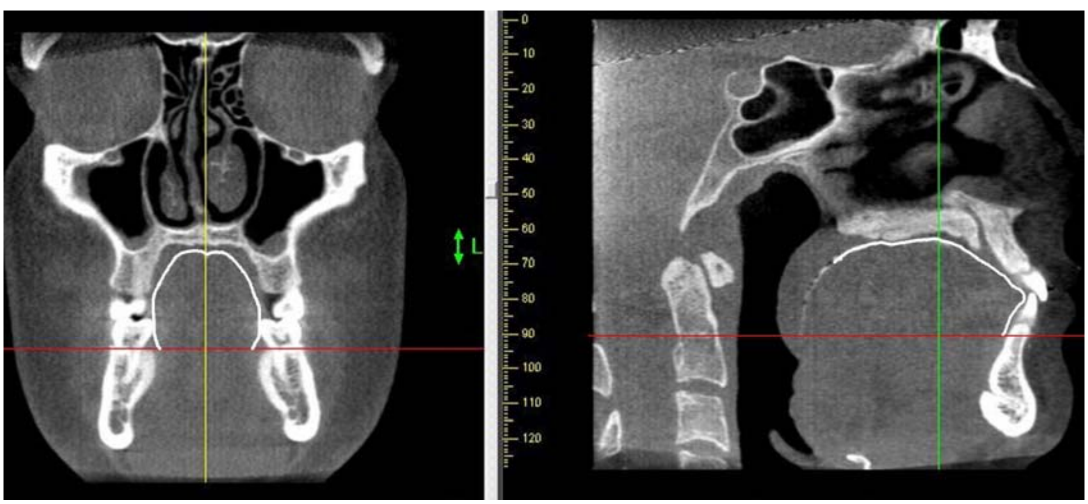

Figure 2-5 Representative subject, Dorsal and lateral aspects of the tongue from contrast medium outline

Prior to exporting the images to be analysed by the after-market software, the i-CAT software allowed for pitch and slice thickness modifications. Slice thickness of 0.3 mm, and pitch of 0.3 mm were selected for the best resolution, as is recommended by the Imaging Sciences International i-CAT manufacturer. Pitch is a measure of the frequency of slices; in other words, how many slices overlap so that information is not lost. Although, it is possible to export the radiographic information with slice thickness and pitch selection, the actual images are acquired by selecting scan time, voxel size and collimation field of view.[14] (Figure 2-6) Clinicians and radiologists are familiar with the vocabulary of slice thickness, pitch, table rotation, radiographic exposure, capture time pertaining to medical spiral CT. However, this vocabulary is not all directly transferable to CBCT radiography, since there is only one rotation of the gantry around the immobile patient.[14,22]

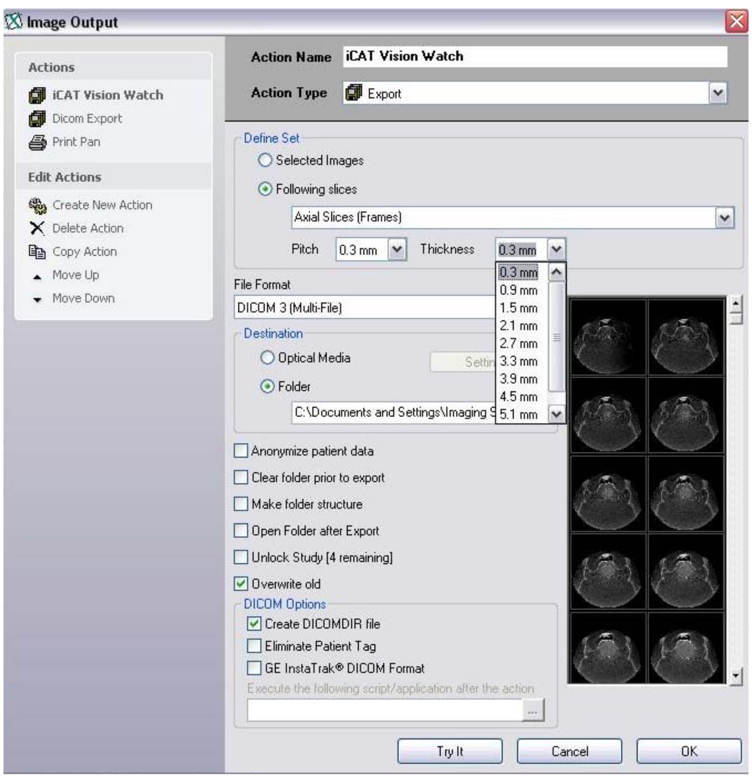

Figure 2-6 Representative subject, I-CAT interface for pitch and slice thickness settings

ii. Dolphin 11.5

The Dolphin Imaging Systems software allows to visualize and rotate three-dimensional volumes for hard tissues and airway. Unfortunately, the software was designed to allow only airway volume measurement. The volume measurement is obtained by selecting the airway portion of interest, being sinuses, pharyngeal airway portion, or other, and contrasting the density of the airway portion to the density of hard tissue. By seeding two points of different density, all areas of the same low density were selected and the volume of the selected portion of the airway is then obtained.

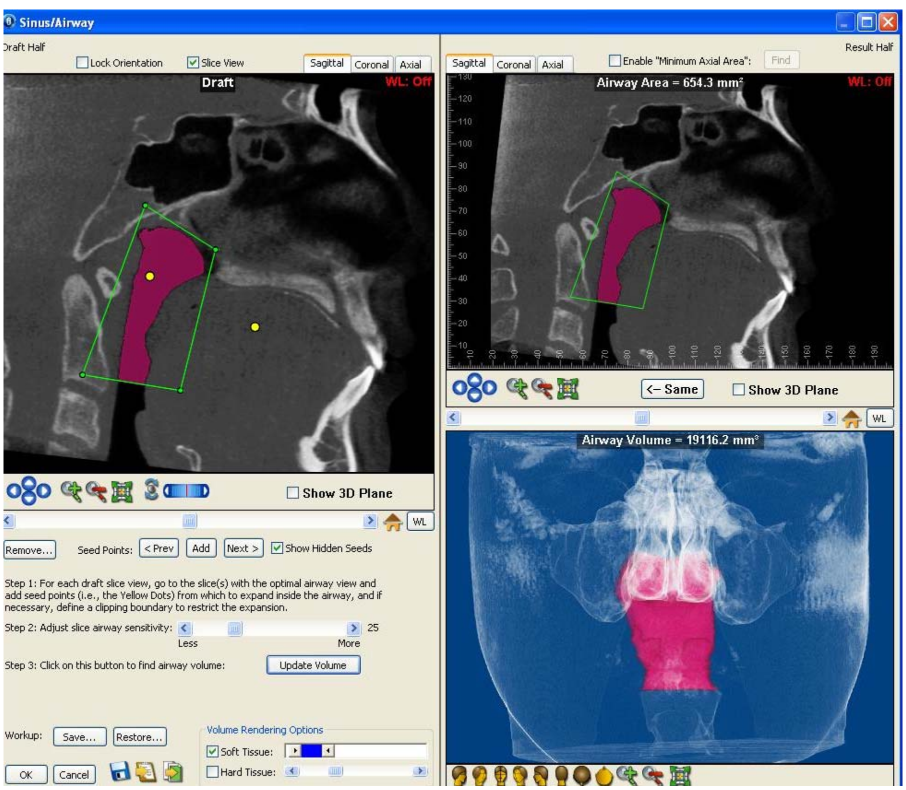

Figure 2-7 Representative subject, Dolphin 11.5 interface with airway volume colored and yellow seed points

This seeding process did not work when selecting soft tissue density versus hard tissue density as the software program was created only to allow density comparison between two points with much greater density contrast – that of the extremely low density of an airway to an extremely high density of hard tissue. For this reason, Dolphin 11.5 software, including the 13.0 beta-testing version, was unable to render the volume measurement of any other structure other than airway.

iii. Mimics 13.1

Mimics 13.1 for X64 Platform V13.1.0.70 from Materialise NV 1992-2009, is used mostly in the fields of engineering, mathematics and physics on any type of dimensional images. Mimics can read different types of file formats, including DICOM files. To obtain the volume of the tongue, the software allowed viewing of each slice in the patient file along coronal, axial and sagittal directions. In Mimics 13.1, the possibility of using both Hounsfield and Grey values allowed to set the threshold from the scan. To segment the tongue soft tissue, the contour of the area of interest was selected and filled in on each slice of interest. Based on the Hounsfield range of values selected initially, the selected areas which fell into that assigned range were then interpolated to form a three-dimensional mask of the volume of interest. Using the volume of the voxels from the scan and the number of voxels selected for a given mask, the volume of the object, in this case the tongue, can be calculated. Linear and angular measurements were calculated, based on table and slice position from the scanner, according to mathematical formulas programmed in the software. The higher the scan resolution, the more accurate the models and measurements would be.

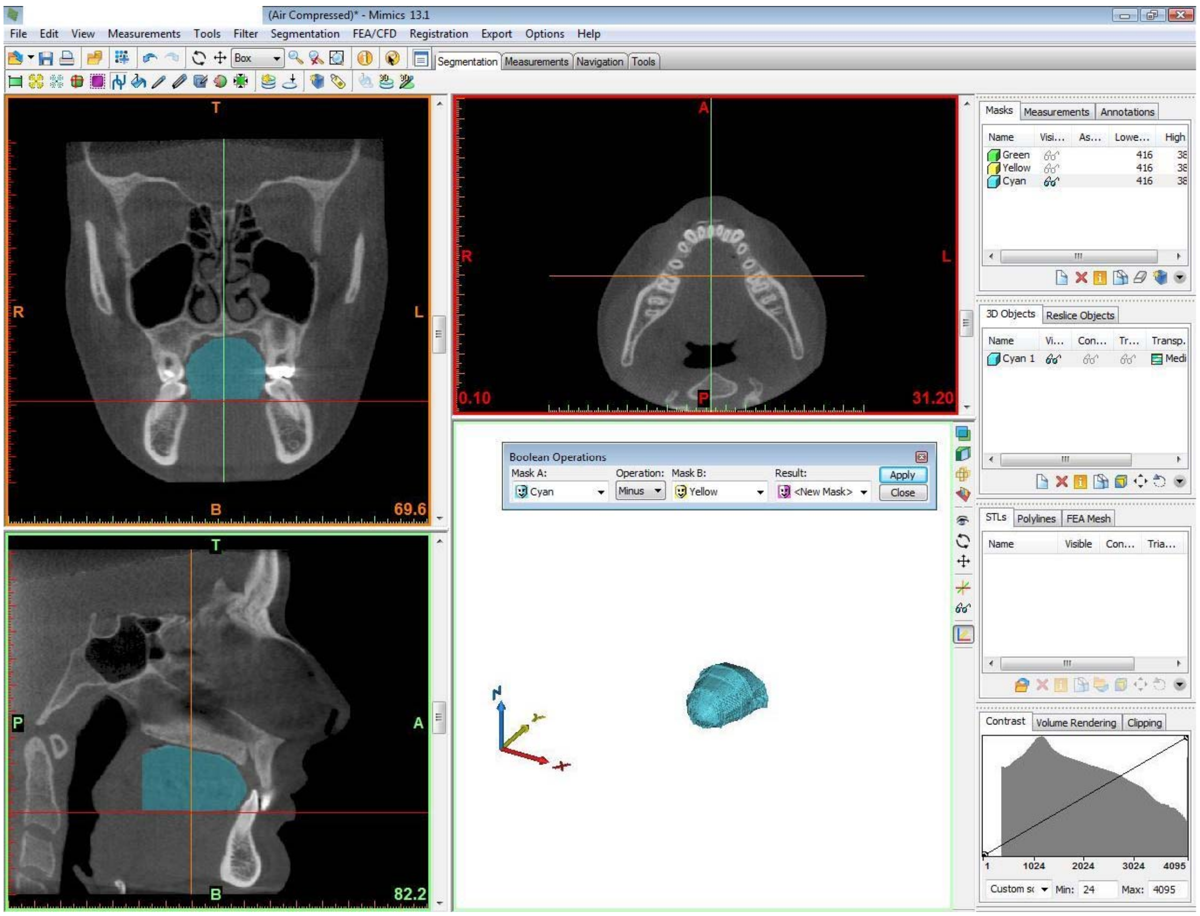

Figure 2-8 Representative subject, Mimics 13.1 interface with tongue segmentation and generated blue mask

iv. Avizo 6.0

Avizo 6.0 Standard allowed a similar approach to volume determination than Mimics 13.1, permitting a Grey value threshold from the scan. However, Avizo 6.0 does not offer the option to set Hounsfield units for the radiographic images as do the other softwares. The segmentation of the tongue was carried out by selecting the area of interest from each slice on one given reconstructed direction, either axial, coronal or sagittal view orientation. The areas of all selected slices were then mathematically summed to calculate the total volume of the selected and unselected region. From the slice position and built in software x, y, z coordinate system, each point's spatial coordinates were obtained and using simple mathematic formulas, linear measurements, as well as angular and perimeter measurements, were calculated. There was no three-dimensional reconstruction in this software version, but two-dimensional views in all three planes of space were available.

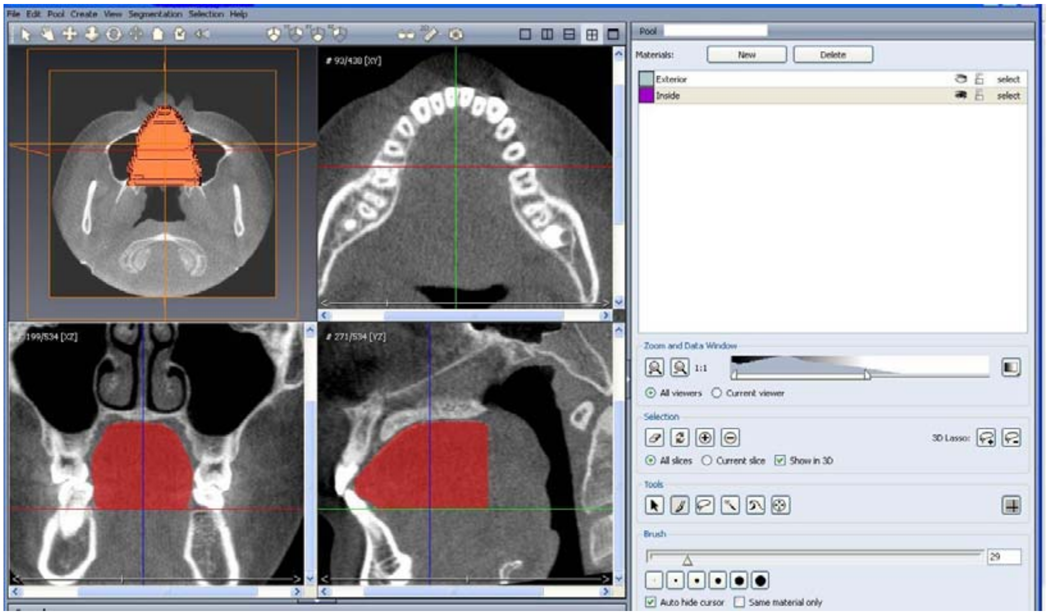

Figure 2-9 Representative subject, Avizo 6.0 interface with tongue segmentation

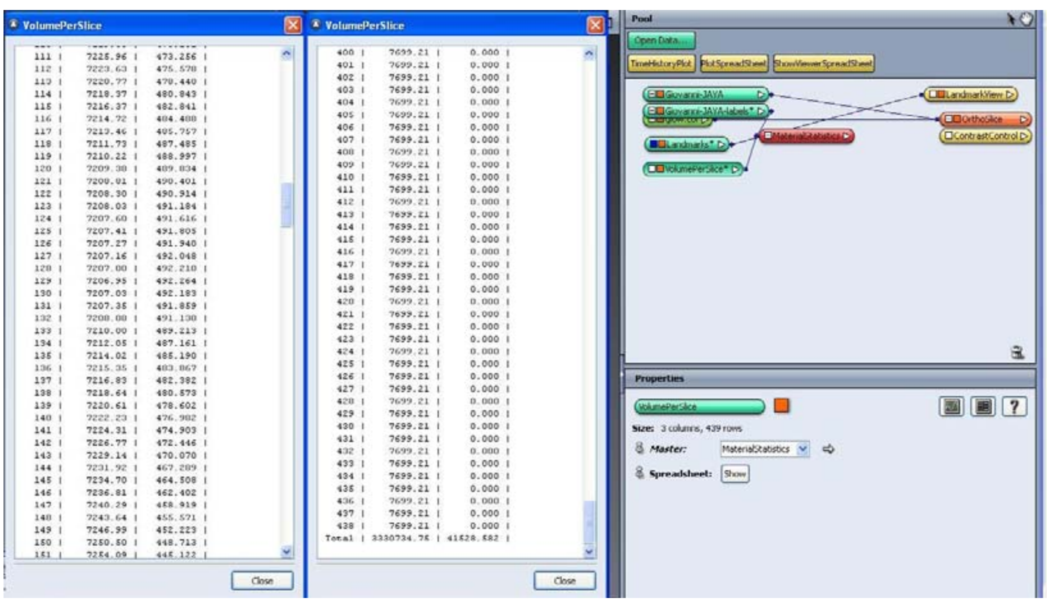

Figure 2-10 Representative subject, Avizo 6.0 output for volume per slice and total volume segmented

v. Anatomage inVivo 5

Anatomage inVivo 5 allowed both a three-dimensional reconstructed virtual model and two-dimensional images in the axial, coronal and sagittal directions. Volume sculpting was carried out on the three-dimensional virtual model, by clipping away unwanted voxels. Each voxel was given opacity and transparency properties. By drawing a line on the view, an imaginary plane was created perpendicular to the view and the volume above or below was “cut away” by making those voxels transparent. This was the essence of volume sculpting. The clipping process permitted “hiding” of voxels to enable sculpting of the tongue. Segmentation is a process of removal of unwanted voxels, rather than that of a selection of voxels along each axial, coronal, or sagittal slice. As the model was sculpted, it could be rotated in any desired direction and the coordinate system would displace and transform itself to maintain the same orientation of the original unsculpted model. Since each voxel was given a different density, it was important to specify the threshold of inclusion through selecting the Hounsfield unit value, which was a measurement of density. Thus all voxels of that density were counted and any voxels of lower density were excluded. As the tongue is a rather uniform soft tissue muscle, the Hounsfield value can be set to include the largest amount of voxels in the volume calculation. The software can calculate the volume of the sculpted model based on the voxels allowed into the calculation, as set by the threshold. Linear and angular measurements were easily obtained with simple mathematics and trigonometry when selecting the voxel points at the location of interest.

Figure 2-11 Representative subject, Anatomage inVivo 5 interface for tongue segmentation

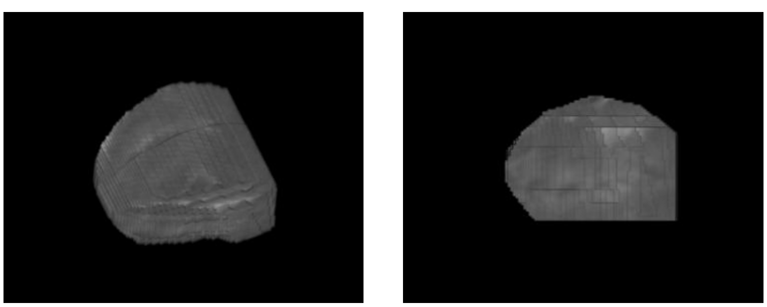

Figure 2-12 Representative subject, Anatomage inVivo 5 segmented tongue – 2 different angled views

d. Statistical analysis

i. Reliability of repeated segmentation measures from each software

Reliability of the measurements gathered was assessed by repeating the measures 3 times for 5 subjects over a span of 12-15 days with at least 4 days interval (Trial 1, Trial 2, Trial 3). The 5 subjects were randomly chosen and the measures were repeated in a random order as per a random number generator.

The appropriate statistical test to determine intra-rater reliability was intraclass correlation coefficient (ICC) with absolute agreement and inspection of the scatter plots for inconsistent data or outliers. Sources of error may come from differences between subjects, operator or rater errors and from random errors inherent to the softwares. The ICC estimates the proportion of total variation that may be attributed to between-subject variability. Values near 1 suggest nearly all variability is essentially biological variance and not related to measurement, whereas values near 0 indicate that variability is primarily a result of measurement problems. [21] When ICC values are below 0.4 there is poor reproducibility, values between 0.4 to 0.75 suggest moderate to fair reproducibility, whereas values above 0.75 indicate excellent reproducibility.[23]

ii. Comparison of tongue volume measurements obtained by the three techniques

Tongue volume measurements were compared between the three softwares with ANOVA statistical test and Pearson correlation coefficient (r) statistical test.

3. Results

a. Normality and model assumptions

The following model assumptions were evaluated: normality, homogenous variance and linearity. The histograms, normal P-P plots and scatterplots are found in Appendix 2.

Overall, the normality and equal variance assumption were only mildly violated. The histograms showed normal data distribution with only mild skewness, and the normal P-P plot of regression standardized residuals displayed values that closely correspond to the 45 degree line. The homogenous variance assumption was satisfied based on the scatterplot of regression standardized residuals versus regression standardized predicted values. The data was normal and within the same range, as the plot did not display any funnel shape or upwards or downwards tendency. The variability was constant and very similar. Essentially, with the exception of two or three points in the scatter plots, there were very few potential outliers. Kolmogorov-Smirnov test was also carried out and confirmed that the data was normal.

b. Intra-examiner reliability

The tongue volume segmentation process was repeated three times with all three softwares for five subjects to assess reliability. The high intra-class correlation coefficient obtained of 0.972 with a 95% confidence interval 0.937 to 0.990 indicated good reliability of the data across all three softwares. However, when considering softwares separately, the Anatomage InVivo 5 software had the lowest ICC coefficient (0.965 and 95% CI (0.852, 0.996)) compared to the other two softwares.   (Appendix 3 Tables A3-3 and A3-4) Interestingly, when comparing the ICC coefficients from each trial separately there was an increase in correlation coefficient from the first trial to the third trial. The first trial (TV1) had a coefficient of 0.924 (95% CI (0.704, 0.991)) which increased at the second trial (TV2) to a coefficient of 0.952 (95% CI (0.798, 0.994)) and increased to a third trial (TV3) coefficient of 0.966 (95% CI (0.856, 0.996)).   (Appendix 3 Table A3-5) The scatterplots (Appendix 3 Figure A3-1) illustrate the high correlation coefficients obtained, since the points are closely situated to the 45 degree line demarcation.

c. Descriptive statistics for tongue volume for each software

The mean tongue volume obtained in this study was 26.82cc. Table 2-1 summarizes the mean tongue volume obtained from each software.

Table 2-1 Descriptive statistics tongue volume per software

Parameter	*n*	*Mean*	*Standard Deviation*	*Standard Error*	*95% CI*	*Minimum value*	*Maximum value*
Tongue volume							
Anatomage	30	26.91cc	6.10cc	1.11cc	(24.63, 29.19)	17.55cc	42.92cc
Avizo	30	26.71cc	5.74cc	1.05cc	(24.56, 28.85)	18.01cc	40.43cc
Mimics	30	26.83cc	5.67cc	1.04cc	(24.72, 28.03)	18.29cc	41.16cc

d. Comparison of tongue volume measurements for the three softwares

The results from ANOVA confirmed that there was no statistical difference between the tongue volume measurements obtained from the three softwares and the p-value recorded was non-significant (p-value=0.991). (Appendix 3 Table A3-1) Pearson correlation coefficients indicated that the measurements between the three softwares were closely related, and r was well above 0.9. (Appendix 3, Table A3-2).

e. Differences in tongue volume by gender and age

Since it was established that there was no statistical difference between the results obtained from the three different after-market softwares used, the differences in tongue volume between men and women are reported for the Avizo 6.0 software in Table 2-2.

Table 2-2 Descriptive statistics tongue volume by gender from Avizo 6.0 software

Parameter	*n*	*Mean*	*Standard Deviation*	*Standard Error*	*95% CI*	*Minimum value*	*Maximum value*
Tongue volume							
Men	15	29.04cc	6.59cc	1.70cc	(25.39, 32.69)	18.01cc	40.43cc
Women	15	24.37cc	3.64cc	0.94cc	(22.36, 26.39)	18.44cc	29.58cc

The results from ANOVA demonstrated that there was a moderate statistical difference between the tongue volume measurements of men and women (p-value=0.023). (Appendix 3, Tables A3-6, A3-7)

On the other hand, when the data was explored for differences between tongue volume measurements depending on age, no statistical difference was found according to the results of the regression analysis (p-value = 0.428) nor of Pearson correlation coefficient (correlation r=0.150). (Appendix 3, Tables A3-8, A3-9)

4. Discussion

a. Reliability of all three softwares

Intra-class correlation coefficient was high for tongue volume measurements between all three softwares and this demonstrated strong reliability. The reliability obtained for each software individually was very high. However, validity of the tongue volume measurements was not assessed in this study, nor was it possible to determine which software had greater accuracy, since none of the tongue volumes measured had a known volume or gold standard to which it could be compared.

b. Comparison of the tongue volumes obtained from the softwares

The software measurements for tongue volume were not clinically nor significantly different as described above. This allows flexibility in the choice of which software clinicians may wish to use for segmentation and obtaining volume calculations. Anatomage inVivo 5 was an easier software to learn and would be more intuitive to clinicians wishing to obtain volume measurements of a segmented object on a daily basis. Avizo 6.0 and Mimics 13.1 had a greater learning curve needing a training session and practice to get familiarized with the softwares. However, Mimics 13.1 allowed more settings control of both Grey values, Hounsfield units and three-dimensional segmentation. Mimics 13.1 could be considered a superior software for future studies and research, especially when measuring volumes which do not have homogenous density. Many other features are available with the Mimics 13.1 software which were not explored for this present study. Some of these features are the possibility of carrying out calculations and Boolean operations on the generated masks, including superimposition of multiple masks.

For a clinician proficient in all three softwares, the ease of use of Anatomage inVivo 5 would be more appealing for volume segmentation. However, it ultimately depends on the area of interest, whether being hard tissue, soft tissue or airway. The differences in volume measurement between different areas of interest of different density was not explored in this study, however knowing the strengths and challenges of each software would allow a clinician to choose the appropriate after-market software of choice. Many after-market softwares also offer other algorithmic options that may make one particular software more attractive to a clinician desiring to purchase an after-market software to meet many diagnostic needs, such as temporo-mandibular joint visualization, implant site visualization, virtual three-dimensional models, etc. These additional features are not currently offered by all after-market softwares as many features are proprietary processes owned by individual companies.

Regardless of the software used, the challenge in visualizing the differences in soft tissue layers from radiographic images meant that there was need for a systematic reproducible method to delineate the tongue. Since it is not possible to differentiate the layers of muscles forming the floor of the mouth from the lower border of the tongue on CBCT radiographic images, a delineation plane was used to demarcate the lower border from easily identifiable artificial landmarks. Similarly, a perpendicular plane to the x-axis passing through the posterior nasal spine was used as the posterior tongue aspect. This allowed reliable tongue segmentation and volume calculation. Furthermore, tongue soft tissue has similar voxel density. Therefore, it is not clear that one of the three softwares would have generated more error when careful segmentation technique was followed.

c. Differences in tongue volume by gender and age

Our results found a moderate statistical difference between the mean tongue volume measurements of men and women of approximately 4.67cc (p-value=0.023) which was consistent with the findings of Ajaj *et al.*[19], Lauder *et al.*[20] and Tamari *et al.*[24] who also noted a larger tongue volume in men compared to women.

No statistical difference was found between tongue volume measurements depending on age according to the regression analysis and correlation r. Observation of the scatterplot (Appendix 3, Figure A3-2) of tongue volume and age suggested a possible quadratic relationship, however when this was explored through regression analysis (Appendix 3, Table A3-10) it would appear that there was no quadratic nor even simple linear relationships. Age appeared not to be a strong predictor since approximately 2% of the variation in tongue volume would be explained by age. Although Temple *et al.*[25] demonstrated that the tongue grew in two parts with the anterior portion reaching its adult size by 8 to 10 years and the posterior portion continuing its growth to reach adult size by 15 to 16 years regardless of gender, the data from this study was unable to show a strong correlation between age and tongue volume. Possibly, this may due to the choice of artificial boundaries delineating the tongue volume measured in this study which did not encompass the most posterior portion of the tongue in the pharyngeal area.

d. Influence of positioning of subjects

In an attempt to most closely reproduce reality, the subjects were placed in a sitting upright position in the i-CAT machine when the CBCT was taken. This is in contrast with the studies which have measured tongue volume from MRI and medical CT where the subjects are placed in a supine position. In a supine position gravity and other forces may play a role on changing the shape and volume of the tongue, which would influence tongue volume measurements.

5. Conclusion

The tongue was visualized on CBCT scan images using a contrast medium such as barium sulfate. The segmented volumes of the tongue obtained from three selected softwares (Avizo 6.0, Mimics 13.1, Anatomage inVivo 5) were not clinically nor statistically different in this study.

6. References

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Chapter III – Association of Tongue Volume and Transverse Palatal Vault Dimensions, Dental Arch Width and Axial Tooth Inclination

1. Introduction

The progress of three-dimensional radiography since it first began in 1967 by Sir Godfrey Hounsfield has been tremendous[1], and its affordability has made such technology more widespread amongst the dental and orthodontic community[2]. Cone Beam Computed Tomography (CBCT) is gaining in popularity as a diagnostic tool. As analyses are developed to aid the clinician in extracting further information from the radiographic images, so is the expansion of our knowledge and understanding.[1,3]

Numerous studies have shed light on the role of the tongue as a critical factor in the neuromuscular balance of forces in the oral cavity[4-8] and its influence on craniofacial skeletal growth[9-15]. The implications of this role are still being uncovered. From studies on glossectomy and tongue volume reduction on animal pig models, it was realized that the anterior inter-dental arch size and midface width were diminished, mandibular anterior length and symphysis area were less developed, alveolar bone height development was decreased as well as overall mandibular length. However, from this model, vertical mandibular growth was not greatly affected, nor was maxillary and skull growth. It appears that there is not enough information to know the effect of tongue posture influence on craniofacial growth, nor the influence of tongue posture of pigs to understand if these findings can be correlated to humans.

From the few studies reporting on relationships between tongue volume and maxillary and mandibular constriction, Bandy *et al*.[3] found that the tongue volume had little influence on mandibular width and length, as well as little effect on degree of interincisal relationship and angle of the lower incisor teeth to the mandibular plane. Yoo *et al*.[4] found similarly that there was little association between tongue volume and lower dental arch size nor mandibular prognathism development in adult women. On the other hand, Tamari *et al*.[5] disproved some of these findings when they showed a higher correlation between tongue volume and the posterior lower dental arch size.

In the present study, we sought to determine relationships between tongue volume and inter-dental arch widths, axial inclinations of first molars and first premolars, the axial cross-sectional palatal vault perimeter, and palatal index as a measure of palatal shape as assessed from radiographic images obtained from CBCT scan reconstructions.

2. Methods

The study was approved by the Health Research Ethics Board (HREB) at the University of Alberta. (Appendix 1)

Patients who required a CBCT radiograph as part of their initial records appointment workup were selected from the University of Alberta graduate orthodontic clinic and the private orthodontic practice of Dr. K. King in Medicine Hat, Alberta. Instruction sheets were offered and informed consent signatures were obtained prior to participation in the study. CBCTs for these patients would have been taken at their usual records appointment as a part of the necessary radiographs; therefore, they were not being unnecessarily subjected to additional radiation. (Appendix 1)

Disposable vials containing 15mL barium sulfate powder was mixed with 5mL water and then given to the patient. After swishing in the mouth for 15 seconds to coat the dorsal and lateral aspects of the tongue, the patient would spit the solution out into a disposable cup and then be seated in the i-CAT machine (Imaging Sciences International, Hatfield, PA). CBCT radiographic images were then taken immediately with a collimation height scan of 13 centimetres, scan time of 20 seconds and resolution of 0.3 millimetre voxel size.

a. Sample

This study encompassed 15 women and 15 men ages 12-years 9-months to 36-years 3-months. Previous studies on tongue volume measurement from Magnetic

Resonance Imaging (MRI) [4,16-19] have included similar sample sizes between 10 subjects to 50 subjects.

b. Measurement technique – tongue volume, palatal vault, arch width and axial inclination

The tongue volume was obtained by segmenting the tongue from the radiographic images on three different analyses softwares: Anatomage inVivo 5, Avizo 6.0, Mimics 13.1. The method was described previously in Chapter II.

Inter-molar and inter-premolar width measurements were obtained from the radiographic images. The distance was measured from the mid-point of the lingual aspect of the cemento-enamel junction (CEJ) of the upper and lower first molars, and likewise for the first premolars.

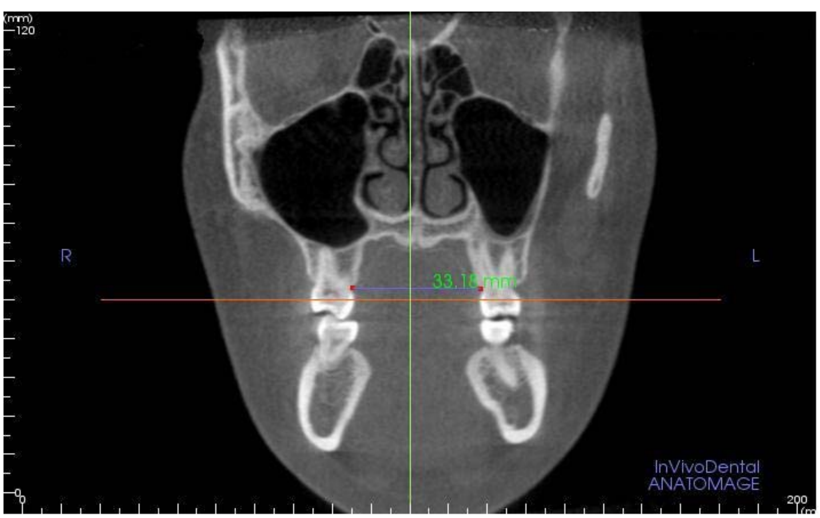


Figure 3-1 Representative subject, Inter-molar width measurement on Anatomage inVivo 5

Tooth axial inclination was determined, rather than buccal crown inclination, using easily identifiable points with high reliability as proposed by Lagravere[6] : the centre of the pulp chamber of the first upper and lower molars and their mesial buccal apex point; the tip of the first upper and lower premolar buccal pulp horn and their buccal root apex.

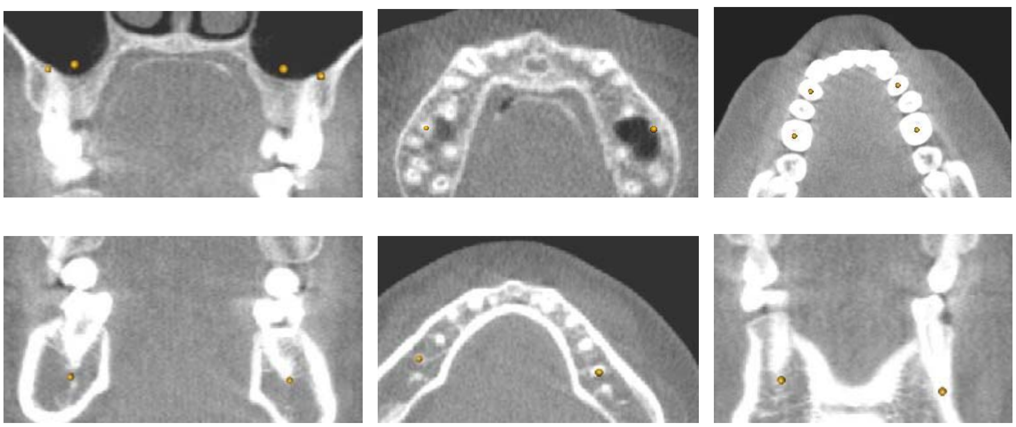


Figure 3-2 Representative patient, Landmark points for axial tooth inclination

The perimeter of the palatal vault was determined by summing the distances between each point placed along the outline of the maxillary palate along two selected slices: point coordinates plotted along the palatal vault in the Avizo 6.0 analysis software at the level of the center of the first upper molars and first upper premolars. Nine points were placed along the palatal vault at the first premolar level representing the CEJ of both opposite teeth, the midpoint between the CEJ and the highest point in the arc on either side of the midline, the most convex point in the arc on either side, the highest point in the arc on either side and the center midline point. Eighteen points were placed to outline the palatal vault at the first molar area.

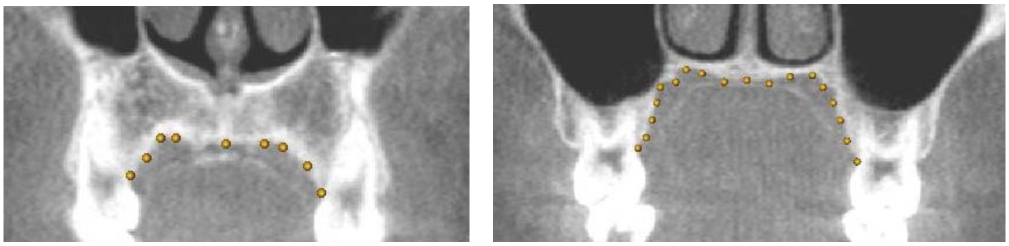


Figure 3-3 Representative patient, Landmark points for axial cross-sectional palatal perimeter at the premolar level and molar level

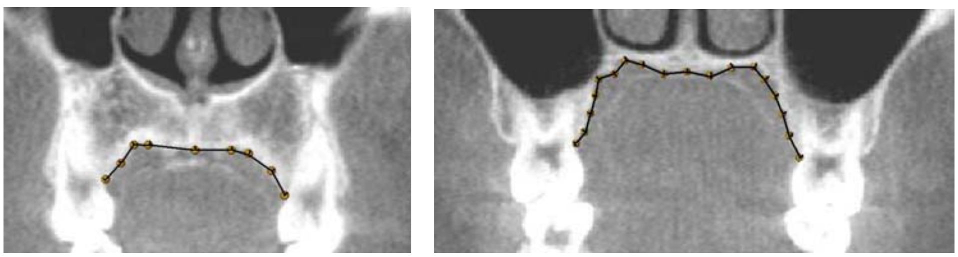


Figure 3-4 Representative subject, Sum of distances between landmark points to obtain perimeter measurement

A second variable was defined to characterize palatal shape by defining a ratio between palatal height versus palatal width as a palatal index. Palatal width was measured as inter-dental width, from either molar to molar or premolar to premolar. A perpendicular to the palatal width line passing through the palate midline point on transverse cross-section was used for palatal height. The ratio between the distance of palatal height to palatal width was determined to be the palatal index for that axial cross-section whether for the first molar or first premolar.

Figure 3-5 Representative subject, Palatal index as a ratio of palatal height to palatal width

Coordinates were obtained for landmark points using the Avizo 6.0 software only. Landmark points could not be plotted on the Anatomage inVivo 5 software and Mimics 13.1 software established a completely different reference system.

c. Statistical analysis

Reliability of the measurements gathered was assessed by repeating the measures 3 times for 5 subjects over a span of 12-15 days with at least 4 days interval. The 5 subjects were randomly chosen and the measures were repeated in a random order as per a random number generator.

Reliability of the tongue volume was previously investigated and described in Chapter II.

The following measurements were assessed for reliability:

- upper first inter-molar and inter-premolar widths on Anatomage inVivo 5, Avizo 6.0 and Mimics 13.1 softwares

- lower first inter-molar and inter-premolar widths on Anatomage inVivo 5, Avizo 6.0 and Mimics 13.1 softwares

- coordinates of x, y, z points corresponding to the center of the lingual surface of the CEJ of the upper first molar and premolar, lower first molar and premolar on Avizo 6.0 software

- coordinates of x, y, z points for axial inclination determination corresponding to the upper first molar pulp chamber center, upper first molar mesial buccal root apex, upper first premolar pulp chamber most occlusal tip, lower first molar pulp chamber center, lower first molar mesial buccal root apex, lower first premolar pulp chamber most occlusal tip, and lower first premolar buccal root apex on Avizo 6.0 software (Figure 3-2)

- coordinates of x, y, z points for palatal vault perimeter determination at the level of the first upper molar through 18 points (of which 9 are key points) selected along the cortical margin of the palatal bone: the cemento-enamel junction of the upper first molars, the midpoint between the CEJ and the highest point in the arc on either side of the midline, the most convex point in the arc on either side, the highest point in the arc on either side and the center midline point, as well as 9 additional points placed between these 9 key points explained above (Figure 3-3)

- coordinates of x, y, z points for palatal vault perimeter determination at the level of the first premolar through 9 points selected along the cortical margin of the palatal bone: the cemento-enamel junction of the upper first molars, the midpoint between the CEJ and the highest point in the arc on either side of the midline, the most convex point in the arc on either side, the highest point in the arc on either side and the center midline point (Figure 3-3)

Since Avizo 6.0 software did not calculate the inter-molar and inter-premolar widths, the three-dimensional coordinates of the points normally selected for these measurements were obtained. However, it was best to determine the reliability of these coordinates, rather than the reliability of the inter-dental width measurement calculated, as the measurement may prove to be reliable and consistent with the measurements from the two other softwares, although the coordinates themselves may not necessarily hold reliability.

The appropriate statistical test to determine intra-rater reliability was intraclass correlation coefficient (ICC) with absolute agreement and inspection of the scatter plots for inconsistent data or outliers. Sources of error may come from differences between subjects, operator or rater errors and from random errors inherent to the softwares. The ICC estimates the proportion of total variation that may be attributed to between-subject variability. Values near 1 suggest nearly all variability is essentially biological variance and not related to measurement, whereas values near 0 indicate that variability is primarily a result of measurement problems.[7] When ICC values are below 0.4 there is poor reproducibility, values between 0.4 to 0.75 suggest moderate to fair reproducibility, whereas values above 0.75 indicate excellent reproducibility.[8]

Tongue volume measurement relationships with the four inter-dental widths: upper and lower inter-molar widths and upper and lower inter-premolar widths were assessed in two different ways. Pearson correlation coefficient (r) and regression analysis were the appropriate statistical test to analyse the relationship. The regression analysis was carried out as a multivariate general linear model incorporating all the dependent variables which could be predicted by the tongue volume.

3. Results

a. Normality and model assumptions

The following model assumptions were evaluated: normality, homogenous variance and linearity. The histograms, normal P-P plots and scatterplots are found in Appendix 2.

Overall, the normality and equal variance assumption were only mildly violated. The histograms showed normal data distribution with only mild skewness, and the normal P-P plot of regression standardized residuals displayed values that closely correspond to the 45 degree line. The homogenous variance assumption was satisfied based on the scatterplot of regression standardized residuals versus regression standardized predicted values. The data was normal and within the same range, as the plot did not display any funnel shape or upwards or downwards tendency. The variability was constant and very similar. Essentially, with the exception of two or three points in the scatter plots, there were very few potential outliers. Kolmogorov-Smirnov test was also carried out and confirmed that the data was normal.

Since regression analysis is robust to mild normality and equal variance violations, multiple regression analyses can still be carried out to determine linear relationships between the tongue volume and upper and lower inter-premolar widths, upper and lower inter-molar widths, palatal perimeter at the premolar and molar level, palatal index at the premolar and molar level and the axial inclination of the upper and lower premolar and molar teeth, in order to verify our hypotheses.

b. Reliability

Overall, intra-examiner reliability was very high as illustrated by an intra-class correlation coefficient that was between 0.956 to 1.000 absolute agreement.

The intra-class correlation coefficients for the identification of the point coordinates x, y, z on Avizo 6.0 software for inter-dental widths was very high.

It varied from near absolute agreement with 0.999 coefficient and a 95% confidence interval of 0.999 to 1.000 for the z coordinate to perfect absolute agreement of 1.000 coefficient with 95% confidence interval of 1.000 to 1.000 for the x and y coordinates. (Appendix 4 Table A4-1)

The intra-class correlation coefficients for the identification of point coordinates x, y, z on Avizo 6.0 software for the palatal perimeter at the premolar and molar levels varied between 0.997 with a 95% confidence interval of 0.996 to 0.998 as the lowest for the z coordinate to perfect agreement coefficient 1.000 with a 95% confidence interval of 0.999 to 1.000 as the highest for the x coordinate. ICC determination is not required for the y coordinate since all landmarks were identified on the same axial slice. (Appendix 4 Table A4-2 Figures A4-1 to A4-4)

The intra-class correlation coefficients for the identification of point coordinates x, y, z on Avizo 6.0 software for axial tooth inclination of the first molars and premolars varied between 0.998 with a 95% confidence interval of 0.996 to 0.998 as the lowest for the y coordinate to perfect agreement 1.000 coefficient with a 95% confidence interval of 0.999 to 1.000 as the highest for the x and z coordinates. (Appendix 4 Table A4-3 Figures A4-5 to A4-7)

The intra-class correlation coefficients for the inter-dental widths when considering all three softwares, varied between 0.956 (95% confidence interval (0.901, 0.984)) as the lowest for the lower inter-molar width to 0.988 (95%

confidence interval (0.973, 0.996)) as the highest coefficient for the upper inter-molar width. (Appendix 5 Table A5-1) However when softwares were considered separately, the Anatomage inVivo 5 software consistently yielded lower ICC coefficients than the other two softwares. (Appendix 5 Table A5-2)

c. Descriptive

The mean tongue volume obtained in this study was 26.82cc with a range of 17.55 to 42.92cc and standard error of 0.61cc, as was reported in the previous Chapter II.

Table 3-1 Descriptive statistics of the different measurements using Avizo 6.0

Parameter	*n*	*Mean*	*Standard Deviation*	*Standard Error*	*95% CI*	*Minimum value*	*Maximum value*
Palatal perimeter							
Premolar level	30	34.50	6.47	1.18	(32.08, 36.92)	21.33	46.38
Molar level	30	49.56	5.50	1.00	(47.51, 51.61)	38.68	63.63
Palatal height							
Premolar level	30	7.31	2.38	0.43	(6.42, 8.20	2.71	13.10
Molar level	30	11.30	2.16	0.40	(10.49, 12.10)	7.84	16.81
Palatal index							
Premolar level	30	0.27	0.07	0.01	(0.24, 0.30)	0.13	0.41
Molar level	30	0.34	0.06	0.01	(0.32, 0.36)	0.23	0.47
Axial inclination							
Upper right premolar	30	-0.57°	5.60°	1.02°	(-2.66, 1.52)	-14.89°	11.05°
Upper left premolar	30	0.75°	10.62°	1.94°	(-3.21, 4.72)	-18.53°	47.87°
Upper right molar	30	-14.21°	5.90°	1.08°	(-16.41, -12.00)	-23.92°	2.26°
Upper left molar	30	-12.90°	8.48°	1.55°	(-16.07, -9.73)	-27.10°	12.77°
Lower right premolar	30	1.96°	5.65°	1.03°	(-0.15, 4.07)	-7.43°	11.54°
Lower left premolar	30	0.63°	5.24°	0.96°	(-1.33, 2.59)	-11.86°	11.18°
Lower right molar	30	-16.65°	9.00°	1.64°	(-20.01, -13.29)	-42.86°	3.10°
Lower left molar	30	-17.76°	6.34°	1.16°	(-20.13, -15.40)	-35.22°	-8.39°

Inter-dental widths, palatal height and palatal perimeter were measured in millimetres
Palatal index is a ratio of palatal height to palatal width
Inclination were measured in degrees

Table 3-2 Descriptive statistics of the different measurements per software

Parameter	*n*	*Mean*	*Standard Deviation*	*Standard Error*	*95% CI*	*Minimum value*	*Maximum value*
Upper inter-premolar width							
Anatomage	30	27.27	2.77	0.51	(26.24, 28.31)	21.31	34.38
Avizo	30	26.88	3.36	0.61	(25.63, 28.14)	19.94	3.45
Mimics	30	27.13	3.02	0.55	(26.00, 28.25)	19.58	33.94
Lower inter-premolar width							
Anatomage	30	24.71	2.33	0.43	(23.84, 25.58)	20.38	30.20
Avizo	30	24.95	2.02	0.37	(24.20, 25.70)	21.77	30.74
Mimics	30	24.72	2.55	0.47	(23.77, 25.67)	20.30	31.05
Upper inter-molar width							
Anatomage	30	33.27	3.25	0.59	(32.06, 34.49)	24.02	42.78
Avizo	30	33.23	3.42	0.62	(31.95, 34.51)	25.75	44.05
Mimics	30	33.69	3.28	0.60	(32.47, 34.92)	24.90	43.08
Lower inter-molar width							
Anatomage	30	33.96	2.70	0.49	(32.96, 34.97)	29.28	40.36
Avizo	30	33.81	2.85	0.52	(32.75, 34.87)	29.03	40.14
Mimics	30	34.11	2.79	0.51	(33.07, 35.16)	29.55	40.59

d. Differences by gender and age

Gender, age and tongue volume were considered as possible predictors of the skeletal variables and the axial teeth inclination. Regression analysis was carried out but the results demonstrated no strong relationships between age and gender with the dependent variables (p-value for age = 0.321, p-value for gender = 0.062). The regression model was repeated to include only gender and tongue volume, but it confirmed the previous finding. Tongue volume alone demonstrated a strong relationship with the dependent variables. (Appendix 6, Tables A6-12, A6-13) Most likely the influence of age and gender are explained within the strong relationship of the tongue volume with the skeletal and axial inclination parameters. Therefore age and gender became redundant in the regression analysis and appeared not to contribute significantly to the model.

e. Associations

i. Tongue volume correlation with inter-dental widths

The tongue volume was most highly correlated with the upper inter-molar width (r ranged between 0.720 to 0.768 dependent on software type) and least correlated with the lower inter-molar width (r ranged between 0.335 to 0.431 depending on software type). (Appendix 6 Tables A6-1 to A6-3)

The regression analysis results supported these findings. (Appendix 6 Tables A6-4 to A6-6) The partial eta square was highest for the upper inter-molar width across all 3 softwares whereas it was the lowest for the lower inter-molar width across all 3 softwares. The R^2 indicated the amount of variation of the variable that could be explained by the independent factor. Therefore about 52% to 59% of the total variation of the upper inter-molar width could be explained by the tongue volume. Only 11% to 18% of the total variation of the lower inter-molar width could be explained by the tongue volume. (Figure 3-6)

The upper inter-premolar and lower inter-premolar width have similar R^2 values and partial eta square results with moderately significant p-values. Approximately 25% to 37% of the total variation of the upper and lower inter-premolar widths could be explained by the tongue volume. (Figure 3-6 below and Appendix 6 Tables A6-4 to A6-6)

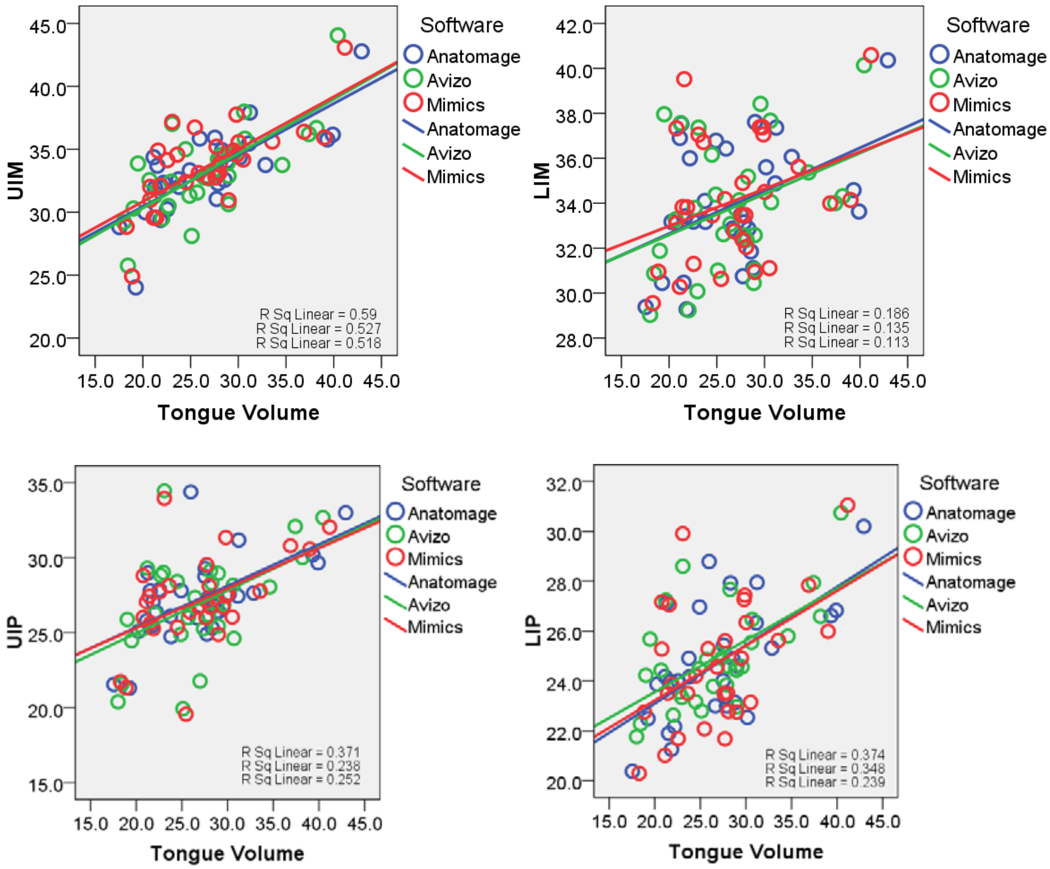


Figure 3-6 Scatterplot of tongue volume versus the upper and lower inter-premolar and molar widths for all three softwares with line at total fit

The following regression equations could be written as per the regression model obtained from the Avizo 6.0 software values: (Appendix 6 Table A6-11)

$\mathit{UpperInterPremolarWidth} = 0.286*\mathit{TongueVolume} + 19.242 + \mathit{error}$

$\mathit{LowerInterPremolar\ Width} = 0.208*\mathit{TongueVolume} + 19.407 + \mathit{error}$

$\mathit{UpperInterMolarWidth} = 0.433*\mathit{TongueVolume} + 21.672 + \mathit{error}$

$\mathit{LowerInterMolarWidth} = 0.182*\mathit{TongueVolume} + 28.944 + \mathit{error}$

$\mathit{PalatalPerimeterPremolar} = 0.495*\mathit{TongueVolume} + 21.290 + \mathit{error}$

$\mathit{PalatalPerimeterMolar} = 0.803*\mathit{TongueVolume} + 28.114 + \mathit{error}$

$\mathit{PalatalIndexPremolar} = 0.048*\mathit{TongueVolume} + 0.195 + \mathit{error}$

$\mathit{PalatalIndexMolar} = 0.122*\mathit{TongueVolume} + 0.246 + \mathit{error}$

ii. Tongue volume correlation with the perimeter of the palatal vault at the molar and premolar level and the palatal indices

Tongue volume measurements were assessed in terms of correlation with the perimeter of the palatal vault obtained at the level of the first upper molar and the first upper premolar.

The tongue volume was most highly correlated with the palatal perimeter at the upper molar level (r of 0.839) and to the palatal perimeter at the premolar level (r of 0.439). The R^2 obtained for these two variables signified that 70% of the total variation of the palatal perimeter at the molar level could be explained by the tongue volume, whereas only 20% of the total variation of the palatal perimeter at the premolar level could be explained by the tongue volume, as illustrated in the scatterplots below. (Figure 3-7 and Appendix 6 Tables A6-7 and A6-8)

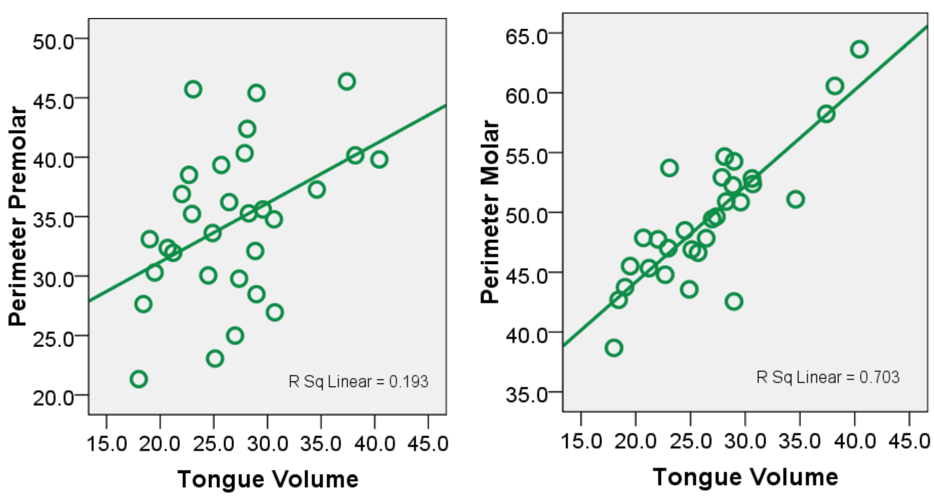


Figure 3-7 Scatterplot of tongue volume versus the palatal perimeter at the premolar and molar level for all three softwares with line at total fit, by Avizo 6.0

On the other hand, tongue volume was only mildly correlated with the palatal indices, and correlation r were low between 0.218 for the palatal index at the premolar level to 0.349 for the palatal index at the molar level. For both palatal indices the effect size noted by the partial eta square value was low. The scatter plots below (Figure 3-8) illustrated these findings. Inspection of the scatter plots did not reveal a visible non-linear pattern. (Appendix 6 Tables A6-7 and A6-8)

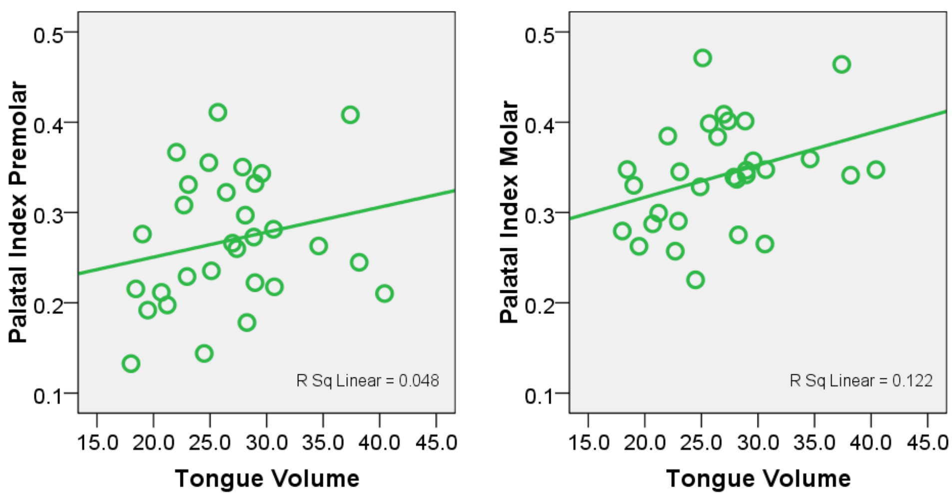


Figure 3-8 Scatterplot of tongue volume versus the palatal index at the premolar and molar level for all three softwares with line at total fit, by Avizo 6.0

iii. Tongue volume correlation with the axial inclination of upper and lower first molars and premolars

Tongue volume measurements were assessed in terms of correlation with the axial inclination of the selected representative teeth: upper and lower first molars and premolars.

Tongue volume had very little correlation with the axial inclination of the upper and lower first molars and premolars. Pearson correlation coefficient demonstrated low inverse correlation coefficients for all the angles. Indeed, partial eta square values were all substantially low, and the R^2 indicated low percentage variation prediction between 0.8 to 15%. (Appendix 6 Tables A6-9 and A6-10)

However, there was strong correlation of the paired angles (upper right and left molars, upper right and left premolars, lower right and left molars, lower right and left premolars), with the lower right and left molar angles being most strongly correlated (r of 0.805 with a strongly significant p-value). (Appendix 6 Table A6-10)

None of the angles correlated strongly with inter-dental widths or palatal perimeters. (Appendix 6 Table A6-10)

iv. Correlation between palatal perimeters and palatal indices

The palatal indices were not strongly correlated with their corresponding palatal perimeters. The correlation r obtained for the palatal index at the molar level was 0.072. Although correlation r obtained for the palatal index at the premolar level was 0.645, it was not better than the correlation r between palatal perimeter at the premolar versus molar level (r=0.628).   The scatterplots below (Figure 3-9) illustrate the difference in correlation significance between the molar and premolar level. (Appendix 6 Table A6-11)

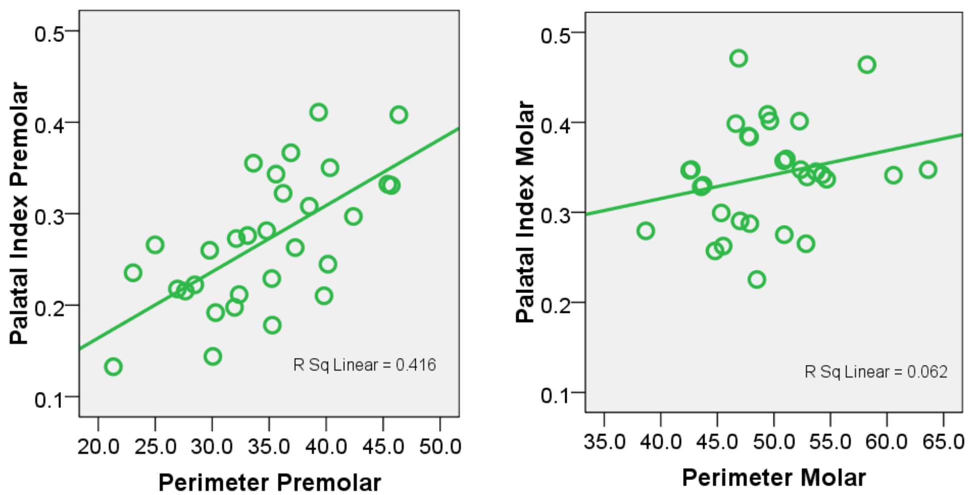


Figure 3-9 Scatterplot of palatal perimeter versus palatal index at premolar and molar level for all three softwares with line at total fit, by Avizo 6.0

4. Discussion

a. Discussion on reliability of the axial inclination of the first molar and premolar teeth

The accuracy of locating points on CBCT images is a valid concern. Linear accuracy of dental measurements on CBCT show high reliability as compared to measurements on dry skull, though for certain measurements, such as arch space requirement, a compounding error resulted in slight underestimation of the true value, as demonstrated in a study by Baumgaertel *et al*.[9] Potential error may arise from the analytical software used, as well as setting the appropriate Hounsfield value.[9] Brown *et al*.[10] determined that the measurement inaccuracies were more likely due to software (software algorithm, spatial and contrast resolution of the scan) and methodology (technical skill of the operator) rather than innate properties of the CBCT image reconstruction. By extension, volume measurements from CBCT may likely have the same sources of error. Liu *et al*.[11] found that tooth volume measurements deviated between -4% to 7% from their actual counterpart, and the authors hypothesised that software smoothing operations and algorithms may reduce volume measurements. Since segmentation is greatly dependent on image thresholding, the choice of one voxel over the other at the junction of the outlined tooth and its surrounding may be source of error. Furthermore, the tooth structure incorporated tissues of different radiographic density and opacity, which may be a factor when calculating the volume from density and threshold settings.[11]

Andrews[12,13] determined the axial inclination of clinical crowns from a perpendicular 90 degree reference plane from the occlusal plane, as established from plaster models. A tangential line to the clinical crown at its height of contour along the buccal surface was then established and the angle between this tangent and the occlusal plane was determined. It is much more challenging to identify distinguishable points on the occlusal plane of the CBCT images as the interdigitation makes separation of the upper from the lower teeth nearly impossible. It would be interesting to investigate if there is a correlation between the root axial inclination and the crown inclination, as this has not yet been reported.

Intra-examiner reliability was determined for the present study by randomly selecting five patients and repeating all measurements collected three times with a four day interval. The repeated measurement was done in a random manner for the five patients. Inter-examiner reliability was not established, but consistency in the methodology and intra-examiner reliability was important for the study.

Reference point choice for CBCT analyses are still being discussed and chosen as technology of CBCT improves. Although presently accepted reference points are unchallenged on two-dimensional images, it is not so clear for certain points on a three-dimensional image. Certain points such as apical root tips are harder to localize as roots merge and delineating one root from the other becomes harder. For example, distinguishing the mesio-buccal apical root from the mesio-lingual apical root of the lower molar can be a challenge, as demonstrated by Lagravere's thesis.[6] Indeed, careful selection of reference points allowed accurate linear and angular measurements from CBCT scans. Lagravere *et al.*[14] and Moreira *et al.*[15] demonstrated accuracy of linear and angular measurements from CBCT scans within 1mm and 1 degree of the true values. The judicious choice of reference points is important for repeatability, ease of location and answering the specific hypotheses of this study.

As explained previously, it is best to determine ICC on the initial x, y, z coordinates rather than the calculated angles from these coordinates, since reliability may be found for the angles but not necessarily in the reverse logic. Indeed, each coordinate x, y and z was found to have high ICC coefficient values all approaching absolute agreement of 1. (Appendix 4 Table A4-3 Figures A4-5 to A4-7) However, ICC was also carried out for the resultant calculated angles from these coordinates and it appears that the ICC coefficient obtained for absolute agreement is 0.911 with a 95% confidence interval of 0.855 to 0.949 (Appendix 4 Table A4-4). It would seem that compounding errors in the coordinates of the landmarks may have resulted in a lower ICC coefficient for the angles calculated although the actual individual x, y, z coordinates have very high agreement. This is not surprising and confirmed the findings of Baumgaertel *et al*.[26] and Brown *et al*.[10] who both found that compounding errors need to be considered.

b. Axial inclination of upper and lower first molars and premolars

Axial inclination measurements were obtained from the angle between 3 coordinate points. Mesio-distal and facio-lingual axial inclination of the dentition are usually considered as angles between a perpendicular line to the median plane and the long axis of the tooth.[12,16] There is variation between the value of the long axis of the root and the long axis of the crown of the tooth, but the overall inclination pattern is consistent.[22-25] It has been established that there is an increasing lingual inclination of the upper teeth from anterior towards posterior, and an increasing lingual inclination of the lower teeth from anterior towards posterior.[22-25]

Table 3-3 Inclination of crown and root of the dentition as a combination of the findings of Andrews[12] and Dempster[17] adapted from Wheeler's Dental Anatomy[16]

Dentition	*Central Incisor*	*Lateral Incisor*	*Canine*	*First Premolar*	*Second Premolar*	*First Molar*	*Second Molar*
Upper	7°	3°	-7°	-5°	-6°	-9°	-10°
Lower	-10°	-10°	-11°	-9°	-9°	-20°	-20°

In the present study, recognition of this increasing inclination was best noted by comparing the mean averages of the angles. Indeed the average of upper premolar angles varied between 0.7 degrees to -0.5 degrees and the average of upper molar angles are at an increased lingual inclination of -12.9 degrees to -14.2 degrees. Similarly, the average of lower premolar angles varied between 0.6 degrees to 1.9 degrees and the average of lower molar angles were at an increased lingual inclination of -16.6 degrees to -17.8 degrees. The 95% confidence intervals of the premolar angles crossed zero, signifying that the inclination angle may also be equivalent to zero, but the 95% confidence interval of the molar angles indicated lingual inclination without crossing zero. (Table 3-1)

The position of the dentition is a balance of inward and outward neuromuscular forces of the oral cavity.[18] Yet, this study had found little relationship between the volume of the tongue and the inclination of the teeth. Perhaps the amount of tooth axial inclination has more to do with limitations in the extent of the alveolar housing in which the teeth are embedded. It is also possible that the sample size of this study was too small to detect the differences and extrapolate relationships, since the variability of the axial inclination angles was large.

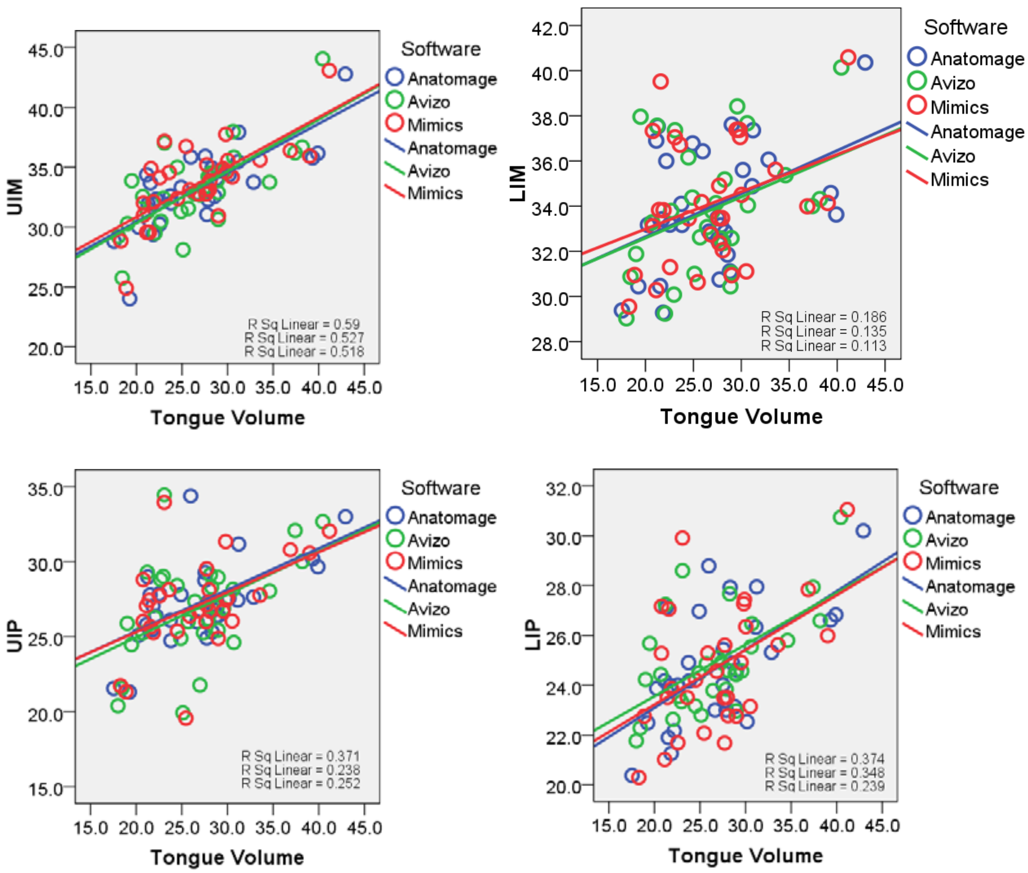
c. Age and gender as predictor factors

From the results of the regression analysis model (Appendix 6, Tables A6-12 to A6-15) including age, gender, and tongue volume as potential predictor factors it would appear that neither age nor gender were statistically significant predictors for the skeletal parameters nor the axial teeth inclination. As was explored in Chapter II, gender and tongue volume were related, but the p-value was only moderately significant. The influence of age and gender on the dependent variables was most likely explained by the strong relationship of the tongue volume with these dependent variables. Therefore age and gender did not appear to have strong relationships with the skeletal and teeth inclination parameters.

d. Tongue volume as a predictor factor

Tongue volume was most strongly correlated with upper inter-molar width and palatal perimeter at the molar level and was least strongly correlated with the axial inclination of the molar and premolar teeth. Tongue volume was moderately correlated with the upper and lower inter-premolar widths as well as the palatal perimeter at the premolar level.

From the above equations section 2.e.i., it was evident that the effect of the tongue volume on the inter-dental widths and the palatal perimeters differed. The slope was steepest for the tongue volume effect on palatal perimeter at the molar level and lowest for the effect on lower inter-molar width, also illustrated in the scatter plots below (Figure 3-10).



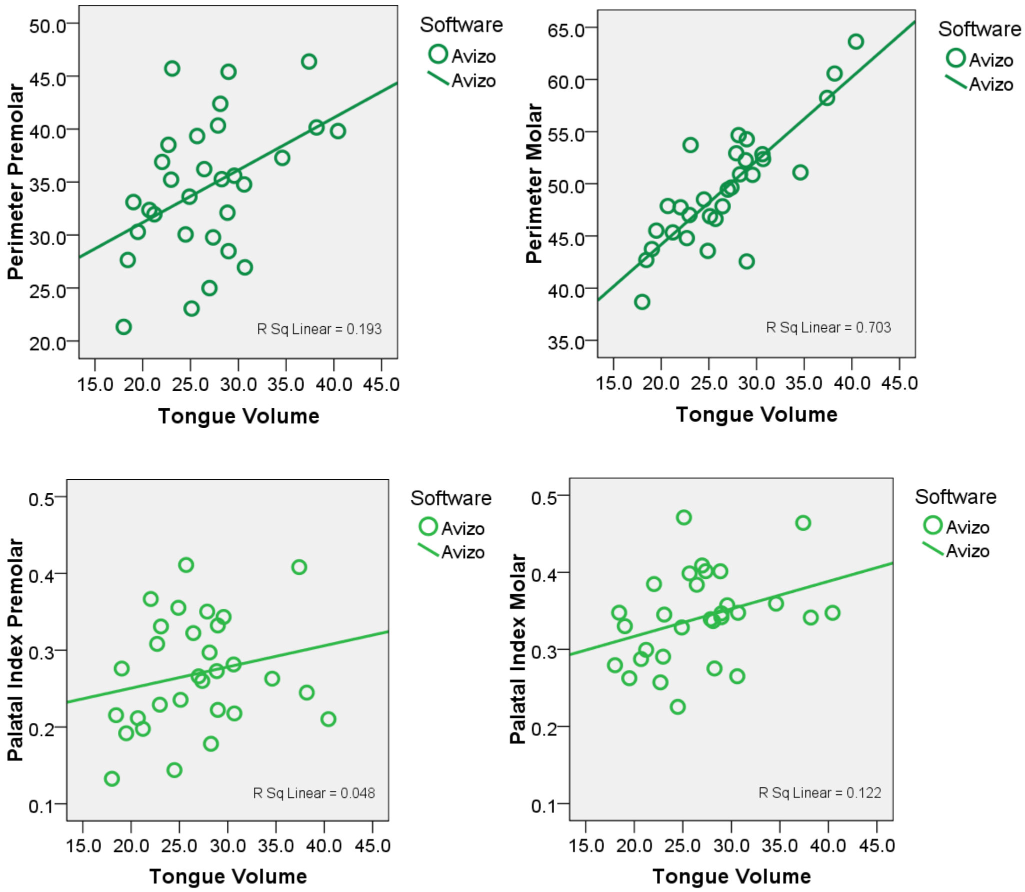


Figure 3-10 Scatterplots of the tongue volume as a predictor factor in upper and lower inter-premolar and inter-molar widths, and palatal perimeter and index at premolar and molar levels

The findings from the present study are confirmed by the studies on human subjects of Bandy *et al*.[3] and Yoo *et al*.[4] who found little influence of the tongue on the width and length of the lower dental arch. On the other hand, Tamari *et al*.[5] found a stronger relationship between the tongue volume and lower dental arch size, with higher correlations at the more posterior part of the dental arch. Interestingly, studies on animal pig models[19-24] found that glossectomizing the tongue lead to a decrease in inter-dental arch sizes, reduced mandibular anterior length and width and overall deficiency in midface width and craniofacial skeletal development. However, differences between pigs and humans with respect to overall shape and size of the tongue and arches may make it difficult to transfer the findings of animal studies to humans.

It would appear that if the tongue size and shape had greater influence on the upper inter-dental arch shape, palatal perimeter and lower anterior inter-dental arch shape, then it could be postulated that if the size of the tongue were reduced, development and growth of the maxillary palatal width, inter-dental width and lower mandibular development would be reduced as well. On the other hand, the weak relationship between tongue size and lower inter-molar width may signify that other influences should be considered in the development of the lower arch. Possibly the size and width development of the mandibular arch is determined more genetically than by a response to soft tissue and growth of the tongue. Further studies are required to determine the other factors influencing craniofacial skeletal growth.

Furthermore, the implications of this study's findings are relevant to treatment considerations of expansion of the maxillary arch. The stability of expanding maxillary alveolar and palatal width may be related to a proportional increase of the volume of the tongue by growth. Indeed, Temple *et al*.[25] demonstrated that the human tongue grew till the age of 15 to 16 years old. Perhaps, expansion of the maxillary arch prior to these years, would allow better stability as the growth of the tongue matches the expansion.

e. Discussion on palatal perimeter and palatal index

One might expect the palatal indices to be closely correlated to the corresponding palatal perimeters since the inter-premolar and inter-molar palatal widths were used in the determination of the palatal index (PI=PH/PW). However, based on Figure 3-9 this was not the case. The correlation coefficients were lower than expected, and in the case of the molar area, were non-significant. This was reinforced by the regression analysis results of the prediction of the tongue volume effect on the palatal perimeters and palatal indices. Only the palatal perimeter at the molar level was strongly associated with the tongue volume. (Appendix 6 Tables A6-10 and A6-11)

From the results of this study, it would appear that neither the palatal perimeter nor the palatal index can sufficiently describe the true palatal shape. A combination of both of these variables were necessary and further variables are possibly required to describe palatal shape, as has been used in the literature.[31-34] From the axial palate cross-section (Figure 3-11), there were differences between palatal shapes with the midline of the palate arching downwards or upwards, which led to different palatal heights. Variations in either palatal height or palatal width may explain the differences in palatal indices and palatal perimeters obtained from the study subjects. For example, patient A (palatal height=12.40mm, palatal width=34.69mm, palatal index= 0.36, perimeter= 50.86mm) had a palatal midline arching upwards compared to patient B (palatal height=12.00mm, palatal width=33.41mm, palatal index=0.36, perimeter=51.09mm) with a palatal midline arching downward. Patient C (palatal height= 12.51mm, palatal width=36.68mm, palatal index=0.34, perimeter=60.57mm) and patient D (palatal height=12.45mm, palatal width=35.84mm, palatal index= 0.34, perimeter= 52.37mm) also had similar palatal index values yet axial cross-section of the palate was a different shape, represented in the perimeter value. On Figure 3-11, the steepness of the midline palatal arching is more pronounced in patient C than in patient D, which did not translate into a difference in palatal index value.

Figure 3-11 Anatomical variations of palate curve axial cross-section at the molar level

Should ethnic, gender and age factors be considered in studying palatal shape and size? Ferrario *et al*.[35] studied the effect of ethnicity and age on palatal size and shape in three ethnic Chilean groups: mestizos, Aymara and non-Aymara. The authors concluded that ethnicity was a consideration in the differences between palatal shape in the adolescent but not the adult Chilean subjects, and age and gender were also a consideration particularly in the posterior palate corresponding to the eruption timing of the second and third molars.[26]

Is it possible that tongue volume and palatal shape vary depending on tongue posture? Lowe *et al*.[27] demonstrated that tongue volume varied greatly (between 44.03 to 99.56 cm^3) between subjects with sleep apnea and lowered tongue posture versus healthy subjects. Obesity was also an influencer on larger tongue surface areas. Although determining the influence of tongue posture was difficult, experiments on animals replicating the altered lowered tongue posture by glossectomy of the tongue of sham pigs have attempted to illustrate the craniofacial possible consequences[6,9,10,12,13], as outlined in Chapter 1.

At present, only one study by Ajaj *et al*.[28] attempted to determine a method to capture images of the tongue dynamically during chewing and swallowing. However recording tongue habits and posture remain a challenge. Measuring tongue volume dynamically and correlating tongue posture and volume with skeletal parameters may further explain the influence of tongue on skeletal growth. Recently, functional MRI allows us to gather real time information on patients while examining their gastro-intestinal movement. This continuous intake of images by acquisition of fast imaging with steady-state precession sequences (MRI by FISP) allowing to assess movement in a defined small field of view may be a future consideration for recording tongue movement and perhaps tongue posture in patients.

5. Conclusion

Minor differences existed between the softwares which were deemed clinically and statistically insignificant in terms of tongue volume and inter-dental arch widths. It was apparent that tongue volume was strongly correlated with upper inter-molar width and to palatal perimeter at the molar level. Indeed, 60% of the variation of upper inter-molar width and 70% of the variation of palatal perimeter at the molar level is explained by the tongue volume. However, only approximately 20% of the variation of palatal perimeter at the premolar level and 15% of the variation of lower inter-molar width were explained by tongue volume.

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Chapter IV General Discussion

1. Introduction

Multiple factors influence the growth of the jaws, both genetic and environmental. The functional matrix theory of growth proposed by Moss[1] outlined the considerable role of the soft tissues in which the skeleton is embedded as a major influence on growth. One of the very important muscles in the oral cavity is the tongue, and many articles[2-4] are shedding light on the role of the tongue on craniofacial growth.

There have been large strides in our understanding of craniofacial growth, but further advancements of the relationship between soft tissue predictors on skeletal growth still need to be explored. Up until the 1970's, it was believed that the tongue followed a linear growth pattern, having a uniform growth across its anterior and posterior portions.[5] Furthermore, the role of the tongue as an influencer on craniofacial skeletal growth was not clearly elucidated. Recently, Temple *et al*.[5] showed that the anterior and posterior tongue portions grew at differential rates and completed their growth at different times. The importance of the tongue as a contributor to arch and palate development is being uncovered through studies on pigs[6-9] and a few observational studies on humans.[3,4,10,11]

This study investigated tongue volume measurement from Cone Beam Computed Tomography (CBCT) scan reconstructions obtained from i-CAT (Imaging Sciences International) using three after-market medical imaging softwares, namely Anatomage inVivo 5 (InVivo 5 Anatomy Imaging Sciences, San Jose, USA), Avizo 6.0 (VSG Visualization Sciences Group, Inc.), Mimics 13.1 (Materialise NV). The tongue volume measurements were related to findings of the maxillary and mandibular inter-dental arch width dimensions, the palatal perimeter and palatal index as a ratio between palatal height to palatal width, and axial inclination of the upper and lower first molar and premolar teeth.

2. General Discussion

a. Tongue volume measurements on three after-market softwares

The i-CAT software allowed rotation of the reconstructed images and modification of the slice thickness and pitch of the scanned reconstruction. Although the software permitted linear measurements such as inter-dental distances, volume segmentation was not a feature. Dolphin 11.5 was a software that enabled three-dimensional CBCT scan reconstruction; however, its volume segmentation capabilities were limited to the airways only. Anatomage inVivo 5 was a software similar to Dolphin 11.5 with the volume segmentation capacity of any volume of interest, including setting of Hounsfield units for this volume. The volume rendering was carried out on the three-dimensional virtual model by clipping away unwanted voxels. On the other hand, Avizo 6.0 and Mimics 13.1 softwares were similar in methodology. Tongue segmentation was obtained from segmentation of the area of interest on each slice on a given reconstructed direction, either axial, coronal or sagittal orientation. However, Mimics 13.1 allowed setting of the Hounsfield units and the Grey value threshold, where as it was not possible from the Avizo software to set Hounsfield units. With the Avizo 6.0 software, the selected voxels were added up from each slice to generate a total tongue volume, whereas with Mimics 13.1 a three-dimensional mask was generated from the selected voxels of each slice. The volume was then calculated from this virtual three-dimensional mask. Since Hounsfield units and Grey value threshold could be changed for the mask, this affected the resultant volume. Although voxels may have been selected in the segmentation process of that slice, by setting the density threshold for the volume calculation, not all the voxels may be included in the resultant volume. This was especially important if selecting voxels for a body tissue with different densities such as teeth. The whole tooth may be segmented from the scan reconstruction, but with different density threshold, the volume calculation could include voxels of very low density such as the pulp chamber or exclude them from the calculation. Since the tongue has overall similar soft tissue density, this was less of a concern and allowed the tongue volume results from the three compared softwares to be quite similar. Indeed, high reliability was found between the three softwares and the differences in tongue volume were non-significant. The operator time to segment the tongues from the CBCT images however was very lengthy and the focus required was very demanding.

b. Relationships between the volume of the tongue and maxillary and mandibular constriction and palatal shape

Palatal shape was characterized by its palatal perimeter at the level of the first molar and premolar, and by its palatal index as a ratio between palatal height on the midline of the palate and palatal width between upper first premolars and molars.[12] The present study demonstrated that the tongue volume had a higher correlation with upper inter-molar width and palatal perimeter at the molar level. Whereas 60% of upper inter-molar width variation and 70% of palatal molar perimeter variation were explained by the tongue volume, only approximately 15% of lower inter-molar width variation and 20% of palatal premolar perimeter variation were explained by the tongue volume. Furthermore, axial root inclination of the upper and lower first molar and premolar teeth were gathered, and the results were consistent with the increasing lingual inclination pattern from anterior to posterior upper and lower arches as described in studies from Dempster *et al*.[13] The tongue volume was not correlated with the axial root inclination of the dentition, according to the results of this study. Inferences to the general population cannot be made, as the patients were neither randomly selected nor representative. All came from the orthodontic patients seen at the University of Alberta, Edmonton, Alberta and the orthodontic patients seen at the private practice of Dr. K King, Medicine Hat, Alberta. Causal inference was not relevant as this was an observational study. Further studies are required to determine what other factors influence craniofacial skeletal growth, as well as the effect of gender, ethnicity and altered tongue posture.

c. Reliability

Although reliability could be easily carried out by repeating the measures over several days, assessing validity of the tongue volumes remained a challenge since no acceptable gold standard has been described in the literature. Lauder *et al*.[14] determined validity of the tongue volume from MRI by repeating their study on rabbits and found the estimated tongue volumes from MRI images to be comparable to the actual tongue volume although the error between the two repeated measure trials in humans was greater than with rabbits. However, the different definitions of tongue muscles to be included in the tongue volume prevented direct comparison of the results of the studies between them and to this present study.

Reliability was assessed by repeating the measures three times for five subjects over a span of twelve to fifteen days with at least four day intervals. The five subjects were randomly chosen and the measures were repeated in a random order as per a random number generator.

Reliability was best assessed by intra-class correlation coefficient (ICC) absolute agreement between all three trials. Although the Repeated Measures ANOVA statistical test allowed pairwise comparison between three trials repeating the data, it did not give information on how reliable the data was since it looked at the averages of all data gathered in that trial comparing it to the average of the other two trials. Repeated Measures ANOVA test was done, but since it did not provide any further information to the ICC, it was not elaborated in this thesis.

However, the one interesting finding provided by the Repeated Measures ANOVA was an apparent trend of lower variation in the spread of the estimated marginal means between the softwares at trial 2 compared to trials 1 and 3, as illustrated in the profile plot below. (Figure 4-1) This profile plot was the most dramatic of all profile plots and best illustrated that the first trial measurement had larger distribution than the other two trials, yet the second trial had the tightest distribution. The results from the Repeated Measures ANOVA were consistent with the ICC indicating that the data was reliable and that the p-value showed no significant difference in the three trials. However, the plot did illustrate the difference in the data spread amongst the three trials as well as for any of the three given softwares.

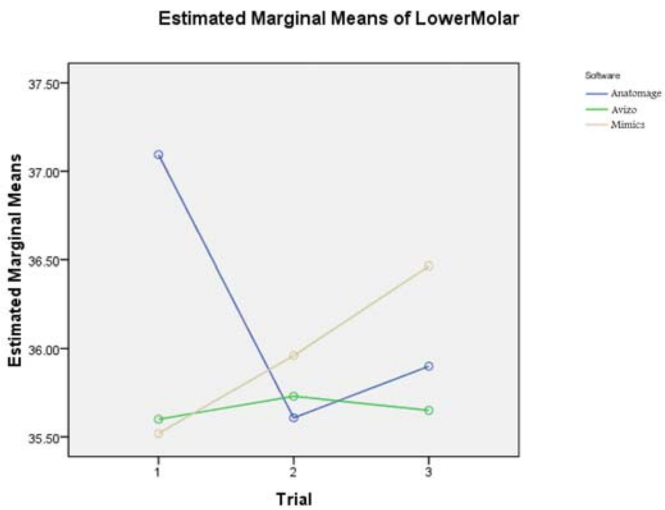

Figure 4-1 Plot of Repeated Measures ANOVA result from the reliability tests on lower molar measurements.

This pattern could be explained by an improvement in the point identification technique and then a relaxation in the technique on the third repeated time. It may also be from an improvement in anatomy identification of the landmarks and better interpretation of radiographic landmarks.

3. Study weaknesses

1- Accuracy and validity of the tongue volume and of the different predicted variables were not assessed and would have increased the strength of this study. There was no gold standard used for this study.

2- Inter-examiner reliability was not assessed in this study either and would have increased the strength of the results of this study.

3- To appropriately segment tongue volumes with the three softwares Anatomage inVivo 5, Avizo 6.0 and Mimics 13.1, a training session was required to learn to use the softwares in depth.

4- It was very time consuming to segment the tongue using CBCT images and collect the x,y,z coordinates of the multiple landmarks required. This is not feasible for most clinicians seeking to obtain tongue volumes of their patients on a daily basis in their private clinics.

5- The use of barium sulfate precludes most clinicians from carrying out a similar study in their private clinics.

6- Although the sample size of this study (30 patients) is within the range of sample sizes of other similar studies measuring tongue volume on magnetic resonance imaging (MRI), a larger sample size would increase the statistical power of this study.

7- To increase sample size to 30 subjects, data was collected from two different clinic locations: the Orthodontic Graduate Clinic of the University of Alberta and the private practice of Dr. K King in Medicine Hat. Having two sites of recruitment as well as different staff taking the CBCT radiographs from the i-CAT machine (Imaging Sciences International, Hatfield, PA) may have potentially included an additional source of error which would be considered a study weakness.

8- This present study attempted to elucidate relationships between tongue volume and inter-arch parameters, palatal shape and axial radicular inclination. It was not possible to determine the relationship of tongue posture on these different parameters from the static CBCT scan reconstruction images.

4. Future research

Future studies are required to understand whether the tongue grows in spurts or phases and how it relates to human general body growth. The contribution of the tongue as a predictor factor on craniofacial growth still remains to be better understood in humans and its role in contributing to certain pathologies, such as underdevelopment of the dental arches, crowding of the dentition, overgrowth of the jaws in individuals with prognathic mandibles.

This present study demonstrated that the two measured markers for palatal shape, palatal perimeter and palatal index, were insufficient to characterize the palatal shape and size from all aspects. Other studies[10,15,16] have considered palatal shape as axial cross-sectional thickness of the palatal bone, palatal volume and area. Further studies are required to better describe palatal shape and size. Only then can relationships between palatal shape and other dimensions, such as tongue volume, be uncovered. Recently, functional MRI allows us to gather real time information on patients while examining their gastro-intestinal movement. This continuous intake of images to assess movement in a defined small field of view may be a future consideration for recording tongue movement and perhaps tongue posture in patients.

5. References

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Appendix Section

Appendix 1

ETHICS APPROVAL FORM - DELEGATED REVIEW

Date:	August 9, 2009	
Principal Investigator:	Carlos Flores Mir	
Study ID:	Pro00005597	
Study Title:	Comparison of tongue volume and size as measured on a CBCT in patients with or without constricted lower dental arches	
Date of Informed Consent:	Approval Date 8/9/2009 8/9/2009	Approved Document Consent Form Information Sheet
Approval Expiry Date:	June 8, 2010	
Sponsor/Funding Agency	Fund for Dentistry	FDENT

Thank you for submitting the above study to the Health Research Ethics Board (Biomedical Panel) and for providing revised versions of the information sheet and consent for parents/adult subjects as well as an assent form for minor subjects. These documents, undated but submitted on July 17, 2009, are approved on behalf of the committee. The protocol involved in this project has been found to be acceptable within the limitations of human experimentation. There are no outstanding ethical issues and the study is approved.

We note that you deleted the original informed consent documents from the documentation section. In future, such items should remain attached so that the HREB record is complete.
Sincerely,

The ethics approval is valid until June 8, 2010. A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. You will receive electronic reminders at 45, 30, 15 and 1 day(s) prior to the expiry date. If you do not renew on or before that date, you will have to re-submit an ethics application.

For studies where investigators must obtain informed consent, signed copies of the consent form must be retained, as should all study related documents, so as to be available to the HREB on request. They should be kept for the duration of the project and for at least seven years following its completion.

Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Alberta Health Services or other local health care institutions for the purposes of research. We assume that appropriate administrative approval has been obtained from the Department of Dentistry clinic where this research will take place.

J. Stephen Bamforth, MD
Associate Chair, Health Research Ethics Board (Biomedical Panel)

Note: This correspondence includes an electronic signature (validation and approval via an online system).

INFORMATION SHEET

Title of Project: Comparison of tongue volume and size in patients with and without constricted lower dental arches as measured from a CBCT

Principal Investigator(s): Dr. Carlos Flores-Mir

Sub-Investigator(s): Dr. Marie-Alice Mandich, Dr. Paul Major

Note: if you are consenting on behalf of minor child then the words you and your should be read as your child and his/her.

Background: There are only a couple of published studies that have examined the tongue with a magnetic resonance image (MRI) with respect to airway, weight of the patients and volume of the mouth.

Purpose: To compare the tongue volume and size in orthodontic patients with or without constricted lower jaw arches, as measured from computer generated (CBCT) images with the use of a contrast medium.

Procedures: You are undergoing procedures required by your orthodontist, including a CBCT image. If you agree to take part in the study, at a scheduled appointment, you will be asked to swish and spit out a contrast liquid (Barium sulfate) just prior to your normally scheduled CBCT image. This contrast liquid improves the tongue outline in the obtained images. No additional procedure is necessary. The contrast liquid has no taste, only a sandy feeling. After the image is taken, you can rinse his/her mouth.

Possible Benefits: There will be no direct benefit to you, but the information we obtain may help us better understand the association between tongue size and the form of the dental arches.

Possible Risks: There are no risks with this contrast liquid, as it is a standard contrast medium used for several medical diagnostic imaging procedures. You are NOT being subjected to additional x-rays. The use of the contrast material will not affect the quality of the diagnostic imaging.

Confidentiality: Personal records relating to this study will be kept confidential for at least 5 years. However, the only personal information about you required is age and gender. Therefore there is no reasonable way the information obtained for the study could be linked to your personal records. Any report published as a result of this study will not identify you by name or initials.

Voluntary Participation: You are free to decline to enter this research study. Your regular orthodontic care will not be affected if you decide to do so.

Liability: By signing this consent you are not releasing the investigator(s) or the institution from their legal and professional responsibilities.

Contact Names and Telephone Numbers**:** If you have any concerns regarding your rights as a study participant, you may contact the Chairperson of the Department of Dentistry of the University of Alberta, at (780) 492-3312 or the Health Research Ethics Board, at (780) 492-9724.

Please contact any of the individuals identified below if you have any questions or concerns about the study at any time:

Principal Investigator(s): Dr. Carlos Flores-Mir (780) 492-7409

Sub-Investigator(s): Dr. Marie-Alice Mandich (780) 492-3065,
Dr. Paul Major (780) 492-7696

PATIENT CONSENT FORM

Title of Project: Comparison of tongue volume and size in patients with and without constricted lower dental arches as measured from a CBCT

Principal Investigator(s): Phone Number(s):
Carlos Flores-Mir (780) 492-7409

Sub-Investigator(s): Phone Number(s):
Marie-Alice Mandich (780) 492-3065
Paul Major (780) 492-7696

You are scheduled to have your records appointment today. During the appointment, you will be asked to swish very hard (so that it goes everywhere on your tongue) and spit a small amount of contrast liquid just before your radiograph images are taken. The contrast liquid has no taste, only a sandy feeling. After the image is taken, you can rinse your mouth.

Do you agree to participate? YES ☐ NO ☐

Name ______________________________ Date __________

Signature of Investigator or Designee ______________________ Date __________

Appendix 2 Normality and model assumptions

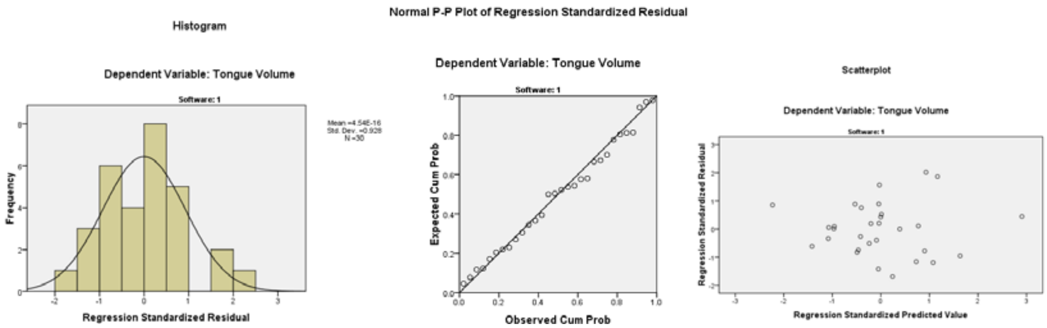


Figure A2-1 Graphs for regression standardized residuals of tongue volume with Anatomage inVivo 5 software

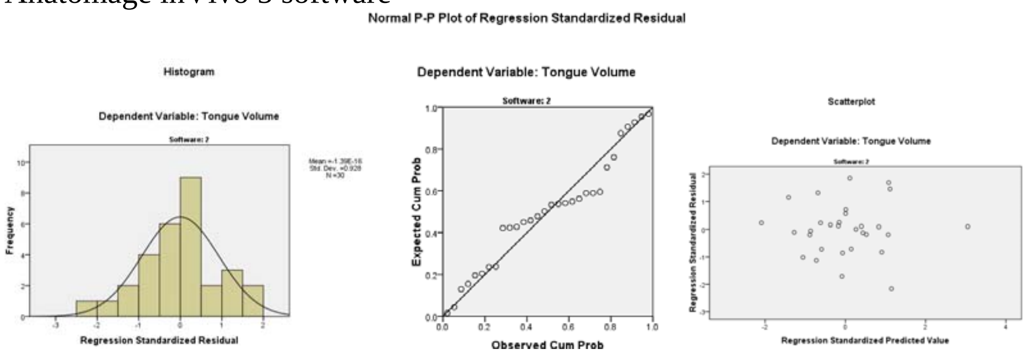


Figure A2-2 Graphs for regression standardized residuals of tongue volume with Avizo 6.0 software

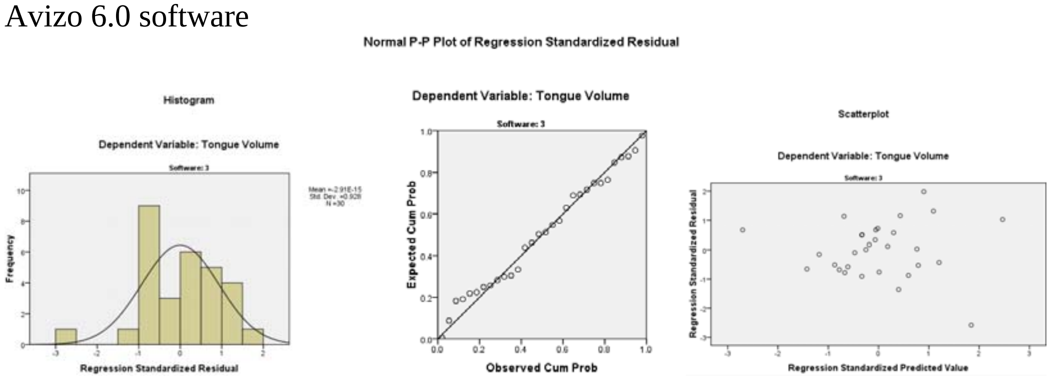


Figure A2-3 Graphs for regression standardized residuals of tongue volume with Mimics 13.1 software

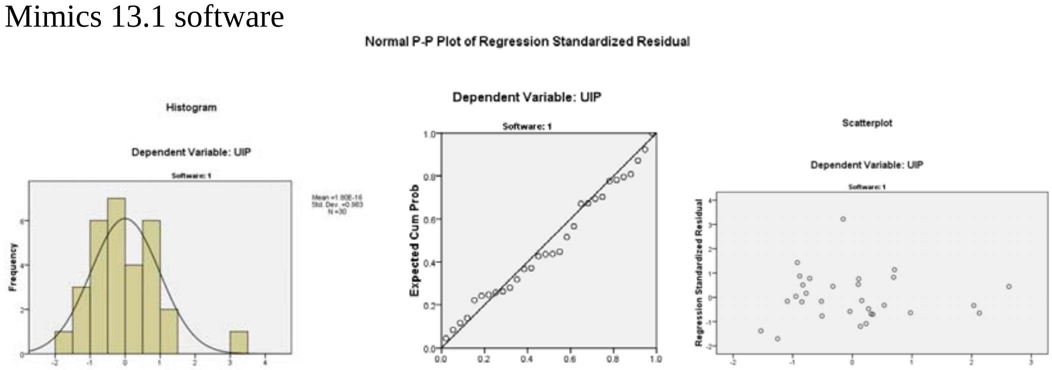


Figure A2-4 Graphs for regression standardized residuals of upper inter-premolar width with Anatomage inVivo 5 software

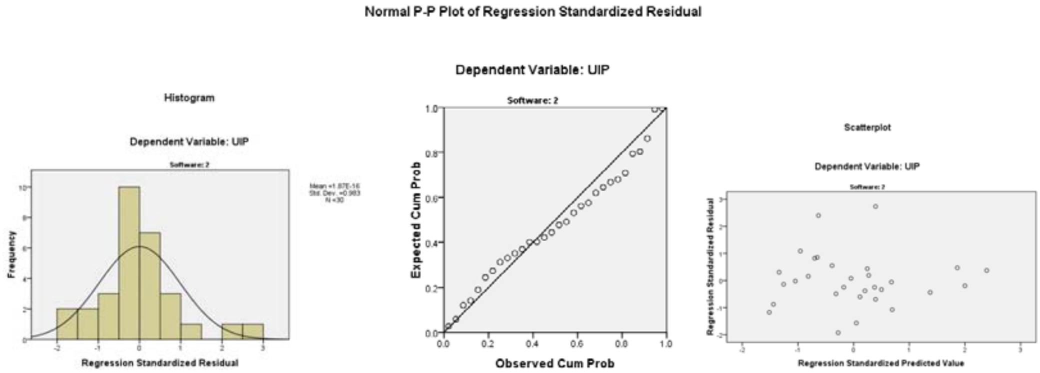


Figure A2-5 Graphs for regression standardized residuals of upper inter-premolar width with Avizo 6.0 software

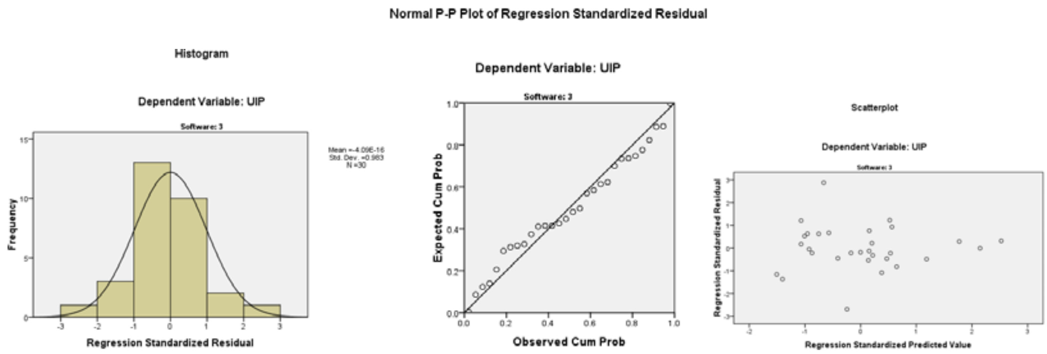


Figure A2-6 Graphs for regression standardized residuals of upper inter-premolar width with Mimics 13.1 software

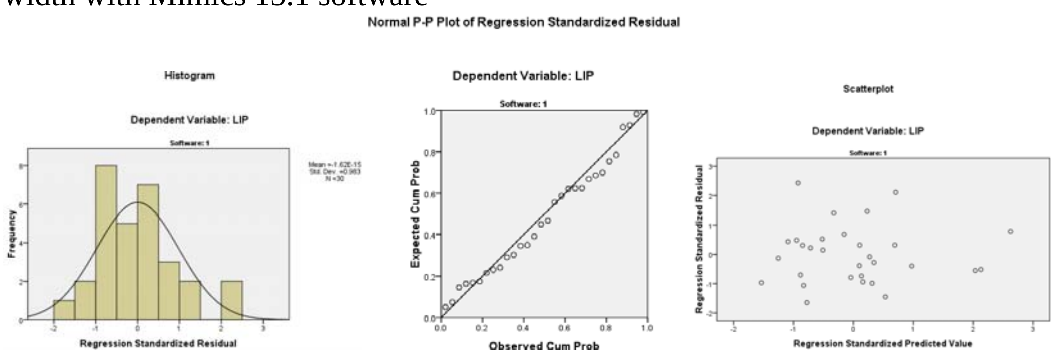


Figure A2-7 Graphs for regression standardized residuals of lower inter-premolar width with Anatomage inVivo 5 software

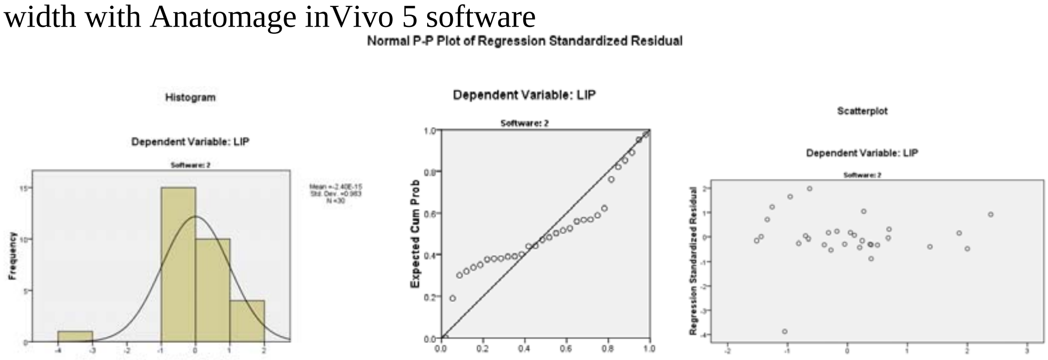


Figure A2-8 Graphs for regression standardized residuals of lower inter-premolar width with Avizo 6.0 software

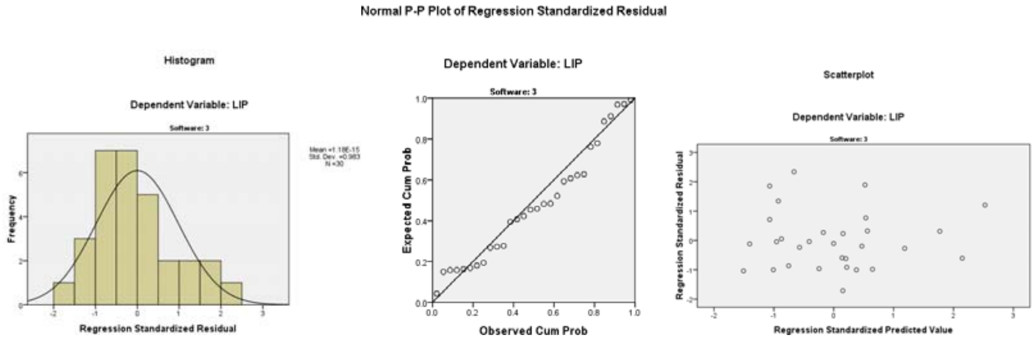


Figure A2-9 Graphs for regression standardized residuals of lower inter-premolar width with Mimics 13.1 software

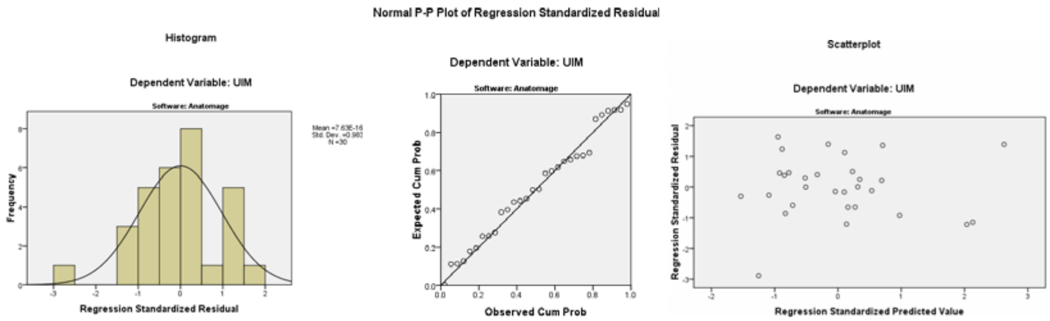


Figure A2-10 Graphs for regression standardized residuals of upper inter-molar width with Anatomage inVivo 5 software

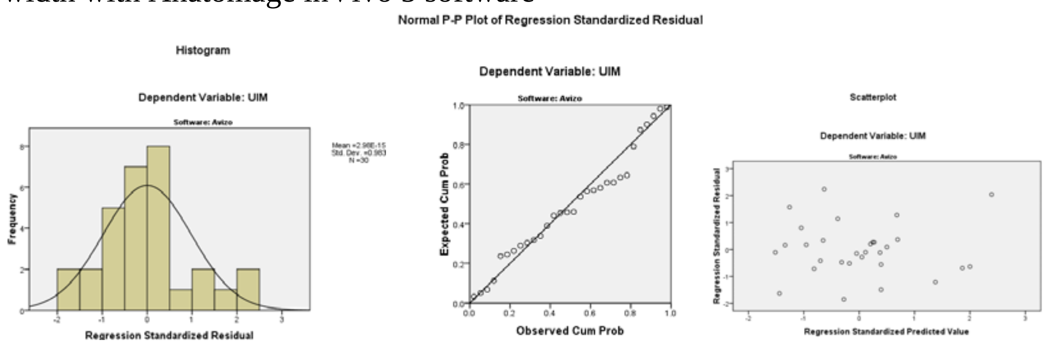


Figure A2-11 Graphs for regression standardized residuals of upper inter-molar width with Avizo 6.0 software

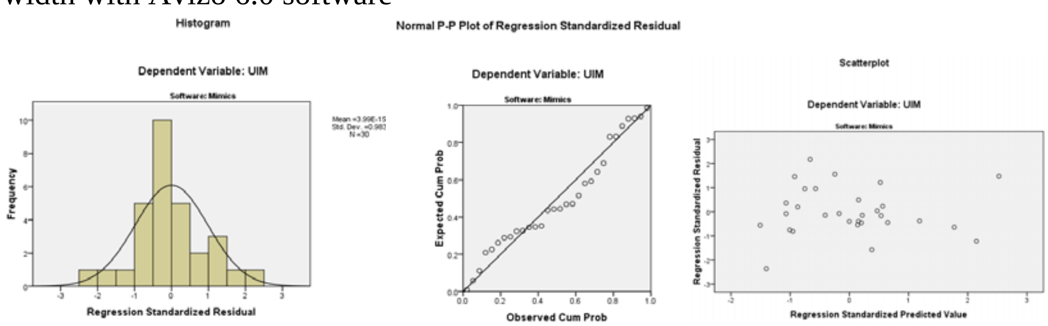


Figure A2-12 Graphs for regression standardized residuals of upper inter-molar width with Mimics 13.1 software

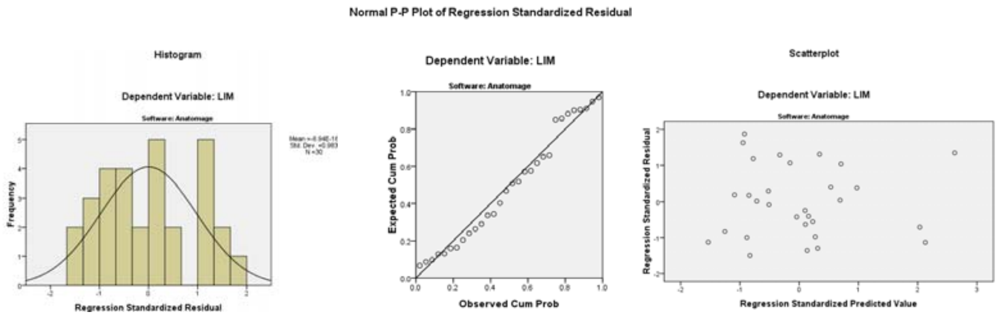


Figure A2-13 Graphs for regression standardized residuals of lower inter-molar width with Anatomage inVivo 5 software

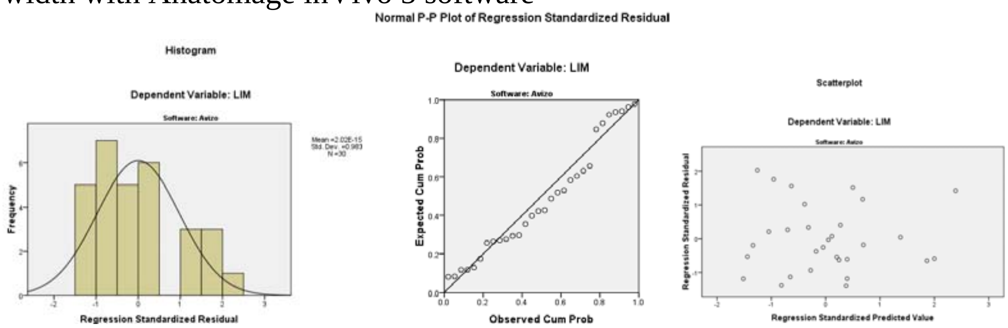


Figure A2-14 Graphs for regression standardized residuals of lower inter-molar width with Avizo 6.0 software

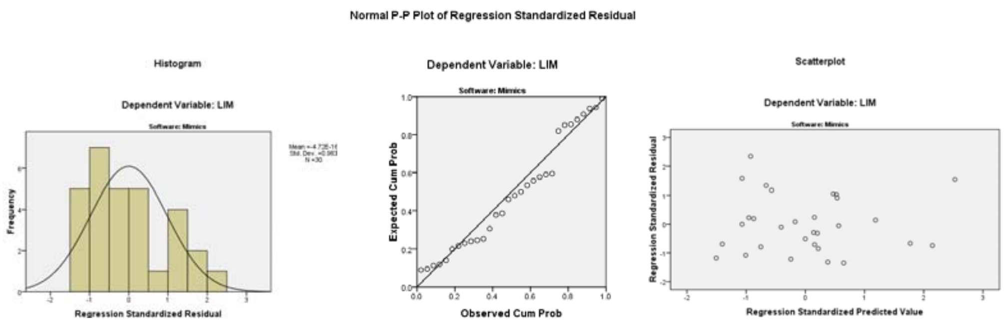


Figure A2-15 Graphs for regression standardized residuals of lower inter-molar width with Mimics 13.1 software

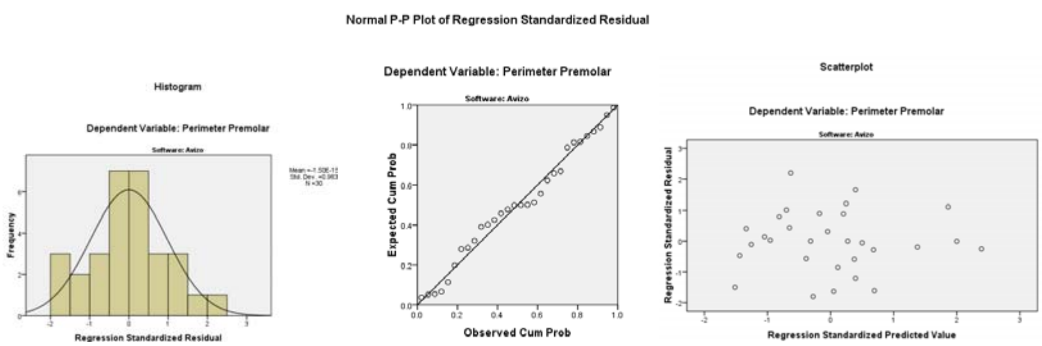


Figure A2-16 Graphs for regression standardized residuals of palatal perimeter at the premolar level

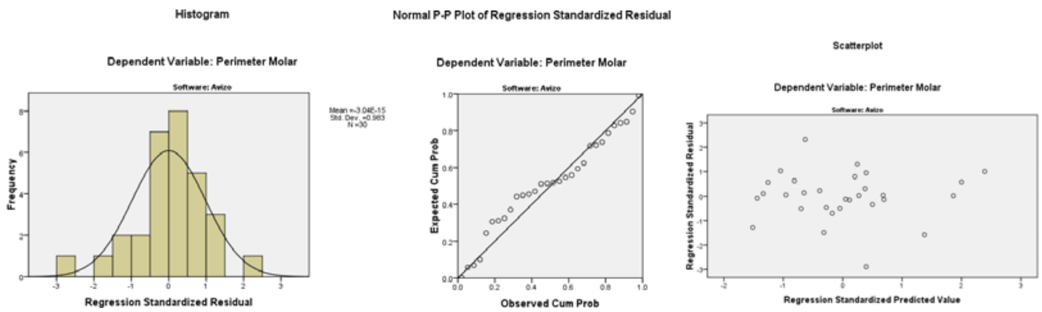


Figure A2-17 Graphs for regression standardized residuals of palatal perimeter at the molar level

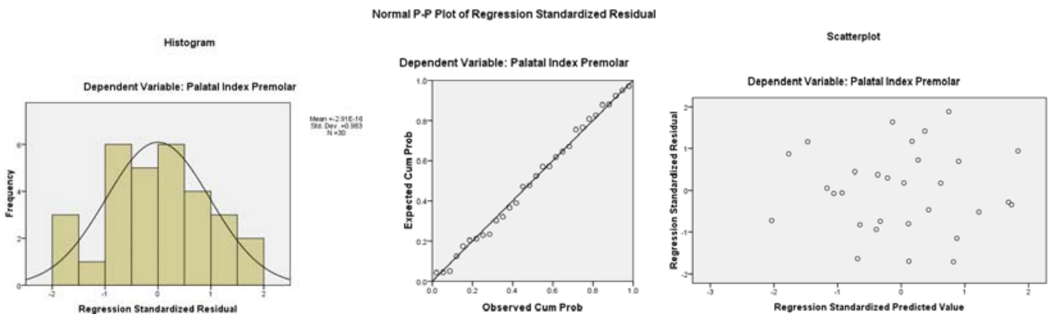


Figure A2-18 Graphs for regression standardized residuals of palatal index at the premolar level

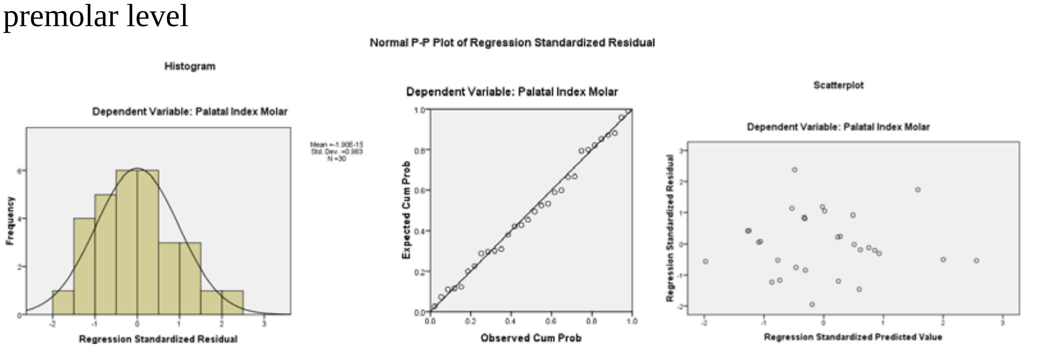


Figure A2-19 Graphs for regression standardized residuals of palatal index at the molar level

Appendix 3 Tongue volume

Table A3-1 ANOVA Tongue volume descriptive statistics by software

Parameter	*F(2,87)*	*p-value*	*Partial Eta Squared* η^2
Tongue volume between softwares	0.009	0.991	0.000

Table A3-2 Pearson Correlation Coefficient of the tongue volume measurements from the different softwares

Parameter	*n*	*Correlation Coefficient*
Tongue volume correlation		
Anatomage vs. Avizo	30	0.932
Anatomage vs. Mimics	30	0.928
Avizo vs. Mimics	30	0.986

Table A3-3 ICC for Tongue Volume (TV1, TV2, TV3) of all 3 softwares

Parameter	*ICC*	*95% CI*
Tongue Volume	0.972	[0.937, 0.990]

Table A3-4 ICC for Tongue Volume (TV1, TV2, TV3) for each software: Anatomage inVivo 5 software

Parameter	*ICC*	*95% CI*
Tongue volume by software		
Anatomage	0.965	[0.852, 0.996]
Avizo	0.990	[0.955, 0.999]
Mimics	0.976	[0.898, 0.997]

Table A3-5 ICC for Tongue Volume of all 3 softwares by trial (TV1, TV2, TV3)

Parameter	*ICC*	*95% CI*
Tongue volume by trial		
Trial 1 (TV1)	0.924	[0.704, 0.991]
Trial 2 (TV2)	0.952	[0.798, 0.994]
Trial 3 (TV3)	0.966	[0.856, 0.996]

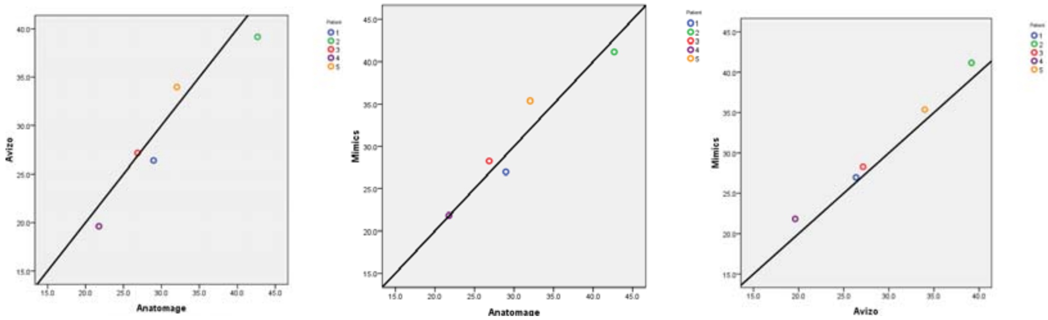


Figure A3-1 Scatterplot of ICC coefficients for tongue volume reliability values of all three softwares for the second trial (TV2), 45 degree line added for comparison

Table A3-6 ANOVA Tongue volume by gender and T-test

Parameter	*F(1,28)*	*p-value*
Tongue volume between genders	5.764	0.023

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Tongue Volume	Equal variances assumed	2.809	.105	-2.401	28	.023	-4.67	1.94	-8.65	-0.68
	Equal variances not assumed			-2.401	21.811	.025	-4.67	1.94	-8.70	-0.63

Table A3-7 Non-Parametric, Kruskal-Wallis Tongue volume by gender

Parameter	*Chi-Square*	*p-value*
Tongue volume between genders	4.742	0.029

Ranks

	Ge...	N	Mean Rank
Tongue Volume	M	15	19.00
	F	15	12.00
	Total	30	

Table A3-8 Correlation r between tongue volume and age

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs Age	30	0.150

Table A3-9 Regression analysis between tongue volume and age

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.150[a]	.023	-.012	5.77738854E0

a. Predictors: (Constant), Age

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	21.578	1	21.578	.646	.428[a]
	Residual	934.590	28	33.378		
	Total	956.168	29			

a. Predictors: (Constant), Age

b. Dependent Variable: Tongue Volume

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	23.928	3.612		6.625	.000
	Age	.158	.196	.150	.804	.428

a. Dependent Variable: Tongue Volume

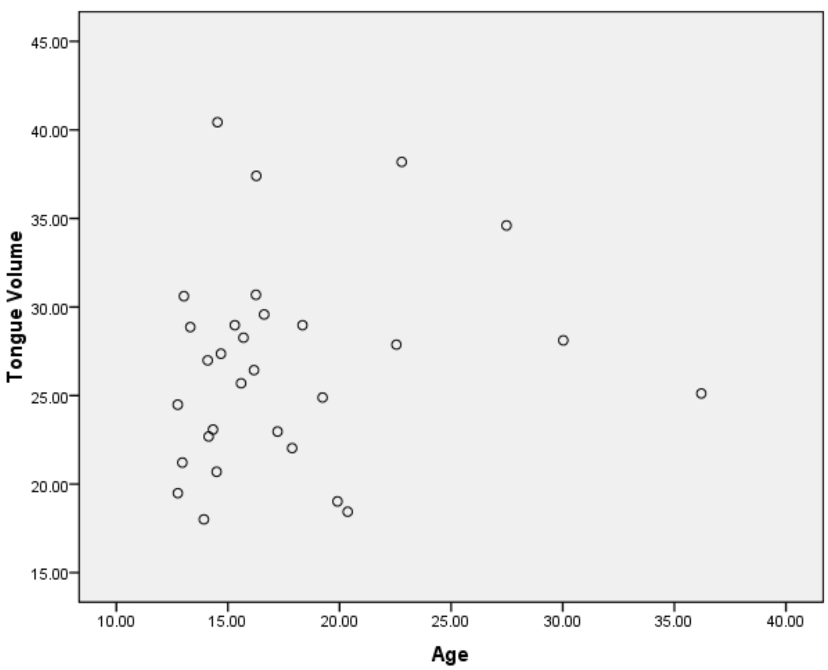


Figure A3-2 Scatterplot of tongue volume by age

Table A3-10 Regression analysis between tongue volume and age-squared exploring quadratic relationship

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.218[a]	.048	-.023	5.80747009E0

a. Predictors: (Constant), ageSq, Age

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	45.547	2	22.773	.675	.517[a]
	Residual	910.621	27	33.727		
	Total	956.168	29			

a. Predictors: (Constant), ageSq, Age

b. Dependent Variable: Tongue Volume

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	13.146	13.296		.989	.332
	Age	1.222	1.277	1.165	.956	.347
	ageSq	-.023	.028	-1.027	-.843	.407

a. Dependent Variable: Tongue Volume

Table A3-11 Regression analysis between tongue volume and age, excluding ages above 25 years old

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.137[a]	.019	-.020	5.90018325E0

a. Predictors: (Constant), Age

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16.724	1	16.724	.480	.495[a]
	Residual	870.304	25	34.812		
	Total	887.028	26			

a. Predictors: (Constant), Age

b. Dependent Variable: Tongue Volume

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	21.891	6.631		3.301	.003
	Age	.281	.405	.137	.693	.495

a. Dependent Variable: Tongue Volume

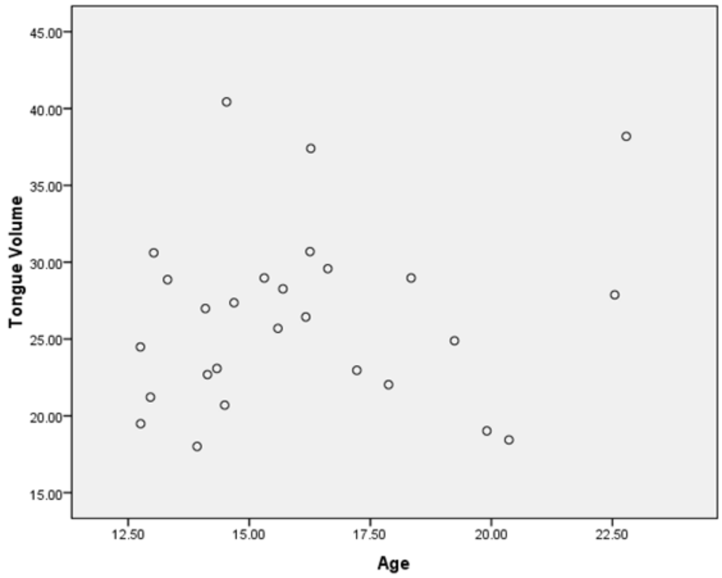


Figure A3-3 Scatterplot of tongue volume by age, excluding ages above 25 years old

Appendix 4 ICC x, y, z coordinates as identified on Avizo 6.0 software

Table A4-1 ICC for coordinate variables (x, y, z) for the inter-dental width calculation of first upper and lower molars and premolars for all three repeated measures (Trial 1, Trial 2, Trial 3): UIP, LIP, UIM, LIM

Parameter	*ICC*	*95% CI*
x coordinate	1.000	[1.000, 1.000]
y coordinate	1.000	[1.000, 1.000]
z coordinate	0.999	[0.999, 1.000]

Table A4-2 ICC for coordinate variables (x, z) for the palatal perimeter from Avizo 6.0 for all three repeated measures (Trial 1, Trial 2, Trial 3)

Parameter	*ICC*	*95% CI*
Perimeter at premolar level		
x coordinate	1.000	[0.999, 1.000]
z coordinate	0.998	[0.997, 0.999]
Perimeter at molar level		
x coordinate	0.998	[0.997, 0.999]
z coordinate	0.997	[0.996, 0.998]

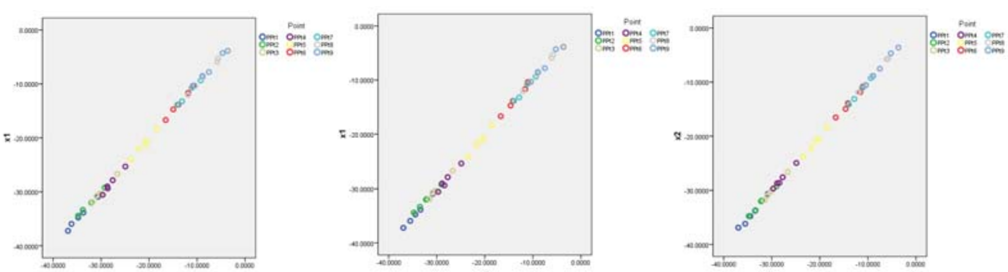


Figure A4-1 Scatter plot of the x coordinates of the palatal perimeter at the premolar level for all three trials (x1, x2, x3)

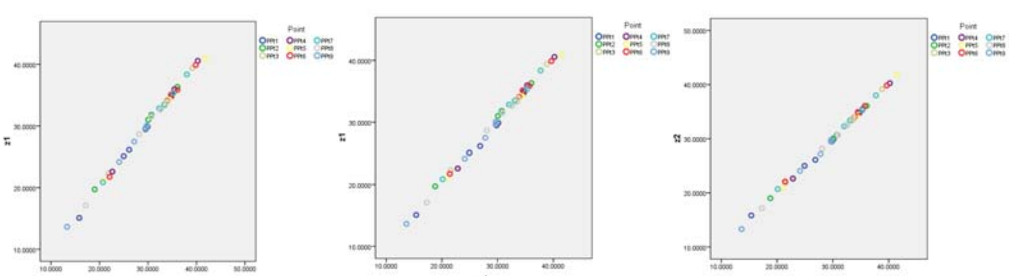


Figure A4-2 Scatter plot of the z coordinates of the palatal perimeter at the premolar level for all three trials (z1, z2, z3)

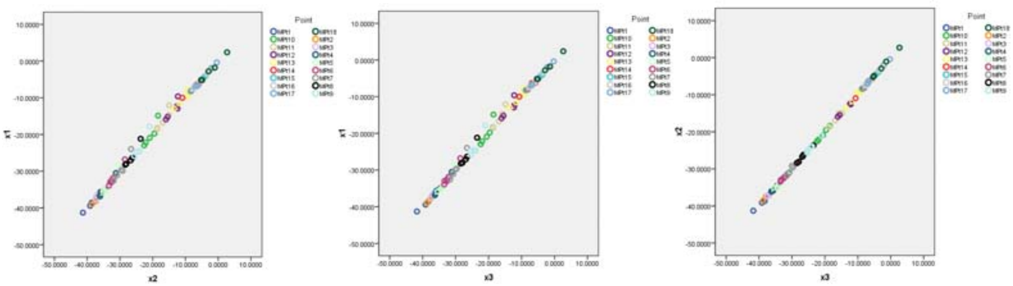


Figure A4-3 Scatter plot of the x coordinates of the palatal perimeter at the molar level for all three trials (x1, x2, x3)

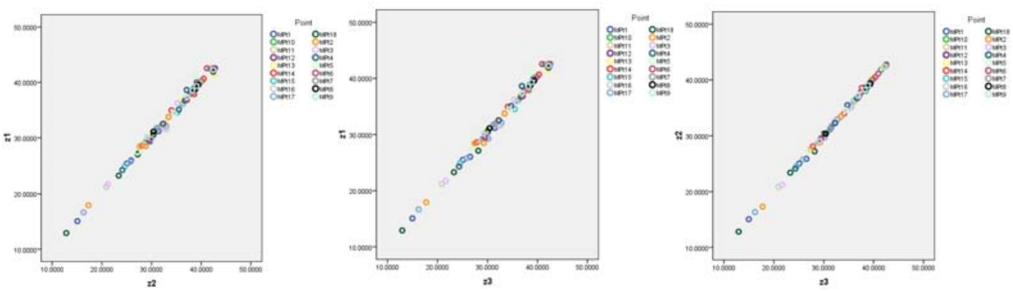


Figure A4-4 Scatter plot of the z coordinates of the palatal perimeter at the molar level for all three trials (z1, z2, z3)

Table A4-3 ICC for coordinate variables (x, y, z) for the axial tooth inclination for all three repeated measures (Trial 1, Trial 2, Trial 3)

Parameter	*ICC*	*95% CI*
x coordinate	1.000	[0.999, 1.000]
y coordinate	0.998	[0.996, 0.998]
z coordinate	1.000	[0.999, 1.000]

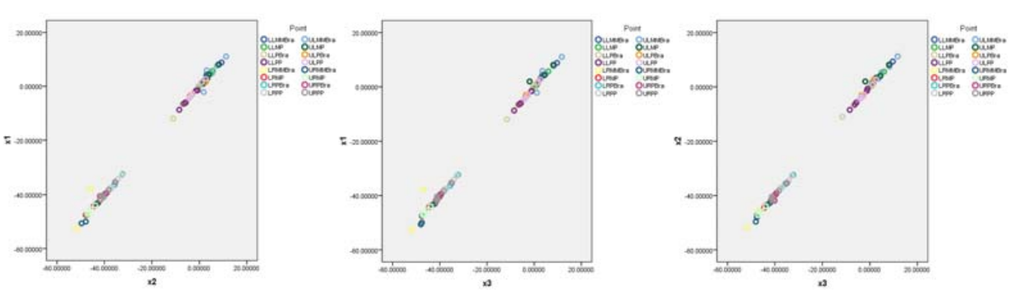


Figure A4-5 Scatter plot of the x coordinates used for the axial tooth inclination for all three trials (x1, x2, x3)

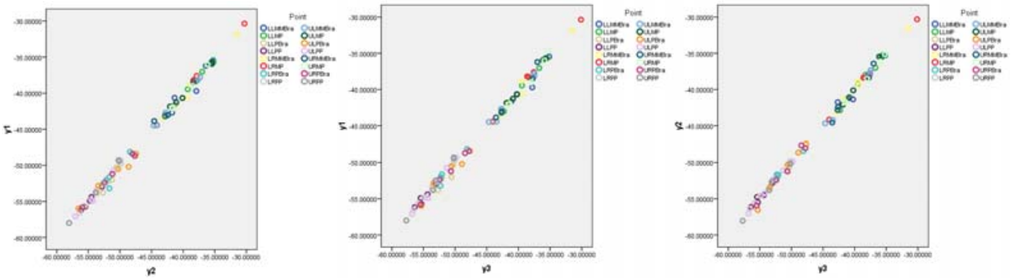


Figure A4-6 Scatter plot of the y coordinates used for the axial tooth inclination for all three trials (y1, y2, y3)

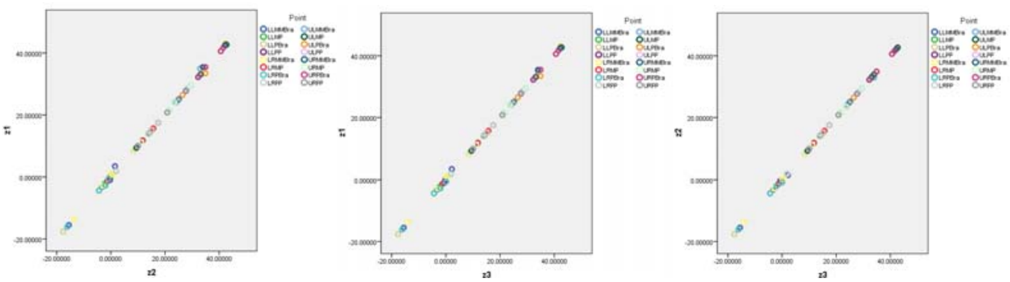


Figure A4-7 Scatter plot of the z coordinates used for the axial tooth inclination for all three trials (z1, z2, z3)

Table A4-4 ICC for axial tooth inclination angles calculated from the coordinates for all three trials

Parameter	*ICC*	*95% CI*
Axial inclination	0.911	[0.855, 0.949]

Appendix 5 Reliability of the 3 softwares

Table A5-1 ICC for upper and lower inter-premolar width, upper and lower inter-molar width for all 3 repeated measures (Trial 1,Trial 2,Trial 3) of all 3 softwares

Parameter	*ICC*	*95% CI*
Upper inter-premolar width	0.979	[0.951, 0.992]
Lower inter-premolar width	0.964	[0.918, 0.987]
Upper inter-molar width	0.988	[0.973, 0.996]
Lower inter-molar width	0.956	[0.901, 0.984]

Table A5-5 ICC for upper and lower inter-premolar width, upper and lower inter-molar width for all 3 repeated measures (Trial 1, Trial 2, Trial 3) for each software

Parameter	*ICC*	*95% CI*
Upper Inter-premolar width		
Anatomage	0.975	[0.893, 0.997]
Avizo	0.986	[0.923, 0.998]
Mimics	0.984	[0.929, 0.998]
Lower Inter-premolar width		
Anatomage	0.990	[0.956, 0.999]
Avizo	0.971	[0.870, 0.997]
Mimics	0.946	[0.783, 0.994]
Upper Inter-molar width		
Anatomage	0.982	[0.909, 0.998]
Avizo	0.996	[0.984, 1.000]
Mimics	0.988	[0.948, 0.999]
Lower Inter-molar width		
Anatomage	0.931	[0.470, 0.993]
Avizo	0.991	[0.958, 0.999]
Mimics	0.966	[0.819, 0.996]

Appendix 6 Regression analysis results

Table A6-1 Correlation r between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Anatomage inVivo 5 software

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs. UIP	30	0.609
Tongue Volume vs. LIP	30	0.612
Tongue Volume vs. UIM	30	0.768
Tongue Volume vs. LIM	30	0.431
UIP vs. LIP	30	0.714
UIP vs. UIM	30	0.774
UIP vs. LIM	30	0.596
LIP vs. UIM	30	0.720
LIP vs. LIM	30	0.694
UIM vs. LIM	30	0.661

Table A6-2 Correlation r between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Avizo 6.0 software

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs. UIP	30	0.488
Tongue Volume vs. LIP	30	0.590
Tongue Volume vs. UIM	30	0.726
Tongue Volume vs. LIM	30	0.368
UIP vs. LIP	30	0.676
UIP vs. UIM	30	0.690
UIP vs. LIM	30	0.500
LIP vs. UIM	30	0.794
LIP vs. LIM	30	0.733
UIM vs. LIM	30	0.699

Table A6-3 Correlation r between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Mimics 13.1 software

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs. UIP	30	0.502
Tongue Volume vs. LIP	30	0.489
Tongue Volume vs. UIM	30	0.720
Tongue Volume vs. LIM	30	0.335
UIP vs. LIP	30	0.712
UIP vs. UIM	30	0.610
UIP vs. LIM	30	0.590
LIP vs. UIM	30	0.674
LIP vs. LIM	30	0.793
UIM vs. LIM	30	0.612

Table A6-4 Regression analysis between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Anatomage inVivo 5 software

Multivariate Tests[b,c]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.893	52.306[a]	4.000	25.000	.000	.893
	Wilks' Lambda	.107	52.306[a]	4.000	25.000	.000	.893
	Hotelling's Trace	8.369	52.306[a]	4.000	25.000	.000	.893
	Roy's Largest Root	8.369	52.306[a]	4.000	25.000	.000	.893
TongueVolume	Pillai's Trace	.620	10.193[a]	4.000	25.000	.000	.620
	Wilks' Lambda	.380	10.193[a]	4.000	25.000	.000	.620
	Hotelling's Trace	1.631	10.193[a]	4.000	25.000	.000	.620
	Roy's Largest Root	1.631	10.193[a]	4.000	25.000	.000	.620

a. Exact statistic

b. Software = 1

c. Design: Intercept + TongueVolume

Tests of Between-Subjects Effects[e]

Source	Dependent	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	UIP	82.691[a]	1	82.691	16.503	.000	.371
	LIP	59.107[b]	1	59.107	16.762	.000	.374
	UIM	181.011[c]	1	181.011	40.279	.000	.590
	LIM	39.345[d]	1	39.345	6.390	.017	.186
Intercept	UIP	558.451	1	558.451	111.452	.000	.799
	LIP	482.012	1	482.012	136.689	.000	.830
	UIM	703.969	1	703.969	156.647	.000	.848
	LIM	1180.849	1	1180.849	191.782	.000	.873
TongueVolume	UIP	82.691	1	82.691	16.503	.000	.371
	LIP	59.107	1	59.107	16.762	.000	.374
	UIM	181.011	1	181.011	40.279	.000	.590
	LIM	39.345	1	39.345	6.390	.017	.186
Error	UIP	140.300	28	5.011			
	LIP	98.737	28	3.526			
	UIM	125.832	28	4.494			
	LIM	172.403	28	6.157			
Total	UIP	22533.123	30				
	LIP	18479.815	30				
	UIM	33522.281	30				
	LIM	34817.668	30				
Corrected Total	UIP	222.990	29				
	LIP	157.844	29				
	UIM	306.843	29				
	LIM	211.748	29				

a. R Squared = .371 (Adjusted R Squared = .348)

b. R Squared = .374 (Adjusted R Squared = .352)

c. R Squared = .590 (Adjusted R Squared = .575)

d. R Squared = .186 (Adjusted R Squared = .157)

e. Software = 1

Parameter Estimates[a]

Dependent Variable	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
UIP	Intercept	19.825	1.878	10.557	.000	15.978	23.671	.799
	TongueVolume	.277	.068	4.062	.000	.137	.416	.371
LIP	Intercept	18.418	1.575	11.691	.000	15.191	21.645	.830
	TongueVolume	.234	.057	4.094	.000	.117	.351	.374
UIM	Intercept	22.258	1.778	12.516	.000	18.615	25.901	.848
	TongueVolume	.409	.065	6.347	.000	.277	.542	.590
LIM	Intercept	28.828	2.082	13.849	.000	24.564	33.092	.873
	TongueVolume	.191	.076	2.528	.017	.036	.346	.186

a. Software = 1

Table A6-5 Regression analysis between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Avizo 6.0 software

Multivariate Tests[b,c]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.874	43.188[a]	4.000	25.000	.000	.874
	Wilks' Lambda	.126	43.188[a]	4.000	25.000	.000	.874
	Hotelling's Trace	6.910	43.188[a]	4.000	25.000	.000	.874
	Roy's Largest Root	6.910	43.188[a]	4.000	25.000	.000	.874
TongueVolume	Pillai's Trace	.581	8.650[a]	4.000	25.000	.000	.581
	Wilks' Lambda	.419	8.650[a]	4.000	25.000	.000	.581
	Hotelling's Trace	1.384	8.650[a]	4.000	25.000	.000	.581
	Roy's Largest Root	1.384	8.650[a]	4.000	25.000	.000	.581

a. Exact statistic

b. Software = 2

c. Design: Intercept + TongueVolume

Tests of Between-Subjects Effects[e]

Source	Depend...	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	UIP	78.226[a]	1	78.226	8.767	.006	.238
	LIP	41.181[b]	1	41.181	14.947	.001	.348
	UIM	179.105[c]	1	179.105	31.259	.000	.527
	LIM	31.750[d]	1	31.750	4.374	.046	.135
Intercept	UIP	475.179	1	475.179	53.255	.000	.655
	LIP	483.357	1	483.357	175.437	.000	.862
	UIM	602.773	1	602.773	105.200	.000	.790
	LIM	1075.112	1	1075.112	148.126	.000	.841
TongueVolume	UIP	78.226	1	78.226	8.767	.006	.238
	LIP	41.181	1	41.181	14.947	.001	.348
	UIM	179.105	1	179.105	31.259	.000	.527
	LIM	31.750	1	31.750	4.374	.046	.135
Error	UIP	249.834	28	8.923			
	LIP	77.145	28	2.755			
	UIM	160.434	28	5.730			
	LIM	203.226	28	7.258			
Total	UIP	22005.705	30				
	LIP	18792.642	30				
	UIM	33467.855	30				
	LIM	34529.136	30				
Corrected Total	UIP	328.060	29				
	LIP	118.325	29				
	UIM	339.539	29				
	LIM	234.976	29				

a. R Squared = .238 (Adjusted R Squared = .211)

b. R Squared = .348 (Adjusted R Squared = .325)

c. R Squared = .527 (Adjusted R Squared = .511)

d. R Squared = .135 (Adjusted R Squared = .104)

e. Software = 2

Parameter Estimates[a]

Dependent Va...	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
UIP	Intercept	19.242	2.637	7.298	.000	13.841	24.644	.655
	TongueVolume	.286	.097	2.961	.006	.088	.484	.238
LIP	Intercept	19.407	1.465	13.245	.000	16.406	22.409	.862
	TongueVolume	.208	.054	3.866	.001	.098	.317	.348
UIM	Intercept	21.672	2.113	10.257	.000	17.344	26.001	.790
	TongueVolume	.433	.077	5.591	.000	.274	.591	.527
LIM	Intercept	28.944	2.378	12.171	.000	24.072	33.815	.841
	TongueVolume	.182	.087	2.092	.046	.004	.361	.135

a. Software = 2

Table A6-6 Regression analysis between tongue volume, upper and lower inter-molar and inter-premolar widths (UIP, LIP, UIM, LIM) of Mimics 13.1 software

Multivariate Tests[b,c]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.865	40.212[a]	4.000	25.000	.000	.865
	Wilks' Lambda	.135	40.212[a]	4.000	25.000	.000	.865
	Hotelling's Trace	6.434	40.212[a]	4.000	25.000	.000	.865
	Roy's Largest Root	6.434	40.212[a]	4.000	25.000	.000	.865
TongueVolume	Pillai's Trace	.559	7.921[a]	4.000	25.000	.000	.559
	Wilks' Lambda	.441	7.921[a]	4.000	25.000	.000	.559
	Hotelling's Trace	1.267	7.921[a]	4.000	25.000	.000	.559
	Roy's Largest Root	1.267	7.921[a]	4.000	25.000	.000	.559

a. Exact statistic

b. Software = 3

c. Design: Intercept + TongueVolume

Tests of Between-Subjects Effects[e]

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	UIP	66.421[a]	1	66.421	9.425	.005	.252
	LIP	45.051[b]	1	45.051	8.817	.006	.239
	UIM	161.690[c]	1	161.690	30.076	.000	.518
	LIM	25.461[d]	1	25.461	3.550	.070	.113
Intercept	UIP	495.317	1	495.317	70.282	.000	.715
	LIP	440.387	1	440.387	86.187	.000	.755
	UIM	630.121	1	630.121	117.210	.000	.807
	LIM	1094.586	1	1094.586	152.617	.000	.845
TongueVolume	UIP	66.421	1	66.421	9.425	.005	.252
	LIP	45.051	1	45.051	8.817	.006	.239
	UIM	161.690	1	161.690	30.076	.000	.518
	LIM	25.461	1	25.461	3.550	.070	.113
Error	UIP	197.332	28	7.048			
	LIP	143.071	28	5.110			
	UIM	150.528	28	5.376			
	LIM	200.819	28	7.172			
Total	UIP	22337.806	30				
	LIP	18524.925	30				
	UIM	34362.701	30				
	LIM	35139.912	30				
Corrected Total	UIP	263.752	29				
	LIP	188.123	29				
	UIM	312.218	29				
	LIM	226.280	29				

a. R Squared = .252 (Adjusted R Squared = .225)

b. R Squared = .239 (Adjusted R Squared = .212)

c. R Squared = .518 (Adjusted R Squared = .501)

d. R Squared = .113 (Adjusted R Squared = .081)

e. Software = 3

Parameter Estimates[a]

Dependent Variable	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
UIP	Intercept	19.967	2.382	8.383	.000	15.088	24.846	.715
	TongueVolume	.267	.087	3.070	.005	.089	.445	.252
LIP	Intercept	18.827	2.028	9.284	.000	14.673	22.981	.755
	TongueVolume	.220	.074	2.969	.006	.068	.371	.239
UIM	Intercept	22.521	2.080	10.826	.000	18.260	26.782	.807
	TongueVolume	.416	.076	5.484	.000	.261	.572	.518
LIM	Intercept	29.682	2.403	12.354	.000	24.760	34.604	.845
	TongueVolume	.165	.088	1.884	.070	-.014	.345	.113

a. Software = 3

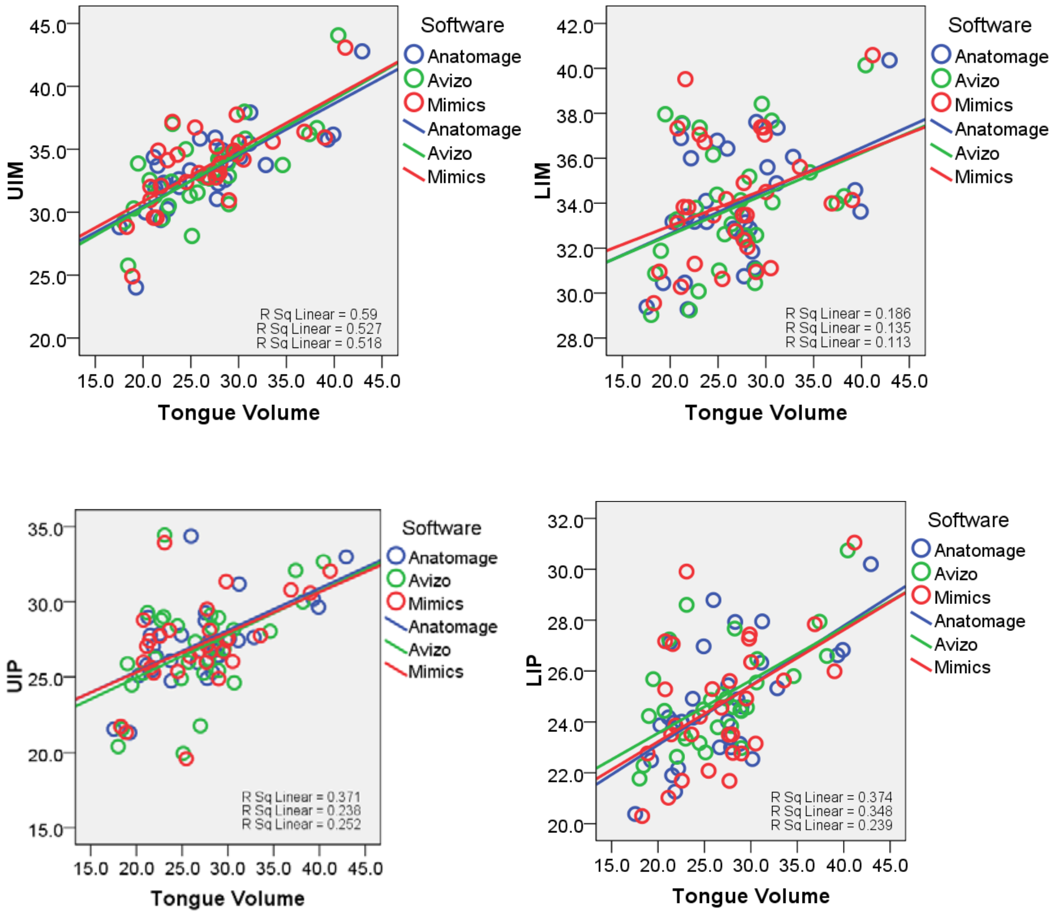


Figure A6-1 Scatterplot of tongue volume versus the upper and lower inter-premolar and molar widths for all three softwares with line at total fit

Table A6-7 Correlation r between tongue volume and palatal perimeter at premolar and molar level

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs. Perimeter Premolar	30	0.439
Tongue Volume vs. Perimeter Molar	30	0.839
Tongue Volume vs. Palatal Index Premolar	30	0.218
Tongue Volume vs. Palatal Index Molar	30	0.349
Perimeter Premolar vs. Perimeter Molar	30	0.628
Perimeter Premolar vs. Palatal Index Premolar	30	0.645
Perimeter Premolar vs. Palatal Index Molar	30	0.072
Perimeter Molar vs. Palatal Index Premolar	30	0.236
Perimeter Molar vs. Palatal Index Molar	30	0.250
Palatal Index Premolar vs. Palatal Index Molar	30	0.520

Table A6-8 Regression analysis between tongue volume and palatal perimeter at premolar and molar level

Multivariate Tests[b,c]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.839	32.529[a]	4.000	25.000	.000	.839
	Wilks' Lambda	.161	32.529[a]	4.000	25.000	.000	.839
	Hotelling's Trace	5.205	32.529[a]	4.000	25.000	.000	.839
	Roy's Largest Root	5.205	32.529[a]	4.000	25.000	.000	.839
TongueVolume	Pillai's Trace	.735	17.355[a]	4.000	25.000	.000	.735
	Wilks' Lambda	.265	17.355[a]	4.000	25.000	.000	.735
	Hotelling's Trace	2.777	17.355[a]	4.000	25.000	.000	.735
	Roy's Largest Root	2.777	17.355[a]	4.000	25.000	.000	.735

a. Exact statistic

b. Software = Avizo

c. Design: Intercept + TongueVolume

Tests of Between-Subjects Effects[e]

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	Perimeter Premolar	234.001[a]	1	234.001	6.678	.015	.193
	Perimeter Molar	616.633[b]	1	616.633	66.331	.000	.703
	Palatal Index Premolar	.007[c]	1	.007	1.400	.247	.048
	Palatal Index Molar	.012[d]	1	.012	3.895	.058	.122
Intercept	Perimeter Premolar	581.703	1	581.703	16.601	.000	.372
	Perimeter Molar	1014.315	1	1014.315	109.110	.000	.796
	Palatal Index Premolar	.049	1	.049	9.396	.005	.251
	Palatal Index Molar	.077	1	.077	24.745	.000	.469
TongueVolume	Perimeter Premolar	234.001	1	234.001	6.678	.015	.193
	Perimeter Molar	616.633	1	616.633	66.331	.000	.703
	Palatal Index Premolar	.007	1	.007	1.400	.247	.048
	Palatal Index Molar	.012	1	.012	3.895	.058	.122
Error	Perimeter Premolar	981.146	28	35.041			
	Perimeter Molar	260.296	28	9.296			
	Palatal Index Premolar	.146	28	.005			
	Palatal Index Molar	.088	28	.003			
Total	Perimeter Premolar	36925.936	30				
	Perimeter Molar	74562.270	30				
	Palatal Index Premolar	2.327	30				
	Palatal Index Molar	3.585	30				
Corrected Total	Perimeter Premolar	1215.147	29				
	Perimeter Molar	876.929	29				
	Palatal Index Premolar	.153	29				
	Palatal Index Molar	.100	29				

a. R Squared = .193 (Adjusted R Squared = .164)

b. R Squared = .703 (Adjusted R Squared = .693)

c. R Squared = .048 (Adjusted R Squared = .014)

d. R Squared = .122 (Adjusted R Squared = .091)

e. Software = Avizo

Parameter Estimates[a]

Dependent Variable	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
Perimeter Premolar	Intercept	21.290	5.225	4.074	.000	10.587	31.994	.372
	TongueVolume	.495	.191	2.584	.015	.103	.887	.193
Perimeter Molar	Intercept	28.114	2.691	10.446	.000	22.600	33.627	.796
	TongueVolume	.803	.099	8.144	.000	.601	1.005	.703
Palatal Index Premolar	Intercept	.195	.064	3.065	.005	.065	.326	.251
	TongueVolume	.003	.002	1.183	.247	-.002	.008	.048
Palatal Index Molar	Intercept	.246	.049	4.974	.000	.144	.347	.469
	TongueVolume	.004	.002	1.974	.058	.000	.007	.122

a. Software = Avizo

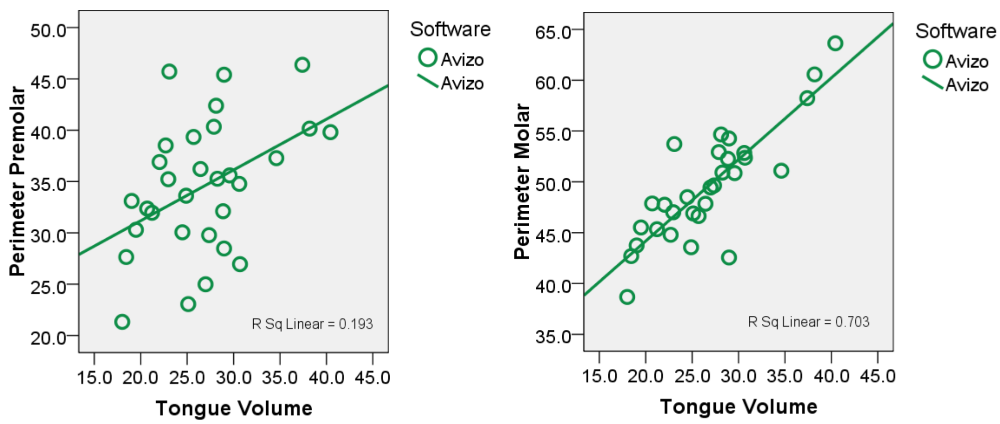


Figure A6-2 Scatterplot of tongue volume versus the palatal perimeter at the premolar and molar level for all three softwares with line at total fit

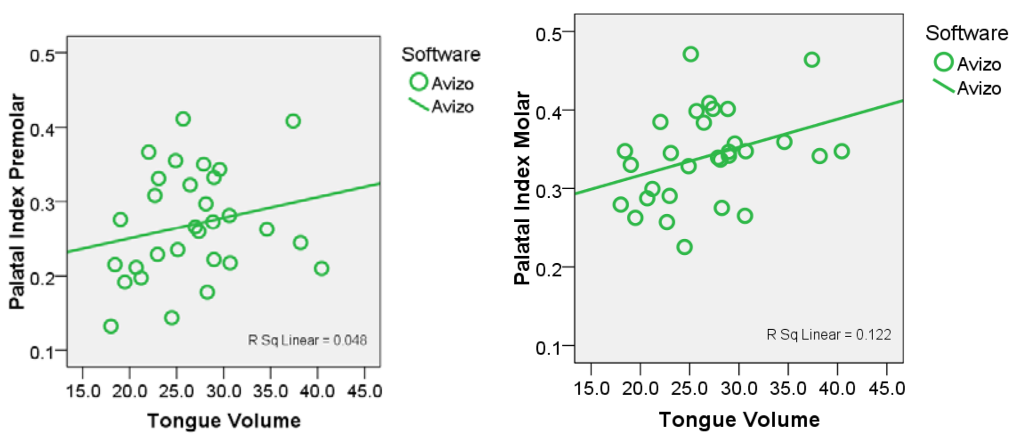


Figure A6-3 Scatterplot of tongue volume versus the palatal index at the premolar and molar level for all three softwares with line at total fit

Table A6-9 Correlation r between tongue volume and axial inclination angles

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Tongue Volume vs. Angle URP	30	-0.305
Tongue Volume vs. Angle ULP	30	-0.141
Tongue Volume vs. Angle URM	30	-0.089
Tongue Volume vs. Angle ULM	30	-0.145
Tongue Volume vs. Angle LRP	30	-0.201
Tongue Volume vs. Angle LLP	30	-0.265
Tongue Volume vs. Angle LRM	30	0.277
Tongue Volume vs. Angle LLM	30	0.389

Table A6-10 Regression analysis between tongue volume, inter-dental widths, palatal perimeters and axial inclination angles

Multivariate Tests[b,c]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	.919	12.210[a]	14.000	15.000	.000	.919
	Wilks' Lambda	.081	12.210[a]	14.000	15.000	.000	.919
	Hotelling's Trace	11.396	12.210[a]	14.000	15.000	.000	.919
	Roy's Largest Root	11.396	12.210[a]	14.000	15.000	.000	.919
TongueVolume	Pillai's Trace	.854	6.260[a]	14.000	15.000	.001	.854
	Wilks' Lambda	.146	6.260[a]	14.000	15.000	.001	.854
	Hotelling's Trace	5.843	6.260[a]	14.000	15.000	.001	.854
	Roy's Largest Root	5.843	6.260[a]	14.000	15.000	.001	.854

a. Exact statistic

b. Software = 2

c. Design: Intercept + TongueVolume

Parameter Estimates[a]

Dependent Variable	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Partial Eta Squared
UIP	Intercept	19.242	2.637	7.298	.000	13.841	24.644	.655
	TongueVolume	.286	.097	2.961	.006	.088	.484	.238
LIP	Intercept	19.407	1.465	13.245	.000	16.406	22.409	.862
	TongueVolume	.208	.054	3.866	.001	.098	.317	.348
UIM	Intercept	21.672	2.113	10.257	.000	17.344	26.001	.790
	TongueVolume	.433	.077	5.591	.000	.274	.591	.527
LIM	Intercept	28.944	2.378	12.171	.000	24.072	33.815	.841
	TongueVolume	.182	.087	2.092	.046	.004	.361	.135
Perimeter Premolar	Intercept	21.290	5.225	4.074	.000	10.587	31.994	.372
	TongueVolume	.495	.191	2.584	.015	.103	.887	.193
Perimeter Molar	Intercept	28.114	2.691	10.446	.000	22.600	33.627	.796
	TongueVolume	.803	.099	8.144	.000	.601	1.005	.703
Angle URP	Intercept	7.375	4.793	1.539	.135	-2.442	17.192	.078
	TongueVolume	-.298	.176	-1.695	.101	-.657	.062	.093
Angle ULP	Intercept	7.709	9.443	.816	.421	-11.633	27.052	.023
	TongueVolume	-.261	.346	-.753	.458	-.969	.448	.020
Angle URM	Intercept	-11.758	5.279	-2.228	.034	-22.571	-.946	.151
	TongueVolume	-.092	.193	-.474	.639	-.488	.304	.008
Angle ULM	Intercept	-7.168	7.535	-.951	.350	-22.603	8.267	.031
	TongueVolume	-.215	.276	-.777	.443	-.780	.351	.021
Angle LRP	Intercept	7.234	4.976	1.454	.157	-2.958	17.426	.070
	TongueVolume	-.198	.182	-1.084	.288	-.571	.176	.040
Angle LLP	Intercept	7.091	4.539	1.562	.129	-2.206	16.388	.080
	TongueVolume	-.242	.166	-1.455	.157	-.583	.099	.070
Angle LRM	Intercept	-28.260	7.767	-3.638	.001	-44.170	-12.350	.321
	TongueVolume	.435	.285	1.528	.138	-.148	1.018	.077
Angle LLM	Intercept	-29.225	5.243	-5.574	.000	-39.964	-18.486	.526
	TongueVolume	.429	.192	2.235	.034	.036	.823	.151

a. Software = 2

Tests of Between-Subjects Effects[o]

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	UIP	78.226[a]	1	78.226	8.767	.006	.238
	LIP	41.181[b]	1	41.181	14.947	.001	.348
	UIM	179.105[c]	1	179.105	31.259	.000	.527
	LIM	31.750[d]	1	31.750	4.374	.046	.135
	Perimeter Premolar	234.001[e]	1	234.001	6.678	.015	.193
	Perimeter Molar	616.633[f]	1	616.633	66.331	.000	.703
	Angle URP	84.678[g]	1	84.678	2.873	.101	.093
	Angle ULP	64.912[h]	1	64.912	.567	.458	.020
	Angle URM	8.033[i]	1	8.033	.225	.639	.008
	Angle ULM	44.035[j]	1	44.035	.604	.443	.021
	Angle LRP	37.337[k]	1	37.337	1.175	.288	.040
	Angle LLP	56.002[l]	1	56.002	2.118	.157	.070
	Angle LRM	180.836[m]	1	180.836	2.336	.138	.077
	Angle LLM	176.129[n]	1	176.129	4.993	.034	.151
Intercept	UIP	475.179	1	475.179	53.255	.000	.655
	LIP	483.357	1	483.357	175.437	.000	.862
	UIM	602.773	1	602.773	105.200	.000	.790
	LIM	1075.112	1	1075.112	148.126	.000	.841
	Perimeter Premolar	581.703	1	581.703	16.601	.000	.372
	Perimeter Molar	1014.315	1	1014.315	109.110	.000	.796
	Angle URP	69.797	1	69.797	2.368	.135	.078
	Angle ULP	76.274	1	76.274	.667	.421	.023
	Angle URM	177.427	1	177.427	4.962	.034	.151
	Angle ULM	65.936	1	65.936	.905	.350	.031
	Angle LRP	67.155	1	67.155	2.114	.157	.070
	Angle LLP	64.532	1	64.532	2.441	.129	.080
	Angle LRM	1024.895	1	1024.895	13.238	.001	.321
	Angle LLM	1096.066	1	1096.066	31.074	.000	.526
TongueVolume	UIP	78.226	1	78.226	8.767	.006	.238
	LIP	41.181	1	41.181	14.947	.001	.348
	UIM	179.105	1	179.105	31.259	.000	.527
	LIM	31.750	1	31.750	4.374	.046	.135
	Perimeter Premolar	234.001	1	234.001	6.678	.015	.193
	Perimeter Molar	616.633	1	616.633	66.331	.000	.703
	Angle URP	84.678	1	84.678	2.873	.101	.093
	Angle ULP	64.912	1	64.912	.567	.458	.020
	Angle URM	8.033	1	8.033	.225	.639	.008
	Angle ULM	44.035	1	44.035	.604	.443	.021
	Angle LRP	37.337	1	37.337	1.175	.288	.040
	Angle LLP	56.002	1	56.002	2.118	.157	.070
	Angle LRM	180.836	1	180.836	2.336	.138	.077
	Angle LLM	176.129	1	176.129	4.993	.034	.151
Error	UIP	249.834	28	8.923			
	LIP	77.145	28	2.755			
	UIM	160.434	28	5.730			
	LIM	203.226	28	7.258			
	Perimeter Premolar	981.146	28	35.041			
	Perimeter Molar	260.296	28	9.296			
	Angle URP	825.320	28	29.476			
	Angle ULP	3203.994	28	114.428			
	Angle URM	1001.210	28	35.757			
	Angle ULM	2040.282	28	72.867			
	Angle LRP	889.562	28	31.770			
	Angle LLP	740.226	28	26.437			
	Angle LRM	2167.757	28	77.420			
	Angle LLM	987.626	28	35.272			
Total	UIP	22005.705	30				
	LIP	18792.642	30				
	UIM	33467.855	30				
	LIM	34529.136	30				
	Perimeter Premolar	36925.936	30				
	Perimeter Molar	74562.270	30				
	Angle URP	919.832	30				
	Angle ULP	3285.830	30				
	Angle URM	7063.527	30				
	Angle ULM	7075.783	30				
	Angle LRP	1041.749	30				
	Angle LLP	808.063	30				
	Angle LRM	10661.215	30				
	Angle LLM	10629.307	30				
Corrected Total	UIP	328.060	29				
	LIP	118.325	29				
	UIM	339.539	29				
	LIM	234.976	29				
	Perimeter Premolar	1215.147	29				
	Perimeter Molar	876.929	29				
	Angle URP	909.998	29				
	Angle ULP	3268.906	29				
	Angle URM	1009.243	29				
	Angle ULM	2084.317	29				
	Angle LRP	926.899	29				
	Angle LLP	796.228	29				
	Angle LRM	2348.593	29				
	Angle LLM	1163.755	29				

a. R Squared = .238 (Adjusted R Squared = .211)

b. R Squared = .348 (Adjusted R Squared = .325)

c. R Squared = .527 (Adjusted R Squared = .511)

d. R Squared = .135 (Adjusted R Squared = .104)

e. R Squared = .193 (Adjusted R Squared = .164)

f. R Squared = .703 (Adjusted R Squared = .693)

g. R Squared = .093 (Adjusted R Squared = .061)

h. R Squared = .020 (Adjusted R Squared = -.015)

i. R Squared = .008 (Adjusted R Squared = -.027)

j. R Squared = .021 (Adjusted R Squared = -.014)

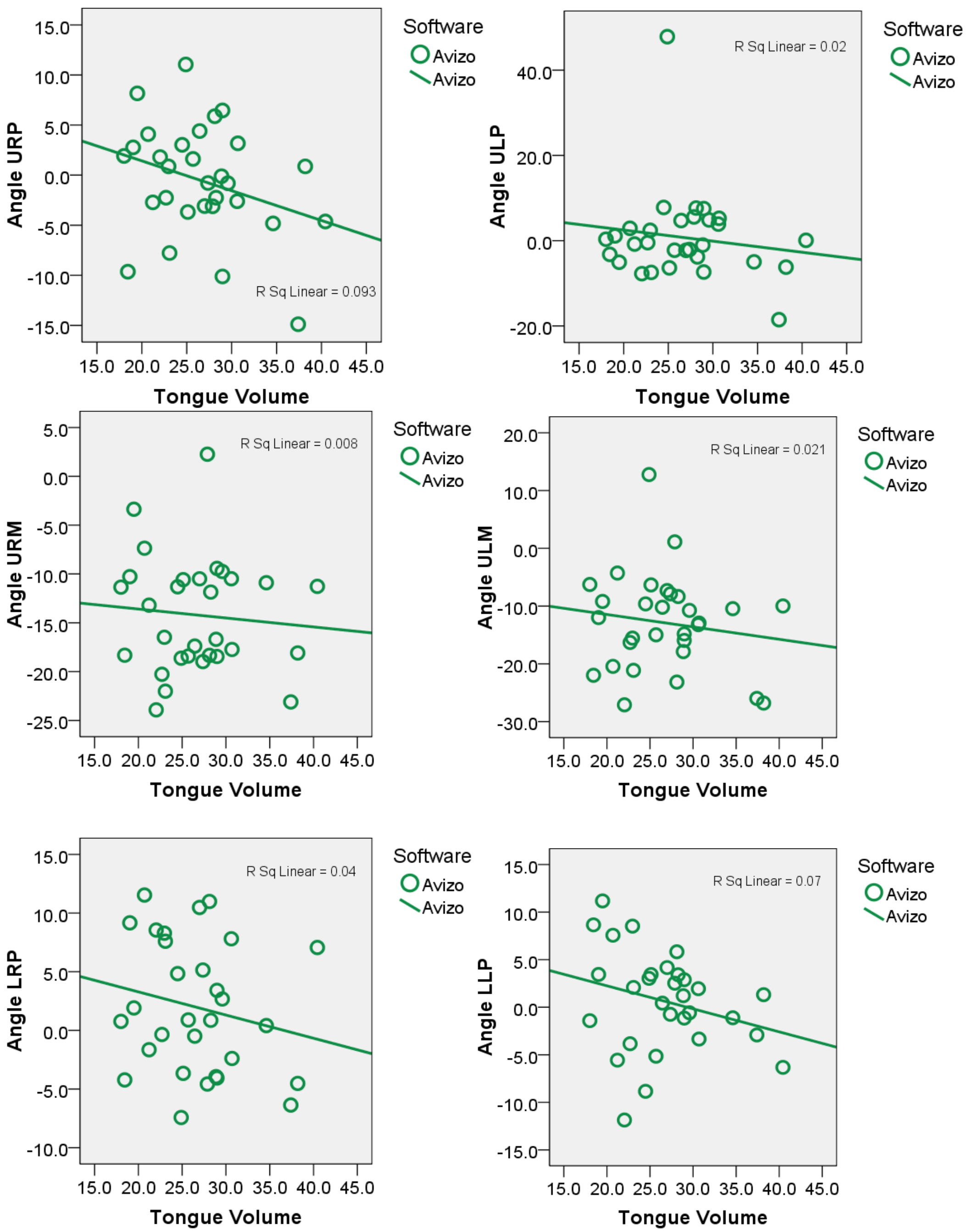
k. R Squared = .040 (Adjusted R Squared = .006)

l. R Squared = .070 (Adjusted R Squared = .037)

m. R Squared = .077 (Adjusted R Squared = .044)

n. R Squared = .151 (Adjusted R Squared = .121)

o. Software = 2


Angle URP
Tongue Volume
R Sq Linear = 0.093
Software
Avizo
Avizo
Angle ULP
Tongue Volume
R Sq Linear = 0.02
Software
Avizo
Avizo
Angle URM
Tongue Volume
R Sq Linear = 0.008
Software
Avizo
Avizo
Angle ULM
Tongue Volume
R Sq Linear = 0.021
Software
Avizo
Avizo
Angle LRP
Tongue Volume
R Sq Linear = 0.04
Software
Avizo
Avizo
Angle LLP
Tongue Volume
R Sq Linear = 0.07
Software
Avizo
Avizo

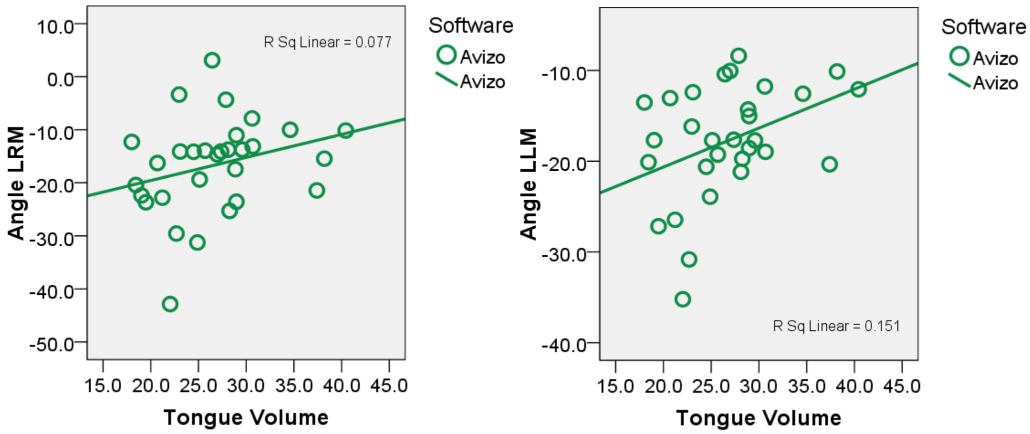


Figure A6-4 Scatterplot of tongue volume versus the axial inclination angles for all three softwares with line at total fit

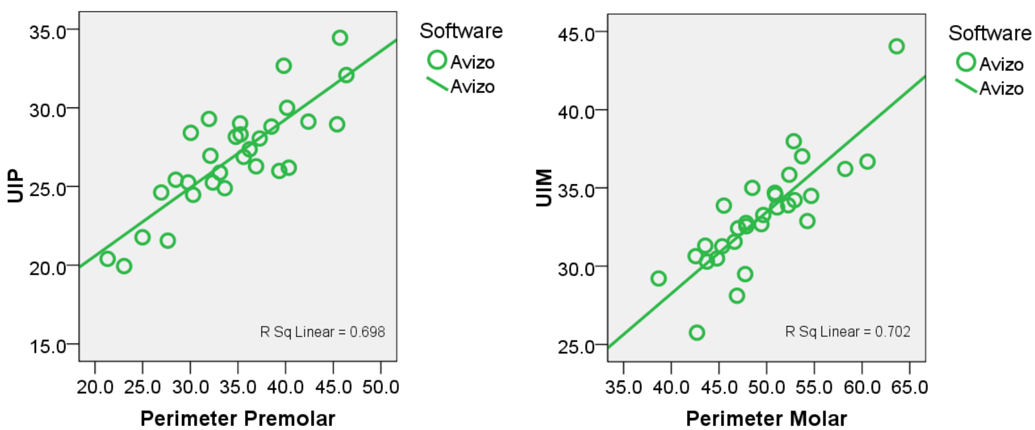


Figure A6-5 Scatterplot of palatal perimeter versus upper inter-premolar and inter-molar widths for all three softwares with line at total fit

Table A6-11 Correlation r between palatal perimeter and palatal index at premolar and molar level

Parameter	*n*	*Correlation Coefficient*
Correlation r		
Perimeter Premolar vs. Perimeter Molar	30	0.628
Perimeter Premolar vs. Palatal Index Premolar	30	0.645
Perimeter Premolar vs. Palatal Index Molar	30	0.072
Perimeter Molar vs. Palatal Index Premolar	30	0.236
Perimeter Molar vs. Palatal Index Molar	30	0.250
Palatal Index Premolar vs. Palatal Index Molar	30	0.520

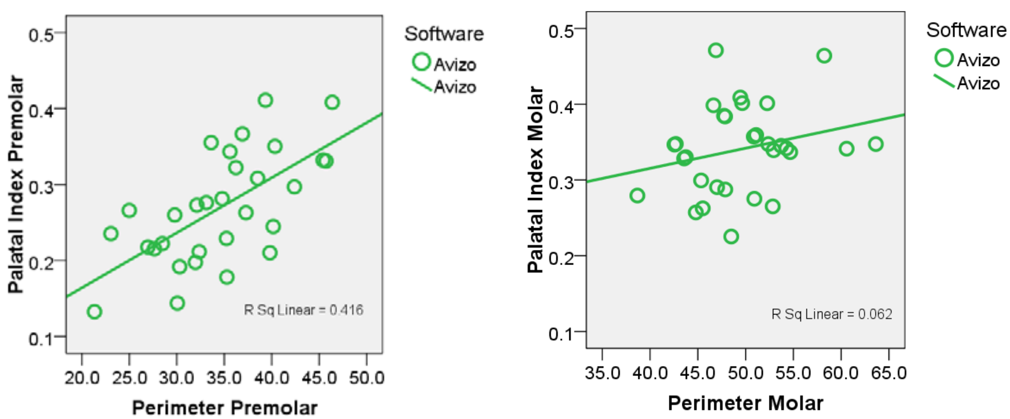


Figure A6-6 Scatterplot of palatal perimeter versus palatal index at premolar and molar level for all three softwares with line at total fit

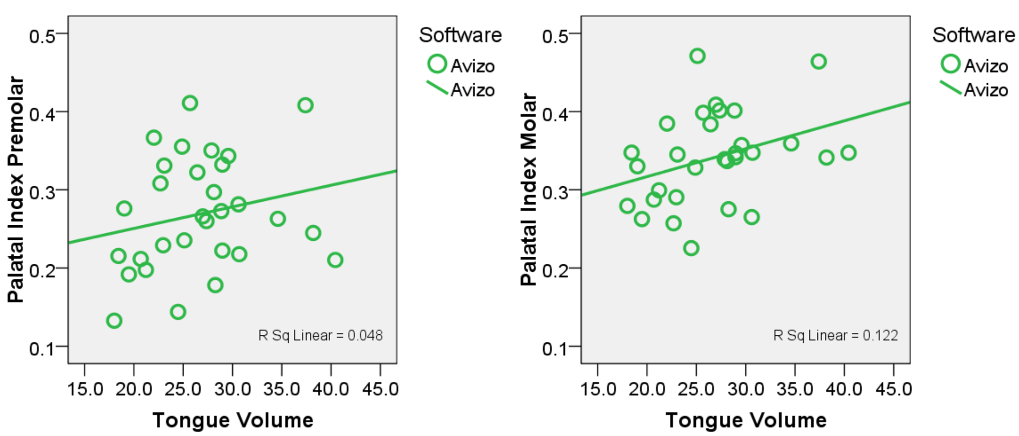


Figure A6-7 Scatterplot of tongue volume versus palatal index for all three softwares with line at total fit

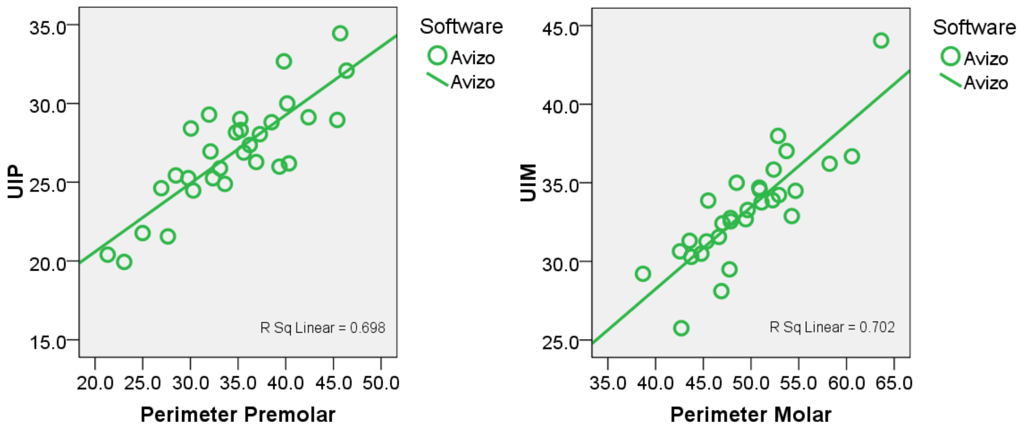


Figure A6-8 Scatterplot of palatal perimeter versus upper inter-dental widths for all three softwares with line at total fit

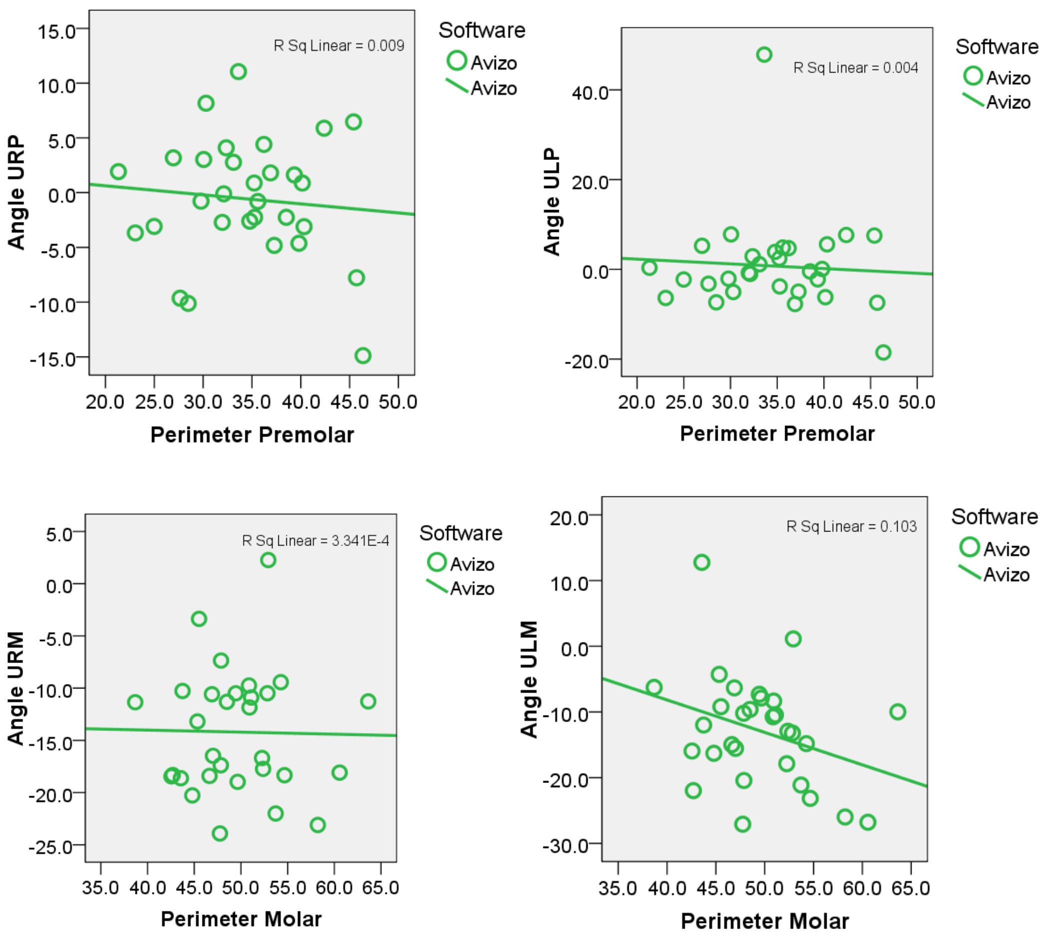


Figure A6-9 Scatterplot of palatal perimeter versus axial inclination of upper premolar and molars for all three softwares with line at total fit

Table A6-12 Regression analysis between tongue volume, age and gender with inter-dental widths, palatal perimeters and axial inclination angles

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.951	13.352[a]	16.000	11.000	.000
	Wilks' Lambda	.049	13.352[a]	16.000	11.000	.000
	Hotelling's Trace	19.420	13.352[a]	16.000	11.000	.000
	Roy's Largest Root	19.420	13.352[a]	16.000	11.000	.000
Age	Pillai's Trace	.659	1.329[a]	16.000	11.000	.321
	Wilks' Lambda	.341	1.329[a]	16.000	11.000	.321
	Hotelling's Trace	1.933	1.329[a]	16.000	11.000	.321
	Roy's Largest Root	1.933	1.329[a]	16.000	11.000	.321
TongueVolume	Pillai's Trace	.845	3.740[a]	16.000	11.000	.016
	Wilks' Lambda	.155	3.740[a]	16.000	11.000	.016
	Hotelling's Trace	5.440	3.740[a]	16.000	11.000	.016
	Roy's Largest Root	5.440	3.740[a]	16.000	11.000	.016
Gendernb	Pillai's Trace	.796	2.686[a]	16.000	11.000	.051
	Wilks' Lambda	.204	2.686[a]	16.000	11.000	.051
	Hotelling's Trace	3.908	2.686[a]	16.000	11.000	.051
	Roy's Largest Root	3.908	2.686[a]	16.000	11.000	.051

a. Exact statistic

b. Design: Intercept + Age + TongueVolume + Gendernb

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	UIP	109.791[a]	3	36.597	4.359	.013
	LIP	52.695[b]	3	17.565	6.959	.001
	UIM	223.856[c]	3	74.619	16.771	.000
	LIM	62.196[d]	3	20.732	3.120	.043
	Perimeter Premolar	420.092[e]	3	140.031	4.579	.011
	Perimeter Molar	620.025[f]	3	206.675	20.917	.000
	Palatal Index Premolar	.054[g]	3	.018	4.778	.009
	Palatal Index Molar	.025[h]	3	.008	2.964	.051
	Angle URP	123.476[i]	3	41.159	1.361	.277
	Angle ULP	429.350[j]	3	143.117	1.310	.292
	Angle URM	14.716[k]	3	4.905	.128	.942
	Angle ULM	44.502[l]	3	14.834	.189	.903
	Angle LRP	77.464[m]	3	25.821	.790	.510
	Angle LLP	110.000[n]	3	36.667	1.389	.268
	Angle LRM	190.284[o]	3	63.428	.764	.524
	Angle LLM	180.353[p]	3	60.118	1.589	.216
Intercept	UIP	392.425	1	392.425	46.745	.000
	LIP	407.103	1	407.103	161.278	.000
	UIM	575.637	1	575.637	129.376	.000
	LIM	911.781	1	911.781	137.205	.000
	Perimeter Premolar	264.368	1	264.368	8.645	.007
	Perimeter Molar	696.320	1	696.320	70.471	.000
	Palatal Index Premolar	.010	1	.010	2.655	.115
	Palatal Index Molar	.030	1	.030	10.636	.003
	Angle URP	20.560	1	20.560	.680	.417
	Angle ULP	.077	1	.077	.001	.979
	Angle URM	148.159	1	148.159	3.873	.060
	Angle ULM	51.390	1	51.390	.655	.426
	Angle LRP	49.649	1	49.649	1.520	.229
	Angle LLP	16.528	1	16.528	.626	.436
	Angle LRM	769.677	1	769.677	9.272	.005
	Angle LLM	764.217	1	764.217	20.205	.000
Age	UIP	28.963	1	28.963	3.450	.075
	LIP	9.400	1	9.400	3.724	.065
	UIM	38.027	1	38.027	8.547	.007
	LIM	27.461	1	27.461	4.132	.052
	Perimeter Premolar	6.768	1	6.768	.221	.642
	Perimeter Molar	.695	1	.695	.070	.793
	Palatal Index Premolar	.000	1	.000	.029	.866
	Palatal Index Molar	.011	1	.011	4.022	.055
	Angle URP	.139	1	.139	.005	.947
	Angle ULP	.022	1	.022	.000	.989
	Angle URM	6.681	1	6.681	.175	.679
	Angle ULM	.312	1	.312	.004	.950
	Angle LRP	20.677	1	20.677	.633	.433
	Angle LLP	53.456	1	53.456	2.025	.167
	Angle LRM	.220	1	.220	.003	.959
	Angle LLM	1.679	1	1.679	.044	.835
TongueVolume	UIP	92.157	1	92.157	10.978	.003
	LIP	32.932	1	32.932	13.046	.001
	UIM	146.454	1	146.454	32.916	.000
	LIM	28.632	1	28.632	4.309	.048
	Perimeter Premolar	384.076	1	384.076	12.560	.002
	Perimeter Molar	529.483	1	529.483	53.586	.000
	Palatal Index Premolar	.026	1	.026	6.923	.014
	Palatal Index Molar	.009	1	.009	3.136	.088
	Angle URP	33.323	1	33.323	1.102	.304
	Angle ULP	.323	1	.323	.003	.957
	Angle URM	9.315	1	9.315	.244	.626
	Angle ULM	34.536	1	34.536	.440	.513
	Angle LRP	7.773	1	7.773	.238	.630
	Angle LLP	70.615	1	70.615	2.675	.114
	Angle LRM	177.828	1	177.828	2.142	.155
	Angle LLM	120.066	1	120.066	3.174	.086
Gendernb	UIP	5.514	1	5.514	.657	.425
	LIP	1.024	1	1.024	.406	.530
	UIM	2.915	1	2.915	.655	.426
	LIM	.960	1	.960	.144	.707
	Perimeter Premolar	185.591	1	185.591	6.069	.021
	Perimeter Molar	3.036	1	3.036	.307	.584
	Palatal Index Premolar	.046	1	.046	11.978	.002
	Palatal Index Molar	.001	1	.001	.243	.626
	Angle URP	37.271	1	37.271	1.232	.277
	Angle ULP	358.102	1	358.102	3.279	.082
	Angle URM	.164	1	.164	.004	.948
	Angle ULM	.097	1	.097	.001	.972
	Angle LRP	25.015	1	25.015	.766	.390
	Angle LLP	3.059	1	3.059	.116	.736
	Angle LRM	9.446	1	9.446	.114	.739
	Angle LLM	3.098	1	3.098	.082	.777
Error	UIP	218.269	26	8.395		
	LIP	65.630	26	2.524		
	UIM	115.683	26	4.449		
	LIM	172.780	26	6.645		
	Perimeter Premolar	795.054	26	30.579		
	Perimeter Molar	256.904	26	9.881		
	Palatal Index Premolar	.099	26	.004		
	Palatal Index Molar	.074	26	.003		
	Angle URP	786.522	26	30.251		
	Angle ULP	2839.556	26	109.214		
	Angle URM	994.527	26	38.251		
	Angle ULM	2039.815	26	78.454		
	Angle LRP	849.434	26	32.671		
	Angle LLP	686.228	26	26.393		
	Angle LRM	2158.309	26	83.012		
	Angle LLM	983.402	26	37.823		
Total	UIP	22005.705	30			
	LIP	18792.642	30			
	UIM	33467.855	30			
	LIM	34529.136	30			
	Perimeter Premolar	36925.936	30			
	Perimeter Molar	74562.270	30			
	Palatal Index Premolar	2.327	30			
	Palatal Index Molar	3.585	30			
	Angle URP	919.832	30			
	Angle ULP	3285.830	30			
	Angle URM	7063.527	30			
	Angle ULM	7075.783	30			
	Angle LRP	1041.749	30			
	Angle LLP	808.063	30			
	Angle LRM	10661.215	30			
	Angle LLM	10629.307	30			
Corrected Total	UIP	328.060	29			
	LIP	118.325	29			
	UIM	339.539	29			
	LIM	234.976	29			
	Perimeter Premolar	1215.147	29			
	Perimeter Molar	876.929	29			
	Palatal Index Premolar	.153	29			
	Palatal Index Molar	.100	29			
	Angle URP	909.998	29			
	Angle ULP	3268.906	29			
	Angle URM	1009.243	29			
	Angle ULM	2084.317	29			
	Angle LRP	926.899	29			
	Angle LLP	796.228	29			
	Angle LRM	2348.593	29			
	Angle LLM	1163.755	29			

a. R Squared = .335 (Adjusted R Squared = .258)
b. R Squared = .445 (Adjusted R Squared = .381)
c. R Squared = .659 (Adjusted R Squared = .620)
d. R Squared = .265 (Adjusted R Squared = .180)
e. R Squared = .346 (Adjusted R Squared = .270)
f. R Squared = .707 (Adjusted R Squared = .673)
g. R Squared = .355 (Adjusted R Squared = .281)
h. R Squared = .255 (Adjusted R Squared = .169)
i. R Squared = .136 (Adjusted R Squared = .036)
j. R Squared = .131 (Adjusted R Squared = .031)
k. R Squared = .015 (Adjusted R Squared = -.099)
l. R Squared = .021 (Adjusted R Squared = -.092)
m. R Squared = .084 (Adjusted R Squared = -.022)
n. R Squared = .138 (Adjusted R Squared = .039)
o. R Squared = .081 (Adjusted R Squared = -.025)
p. R Squared = .155 (Adjusted R Squared = .057)

Table A6-13 Regression analysis between tongue volume and gender with inter-dental widths, palatal perimeters and axial inclination angles

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.949	13.825[a]	16.000	12.000	.000
	Wilks' Lambda	.051	13.825[a]	16.000	12.000	.000
	Hotelling's Trace	18.433	13.825[a]	16.000	12.000	.000
	Roy's Largest Root	18.433	13.825[a]	16.000	12.000	.000
TongueVolume	Pillai's Trace	.835	3.791[a]	16.000	12.000	.012
	Wilks' Lambda	.165	3.791[a]	16.000	12.000	.012
	Hotelling's Trace	5.054	3.791[a]	16.000	12.000	.012
	Roy's Largest Root	5.054	3.791[a]	16.000	12.000	.012
Gendernb	Pillai's Trace	.765	2.437[a]	16.000	12.000	.062
	Wilks' Lambda	.235	2.437[a]	16.000	12.000	.062
	Hotelling's Trace	3.249	2.437[a]	16.000	12.000	.062
	Roy's Largest Root	3.249	2.437[a]	16.000	12.000	.062

a. Exact statistic

b. Design: Intercept + TongueVolume + Gendernb

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	UIP	80.828[a]	2	40.414	4.414	.022
	LIP	43.295[b]	2	21.648	7.790	.002
	UIM	185.829[c]	2	92.915	16.321	.000
	LIM	34.736[d]	2	17.368	2.342	.115
	Perimeter Premolar	413.324[e]	2	206.662	6.959	.004
	Perimeter Molar	619.329[f]	2	309.665	32.457	.000
	Palatal Index Premolar	.054[g]	2	.027	7.419	.003
	Palatal Index Molar	.014[h]	2	.007	2.190	.131
	Angle URP	123.338[i]	2	61.669	2.117	.140
	Angle ULP	429.328[j]	2	214.664	2.041	.149
	Angle URM	8.035[k]	2	4.017	.108	.898
	Angle ULM	44.190[l]	2	22.095	.292	.749
	Angle LRP	56.787[m]	2	28.394	.881	.426
	Angle LLP	56.544[n]	2	28.272	1.032	.370
	Angle LRM	190.064[o]	2	95.032	1.189	.320
	Angle LLM	178.673[p]	2	89.337	2.449	.105
Intercept	UIP	371.312	1	371.312	40.551	.000
	LIP	427.851	1	427.851	153.964	.000
	UIM	551.876	1	551.876	96.940	.000
	LIM	940.651	1	940.651	126.835	.000
	Perimeter Premolar	275.933	1	275.933	9.292	.005
	Perimeter Molar	809.007	1	809.007	84.795	.000
	Palatal Index Premolar	.013	1	.013	3.565	.070
	Palatal Index Molar	.056	1	.056	17.720	.000
	Angle URP	26.146	1	26.146	.897	.352
	Angle ULP	.056	1	.056	.001	.982
	Angle URM	147.777	1	147.777	3.985	.056
	Angle ULM	57.480	1	57.480	.761	.391
	Angle LRP	32.499	1	32.499	1.008	.324
	Angle LLP	58.384	1	58.384	2.131	.156
	Angle LRM	929.835	1	929.835	11.631	.002
	Angle LLM	876.901	1	876.901	24.035	.000
TongueVolume	UIP	76.052	1	76.052	8.306	.008
	LIP	27.490	1	27.490	9.892	.004
	UIM	123.564	1	123.564	21.705	.000
	LIM	19.513	1	19.513	2.631	.116
	Perimeter Premolar	378.815	1	378.815	12.756	.001
	Perimeter Molar	542.515	1	542.515	56.863	.000
	Palatal Index Premolar	.028	1	.028	7.653	.010
	Palatal Index Molar	.014	1	.014	4.362	.046
	Angle URP	33.767	1	33.767	1.159	.291
	Angle ULP	.303	1	.303	.003	.958
	Angle URM	6.758	1	6.758	.182	.673
	Angle ULM	34.577	1	34.577	.458	.504
	Angle LRP	14.005	1	14.005	.435	.515
	Angle LLP	50.680	1	50.680	1.850	.185
	Angle LRM	182.282	1	182.282	2.280	.143
	Angle LLM	130.568	1	130.568	3.579	.069
Gendernb	UIP	2.602	1	2.602	.284	.598
	LIP	2.114	1	2.114	.761	.391
	UIM	6.724	1	6.724	1.181	.287
	LIM	2.986	1	2.986	.403	.531
	Perimeter Premolar	179.323	1	179.323	6.038	.021
	Perimeter Molar	2.697	1	2.697	.283	.599
	Palatal Index Premolar	.047	1	.047	12.846	.001
	Palatal Index Molar	.002	1	.002	.548	.466
	Angle URP	38.660	1	38.660	1.327	.259
	Angle ULP	364.416	1	364.416	3.465	.074
	Angle URM	.002	1	.002	.000	.994
	Angle ULM	.155	1	.155	.002	.964
	Angle LRP	19.450	1	19.450	.604	.444
	Angle LLP	.542	1	.542	.020	.889
	Angle LRM	9.228	1	9.228	.115	.737
	Angle LLM	2.544	1	2.544	.070	.794
Error	UIP	247.232	27	9.157		
	LIP	75.030	27	2.779		
	UIM	153.710	27	5.693		
	LIM	200.241	27	7.416		
	Perimeter Premolar	801.822	27	29.697		
	Perimeter Molar	257.599	27	9.541		
	Palatal Index Premolar	.099	27	.004		
	Palatal Index Molar	.086	27	.003		
	Angle URP	786.660	27	29.136		
	Angle ULP	2839.577	27	105.170		
	Angle URM	1001.208	27	37.082		
	Angle ULM	2040.127	27	75.560		
	Angle LRP	870.112	27	32.226		
	Angle LLP	739.684	27	27.396		
	Angle LRM	2158.529	27	79.946		
	Angle LLM	985.082	27	36.485		
Total	UIP	22005.705	30			
	LIP	18792.642	30			
	UIM	33467.855	30			
	LIM	34529.136	30			
	Perimeter Premolar	36925.936	30			
	Perimeter Molar	74562.270	30			
	Palatal Index Premolar	2.327	30			
	Palatal Index Molar	3.585	30			
	Angle URP	919.832	30			
	Angle ULP	3285.830	30			
	Angle URM	7063.527	30			
	Angle ULM	7075.783	30			
	Angle LRP	1041.749	30			
	Angle LLP	808.063	30			
	Angle LRM	10661.215	30			
	Angle LLM	10629.307	30			
Corrected Total	UIP	328.060	29			
	LIP	118.325	29			
	UIM	339.539	29			
	LIM	234.976	29			
	Perimeter Premolar	1215.147	29			
	Perimeter Molar	876.929	29			
	Palatal Index Premolar	.153	29			
	Palatal Index Molar	.100	29			
	Angle URP	909.998	29			
	Angle ULP	3268.906	29			
	Angle URM	1009.243	29			
	Angle ULM	2084.317	29			
	Angle LRP	926.899	29			
	Angle LLP	796.228	29			
	Angle LRM	2348.593	29			
	Angle LLM	1163.755	29			

a. R Squared = .246 (Adjusted R Squared = .191)
b. R Squared = .366 (Adjusted R Squared = .319)
c. R Squared = .547 (Adjusted R Squared = .514)
d. R Squared = .148 (Adjusted R Squared = .085)
e. R Squared = .340 (Adjusted R Squared = .291)
f. R Squared = .706 (Adjusted R Squared = .684)
g. R Squared = .355 (Adjusted R Squared = .307)
h. R Squared = .140 (Adjusted R Squared = .076)
i. R Squared = .136 (Adjusted R Squared = .072)
j. R Squared = .131 (Adjusted R Squared = .067)
k. R Squared = .008 (Adjusted R Squared = -.066)
l. R Squared = .021 (Adjusted R Squared = -.051)
m. R Squared = .061 (Adjusted R Squared = -.008)
n. R Squared = .071 (Adjusted R Squared = .002)
o. R Squared = .081 (Adjusted R Squared = .013)
p. R Squared = .154 (Adjusted R Squared = .091)

Table A6-14 T-Test for gender and inter-dental widths, palatal perimeters and axial inclination angles

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
UIP	F	15	26.4820	2.46238	.63578
	M	15	27.2800	4.12655	1.06547
LIP	F	15	24.2237	1.15097	.29718
	M	15	25.6753	2.44910	.63236
UIM	F	15	31.7900	2.26410	.58459
	M	15	34.6713	3.83133	.98925
LIM	F	15	33.0980	2.42895	.62715
	M	15	34.5227	3.13000	.80816
Perimeter Premolar	F	15	35.5741	5.34025	1.37885
	M	15	33.4291	7.47080	1.92895
Perimeter Molar	F	15	47.9597	3.82171	.98676
	M	15	51.1600	6.52270	1.68415
Palatal Index Premolar	F	15	.2988	.06439	.01662
	M	15	.2396	.07017	.01812
Palatal Index Molar	F	15	.3394	.04343	.01121
	M	15	.3422	.07233	.01868
Angle URP	F	15	1.1554	5.02988	1.29871
	M	15	-2.3005	5.77081	1.49002
Angle ULP	F	15	4.5327	12.73962	3.28936
	M	15	-3.0305	6.36793	1.64419
Angle URM	F	15	-13.9996	6.59031	1.70161
	M	15	-14.4123	5.34466	1.37998
Angle ULM	F	15	-12.3329	10.14620	2.61974
	M	15	-13.4650	6.72665	1.73681
Angle LRP	F	15	3.1508	6.30830	1.62880
	M	15	.7624	4.83286	1.24784
Angle LLP	F	15	1.0702	5.86275	1.51376
	M	15	.1860	4.69923	1.21334
Angle LRM	F	15	-17.1553	11.72983	3.02863
	M	15	-16.1366	5.44166	1.40503
Angle LLM	F	15	-19.0291	7.64289	1.97339
	M	15	-16.4965	4.61253	1.19095
Tongue Volume	F	15	24.37	3.64	0.94
	M	15	29.04	6.59	1.70

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
UIP	Equal variances assumed	3.054	.092	-.643	28	.525	-.79800	1.24075	-3.33955	1.74355
	Equal variances not assumed			-.643	22.848	.527	-.79800	1.24075	-3.36562	1.76962
LIP	Equal variances assumed	6.195	.019	-2.078	28	.047	-1.45168	.69871	-2.88291	-.02045
	Equal variances not assumed			-2.078	19.896	.051	-1.45168	.69871	-2.90964	.00628
UIM	Equal variances assumed	1.721	.200	-2.508	28	.018	-2.88133	1.14906	-5.23509	-.52758
	Equal variances not assumed			-2.508	22.715	.020	-2.88133	1.14906	-5.26001	-.50266
LIM	Equal variances assumed	1.298	.264	-1.393	28	.175	-1.42467	1.02296	-3.52010	.67077
	Equal variances not assumed			-1.393	26.374	.175	-1.42467	1.02296	-3.52594	.67661
Perimeter Premolar	Equal variances assumed	2.233	.146	.905	28	.373	2.14505	2.37109	-2.71191	7.00202
	Equal variances not assumed			.905	25.345	.374	2.14505	2.37109	-2.73494	7.02504
Perimeter Molar	Equal variances assumed	1.947	.174	-1.640	28	.112	-3.20030	1.95194	-7.19867	.79806
	Equal variances not assumed			-1.640	22.599	.115	-3.20030	1.95194	-7.24217	.84156
Palatal Index Premolar	Equal variances assumed	.018	.895	2.410	28	.023	.05925	.02459	.00888	.10962
	Equal variances not assumed			2.410	27.796	.023	.05925	.02459	.00887	.10964
Palatal Index Molar	Equal variances assumed	2.331	.138	-.127	28	.900	-.00278	.02178	-.04740	.04185
	Equal variances not assumed			-.127	22.933	.900	-.00278	.02178	-.04785	.04230
Angle URP	Equal variances assumed	.151	.701	1.748	28	.091	3.45583	1.97656	-.59297	7.50464
	Equal variances not assumed			1.748	27.487	.092	3.45583	1.97656	-.59637	7.50804
Angle ULP	Equal variances assumed	.498	.486	2.057	28	.049	7.56329	3.67740	.03049	15.09610
	Equal variances not assumed			2.057	20.585	.053	7.56329	3.67740	-.09367	15.22026
Angle URM	Equal variances assumed	.424	.520	.188	28	.852	.41265	2.19085	-4.07511	4.90040
	Equal variances not assumed			.188	26.855	.852	.41265	2.19085	-4.08375	4.90904
Angle ULM	Equal variances assumed	1.069	.310	.360	28	.721	1.13213	3.14317	-5.30637	7.57063
	Equal variances not assumed			.360	24.314	.722	1.13213	3.14317	-5.35062	7.61489
Angle LRP	Equal variances assumed	1.939	.175	1.164	28	.254	2.38837	2.05185	-1.81465	6.59139
	Equal variances not assumed			1.164	26.223	.255	2.38837	2.05185	-1.82752	6.60425
Angle LLP	Equal variances assumed	1.129	.297	.456	28	.652	.88423	1.94001	-3.08970	4.85816
	Equal variances not assumed			.456	26.733	.652	.88423	1.94001	-3.09820	4.86666
Angle LRM	Equal variances assumed	4.563	.042	-.305	28	.763	-1.01866	3.33867	-7.85762	5.82029
	Equal variances not assumed			-.305	19.759	.763	-1.01866	3.33867	-7.98845	5.95112
Angle LLM	Equal variances assumed	2.185	.151	-1.099	28	.281	-2.53260	2.30491	-7.25400	2.18880
	Equal variances not assumed			-1.099	23.004	.283	-2.53260	2.30491	-7.30063	2.23543
Tongue Volume	Equal variances assumed	2.809	.105	-2.401	28	.023	-4.67	1.94	-8.65	-0.68
	Equal variances not assumed			-2.401	21.811	.025	-4.67	1.94	-8.70	-0.63

Table A6-15 Non-Parametric, Kruskal-Wallis for gender by tongue volume and palatal perimeter at the molar level

Ranks

	Ge...	N	Mean Rank	Sum of Ranks
Tongue Volume	M	15	19.00	285.00
	F	15	12.00	180.00
	Total	30		
Perimeter Molar	M	15	18.00	270.00
	F	15	13.00	195.00
	Total	30		

Test Statistics[b]

	Tongue Volume	Perimeter Molar
Mann-Whitney U	60.000	75.000
Wilcoxon W	180.000	195.000
Z	-2.178	-1.555
Asymp. Sig. (2-tailed)	.029	.120
Exact Sig. [2*(1-tailed Sig.)]	.029[a]	.126[a]

a. Not corrected for ties.

b. Grouping Variable: Gendernb