9-2016

A CBCT Study of Pharyngeal Airway Changes Due to Fixed Functional Appliances

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School of Dentistry
in conjunction with the
Faculty of Graduate Studies

A CBCT Study of Pharyngeal Airway Changes Due to Fixed Functional Appliances

by

Scott T. Peterson

A thesis submitted in partial satisfaction of
the requirements for the degree
Master of Science in Orthodontics and Dentofacial Orthopedics

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September 2016

Each person whose signature appears below certifies that this dissertation in his opinion is adequate, in scope and quality, as a dissertation for the degree Master of Science in Orthodontics and Dentofacial Orthodontics.

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ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Greg Olson for being a great mentor and help throughout this program and my research. I would also like to thank the other members of my committee, Dr. Joseph Caruso and Dr. James Farrage, for their guidance and advice throughout this process. It wouldn't have been possible without your mentorship.

To my wife, your love and support through this long road of school and research has been the key to my success and I couldn't have done it without you by my side. Thank you for helping me as well as being a great mother to Taylor and Sienna. Thank you for helping me fulfill my goals and dreams.

I also would like to thank my extended family as well for your constant encouragement and prayers. Finally, most of all, thanks to my Father in Heaven for his countless blessings that he pours upon my family and me.

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ABBREVIATIONS

CBCT	Cone-Beam Computed Tomography
PAS	Pharyngeal Airway Space
ADHD	Attention-Deficit/Hyperactivity Disorder
OSAS	Obstructive Sleep Apnea Syndrome
MARA	Mandibular Anterior Repositioning Appliance
ANS	Anterior Nasal Spine
PNS	Posterior Nasal Spine
P	Palate Point
Et	Tip of Epiglottis
V	C3 Point
PPW	Posterior Pharyngeal Wall
APW	Anterior Pharyngeal Wall
T1	Initial Date of Treatment
T2	Final Date of Treatment

ABSTRACT OF THE THESIS

A CBCT Study of Pharyngeal Airway Changes Due to Fixed Functional Appliances

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Master of Science in Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2016
Dr. Gregory Olson, Chairperson

Introduction: The purpose of this retrospective study, using head and neck Cone-Beam Computed Tomography (CBCT) images, was to measure and compare volumetric, area, and linear changes of the pharyngeal airway space in patients treated with a MARA or Herbst Class II correction appliances.

Materials and Methods: Twenty-six patients treated with a MARA (mean age 13.2), nine with a Herbst (mean age 12.12) , and a control group twenty-five orthodontically treated class I patients (mean age 13.11). T1 and T2 CBCT images were measured and compared between the three groups for area, length, and width measurements along the velo-, oro-, and hypopharyngeal airway as well as the overall volume.

Results: The ANCOVA showed a significant decrease in the change of B length in the MARA and Herbst groups compared to the control group (P=.003). An additional ANCOVA taking gender, expansion, skeletal and dental classifications into account showed no significant changes in all the measurements in the treatment and control groups.

Conclusions: The MARA and Herbst appliance did not show any significant changes in the overall volume, areas, or linear measurements along the pharyngeal airway.

CHAPTER ONE

REVIEW OF THE LITERATURE

Abnormal constriction of the pharyngeal airway space (PAS) is a common occurrence in many patients presenting to the orthodontist. Adolescent patients oftentimes present with decreased pharyngeal airway space, which can be correlated to a variety of conditions including obstructive sleep apnea, mouth breathing, increased size of the tonsils and adenoids, Attention Deficit Hyperactivity Disorder (ADHD), as well as abnormal craniofacial development. [5,6,7,8,9] Approximately 8-10% of school-age children snore with an incidence of 1-3% having obstructive sleep apnea syndrome (OSAS). [9]

Measurement Techniques of the Pharyngeal Airway Space

In the past, most clinicians have measured the pharyngeal airway space from an anteroposteior direction with use of the lateral cephalogram. The introduction of cone beam computed tomography into diagnosis and treatment planning in orthodontics has widened the scope and analysis of the PAS to three dimensions.

Kaur et al took 45 patients from the age of 18-25 and evaluated the airway space in Class I, II, and III patients according to their ANB Class I (ANB angle 2-4°), Class II (ANB angle >4°), Class III (ANB angle ≤2°). They used lateral cephalograms to measure as well as CBCT and evaluated the reliability of each. They found that in the sagittal measurements there was no statistically difference measuring between the two different methods at the nasopharynx, oropharynx, and hypopharynx.[17] The benefit of the CBCT is the ability to measure both the width and the depth of the pharyngeal airway space accurately.

A study performed by Mattos et al showed that a CBCT evaluation of the airway can accurately be made by a resident, orthodontist, or an oral radiologist. They found that the most reliable measurements were anteroposterior linear measurements; cross-sectional areas at the levels of the palatal plane, soft palate, and tongue; and sagittal area and volume. Other measurements were statistical significantly accurate at the level of the vallecula and minimum axial area. [37]

Affected Population

Obstructive sleep apnea syndrome can be a result of a variety of causes. Children with OSAS are diagnosed through overnight polysomnographic examinations, which will be performed if patients exhibit frequent fevers, snoring, daytime sleepiness, inactivity, loss of concentration and other symptoms. [17] One of the main characteristics of OSAS in children is snoring. [13] In many children, it is often associated with enlarged adenoids and tonsils, which tend to decrease at the age of ten. [7] It has been shown that many children with OSAS also have a retrognathic mandible showing as a class II skeletal pattern. [10] OSAS has been treated with mandibular advancing devices (MAD), orthognathic mandibular advancement, continuous positive airway pressure (CPAP) machines, and adenotonsillectomies in children.

The importance of the airway in proper craniofacial development in children is becoming more and more recognized and it may be beneficial to recognize these symptoms in patients at a younger age. Certain children are more susceptible to a narrowing of the pharyngeal airway space (PAS). Many studies have been done to evaluate the different vertical growth patterns in association with skeletal anteroposterior position and narrowing of the PAS.

Freitas et al attempts to clarify this debate about whether the different growth pattern or the malocclusion affects the airway space. The authors' study included 80 untreated patients with a mean age of 11.64, who had not received any previous tonsil or adenoid surgery and had not received any orthodontic treatment. The study comprised of four groups: Class I normal growth, Class I vertical growth, Class II normal growth, and Class II vertical growth. They used McNamara's airway analysis on lateral cephalograms to make their measurements of the airway and compare them to the different groups. [14]

The different patients were classified in their growth pattern by using previously establish standards of normal and vertical growers using FMA, SN.GoGn, and NS.Gn where the vertical growers had a value larger than the mean + 1 Standard Deviation (SD) in each category.

Freitas et al showed that the Class I and Class II groups with vertical growth patterns had a statistically significant smaller upper pharyngeal airway spaces than the Class I and Class II normal growers. They showed that there wasn't a significant difference in the two different malocclusion patterns. There were no significant intergroup differences found in the lower pharyngeal airway space. This study was merely a cephalometric study and did not involve airway flow or three-dimensional analysis and could be added to this study and other studies in the future. [16]

Wang et al also tested the pharyngeal airway space in Class II patients with different vertical growth patterns. Their study showed similar results to Freitas in that the patients with a vertical growth pattern had a narrower pharyngeal airway compared to those with normal or horizontal growth patterns.[18]

Kaur's study utilizing both lateral cephalograms and CBCT measurements showed that the Class II patients had a statistically significant narrower naso, oro, and hypopharynx ($P<.05$) compared to the class I patients. [17]

Furthermore, Iwasaki et al evaluated the upper airway obstruction in Class II children with different growth patterns but also tested air flow. They took 40 Class II children, 20 brachyfacial and 20 dolichofacial, and utilizing a fluid-mechanical simulation, measured the airway velocity and pressure using three-dimensional images of the airway. Their results showed that the size of the upper airway didn't statistically differ; however, the simulated maximal pressure and velocity of the dolichofacial type were significantly higher compared to the brachyfacial type. This shows that the dolichofacial type had more obstructed areas of airflow in the upper airway spaces and more mouth breathers. [32]

In 2013, Zheng et al compared the pharyngeal airway space in Class I, Class II, and Class III patients. They took 20 patients that fit their criteria for each angle classification and measured the most constricted space in the pharyngeal airway using cone beam computed tomography. The authors found differences between the different anteroposterior skeletal patterns. They found that the nasopharyngeal airway in the Class II patients was significantly less than the class I and class III patients. [20]

Claudino et al measured the velopharynx, oropharynx, and nasopharynx in adolescents in all three skeletal groups, Class I, Class II, and Class III. Their findings are similar to many other studies in the fact that the Class II group had a statistically smaller pharyngeal airway areas compared to the other two groups. They also showed that as the ANB increased the airway volume decreases in the lower pharyngeal portion and the velopharynx in both males and females.[21]

Grauer et al found that there was no similarity in airway volumes related to vertical facial proportions in their 62 non-growing patients. He did find that there was a direct correlation of the volume of the inferior component of the PAS and the anteroposterior jaw relationship. They also found that there was a forward inclination of the airway in Class II skeletal patients. [22]

Oh et al also showed, similar to Grauer et al, that in adolescents with skeletal class II, there was a more backward orientation to the Frankfort Horizontal plane. [23]

Orthodontic Treatment Options and Effect on PAS

A prospective longitudinal study performed by Ghodke et al measured the effects of a twin-block functional appliance on the pharyngeal airway passage in Class II malocclusion patients. The researchers took 38 Class II malocclusions subjects between the ages of 8 to 14 and split them into a control and treatment group of 18 and 20 patients respectively. The treatment group received Class II correction by way of a twin-block appliance and the control group only had sectional fixed orthodontics for correction of mild crowding. [26]

The researchers measured the pharyngeal airway passage (PAP) dimension as well as the Posterior Pharyngeal Wall Thickness (PPWT) off of lateral cephalograms taken at the beginning of treatment and approximately six months post treatment.

The skeletal changes were as expected. The change in the effective maxillary length in the treatment group subjects was significantly decreased compared to the control group subjects. (P<.01). The SNB angle was significantly greater in the treatment group as well as the length of the mandible. The FMA also increased in the treatment group. (P<.01)

The PAP dimensional changes were not as extensive as the skeletal changes. There was an increase in the depth of the oropharynx by 1.54 mm in the treatment group compared to a change of .89 mm in the control group. The depth of the hypopharynx was improved significantly in the treatment group. There were other favorable changes but none that were statistically significant. They also showed that the PPWT was maintained in the treatment group.

Their study helped show that the oropharynx and hypopharynx to have an increase in the sagittal dimension with twin-block appliance. The length, thickness, and inclination of the soft palate improved after the correction of the Class II malocclusion subjects. [26]

Jena et al performed a similar experiment that compared the pharyngeal airway passage (PAP) on 16 healthy Class I malocclusions, 16 Class II malocclusion subjects treated with edgewise, 16 Class II malocclusion subjects treated with a Mandibular Protraction Appliance-IV (MPA-IV), and the last group of 21 Class II malocclusion subjects that were corrected by twin-block appliance. Their study found many significant differences with the two functional appliances compared to the control groups but found that the twin-block treated groups created the most improvement of PAP dimensions among all the Class II malocclusions. [27]

Han et al utilized a bionator to treat 24 skeletal Class II patients (ANB>5) and evaluated the pharyngeal airway changes with the use of lateral cephalograms. They had a control group of Class I treated patients with similar ages as the treatment group. Since this study just utilized the anteroposterior measurements from the lateral cephalograms it does not take into account the transverse dimensions in the airway and the changes that could have been occurring laterally. Their study further confirmed the increased change in the oropharyngeal region with treatment of a functional appliance and that change was maintained throughout the growth of the patients. [28]

Another method of treating Class II malocclusions is the use of headgear. Kirjavainen tested the effects of cervical headgear on the upper airway dimensions in forty adolescents with the mean age of 9.1 years with Class II division I malocclusion. The headgear was activated at 500 grams and was expanded 10 mm. The results showed a wider nasopharyngeal space than in the controls but narrower oro and hypopharyngeal spaces. The retropalatal area was widened by the treatment but no significant anteroposterior differences were noted with the use of the cervical pull headgear. [29] The use of the expanded inner bow show similar results in the increase of the nasopharyngeal airway as establish by other studies measuring palatal expansion and airway spaces. [54]

Fixed Functional Appliances

The term functional appliance refers to a variety of removable or fixed appliances designed to alter the mandibular position both sagittally and vertically, resulting in orthodontic and orthopedic changes.[24]

It has been proposed by some authors to use a fixed functional appliance to improve the airways in patients with a skeletal Class II pattern.[30] Itzhaki et al concluded in their study that the Herbst Mandibular Advancement Splint which is similar to the fixed functional appliance in kids may be a moderately effective long-term treatment for patients with OSA. [31]

MARA

The Mandibular Anterior Repositioning Appliance is a tooth-borne function appliance for use in correction of Class II skeletal and dental patients that moves the jaw forward into a Class I occlusion. Pangrazio et al performed a study on 30 Class II patients comparing pretreatment to post treatment cephalometric dental and skeletal changes. They were compared with 21 Class II control subjects from the Michigan longitudinal growth study records. Their study concluded that the MARA is effective in treating Class II malocclusions and resulted in an overall 5.8 mm Class II molar correction by 47% skeletal change (2.7 mm) and a 53% dental change (3.1 mm). The skeletal change was completely due to mandibular growth and also showed that the MARA had no headgear effect on the maxilla like the Herbst appliance. [33,35]

A meta-analysis on the mandibular effects of the MARA appliance in patients with Class II malocclusions was published in 2014. The analysis found seven retrospective clinical controlled studies that compared MARA with controls. Three of the studies had medium quality and the rest were low quality. The analysis determined that there was a significant difference in the total mandibular unit length (1.16mm/yr) and ramus height (1.58 mm/yr) and an increase in corpus length (.21 mm/year.). Analyses of the long-term showed similar results in all three categories. [35] No measurements were taken of the changes in the airway and there lacks any research measuring the effects of the MARA on PAS.

Herbst Appliance

Schutz et al used an acrylic-splint Herbst appliance along with a rapid palatal expander for 16 Class II patients. They were determining the modifications in sleep pattern and in craniofacial morphology of adolescents with mandibular advancement with the Herbst as well as palatal expansion. The 16 subjects were selected during their maximum pubertal growth (12.6 years [±11.5 months]). They took lateral cephalograms, magnetic resonance imaging prior to and after treatment, as well as four polysomnographic recordings obtained with pressurized nasal cannulae that were analyzed for variance.[30]

Schutz's study showed that sleep efficiency, sleep latency, rapid eye movement (REM) sleep latency, and percentage of REM sleep remained stable. They did find that there was a significant reduction in the number of respiratory effort-related arousals (7.06 ± 5.37 to 1.31 ± 1.45 per hour of sleep) due to an increase in the airway volume. Therefore, in the short term, at least a year post treatment, the increase in airway space (posterior airway space enhanced by 3.2 mm) improved the nighttime breathing associated with correction of the mandibular retrognathism (SNB increased (2.50°) ANB angle diminished (2.6°)). The patients had improved respiration and less effort expended in breathing during sleep. The authors reported that the mouth breathing and persistent snoring, which are indicative symptoms of OSA, reported by parents and verified by the evaluations, ceased after treatment. It is difficult in this study to determine whether the benefits were from the Herbst appliance or from the palatal expansion.[30]

Another study was performed that just measured the effects of the Herbst appliance on the airway. Iwasaki et al used three-dimensional cone-beam computed tomography to analyze the enlargement of the pharyngeal airway spaces in Class II patients utilizing a Herbst appliance. They used twenty-four Class II subjects with an ANB $\geq 5°$ and had a control group of twenty Class I subjects of the same age receiving edgewise treatment. They used CBCT images taken before and after treatment to measure the naso, oro, and laryngopharyngeal airway volumes. In the treatment group, the ANB change before and after treatment was significantly greater than the control group. The overall pharyngeal volume was similar in the Herbst and control groups before and after treatment. However, the difference in the changes with treatment and growth were statistically significant in the patients treated with the Herbst appliance, particularly in the Total Pharyngeal Airway Volume, Oropharyngeal Airway Volume, and Laryngopharyngeal Airway Volume, but not in the Retropalatal Pharyngeal Airway Volume.[32]

Conclusions

Abnormal constriction of the pharyngeal airway is a condition that needs to be recognized and assessed by orthodontists. Studies have shown that it is most likely to happen in children with a class II skeletal pattern with a vertical growth pattern. Many types of functional appliance and palatal expanders have shown to aid in the opening of the pharyngeal airway. To this date, very little studies have been conducted to test the effectiveness of the fixed functional appliances on the pharyngeal airway dimensions and their long-term benefits.

CHAPTER TWO

A CBCT STUDY OF PHARYNGEAL AIRWAY CHANGES DUE TO FIXED FUNCTIONAL APPLIANCES

Introduction

Constriction of the pharyngeal airway space (PAS) is a common occurrence in many adolescent patients who seek orthodontic treatment. Inadequate airway has been linked to abnormal craniofacial development.[1,2] Early studies performed by Harvold on infant rhesus monkeys showed that the occlusion of nasal respiration caused narrowing of the dental arches, decreases in maxillary arch length, anterior cross bite, maxillary overjet, and increase in anterior facial height. Experimentally induced abnormal nasal respiration showed long-term changes in oral-facial muscles.[3] Decreased PAS has also been shown to be correlated with a variety of conditions including obstructive sleep apnea, mouth breathing, increased size of the tonsil and adenoids, attention-deficit/hyperactivity disorder (ADHD), as well as other improper craniofacial development.[4,5,6,7,8,9] Approximately 8-12% of school-age children snore with an incidence of 1-3% having obstructive sleep apnea syndrome (OSAS).[10,11]

Affected Population

Obstructive sleep apnea syndrome (OSAS) can be a result of a variety of causes. One characteristic of OSAS is prolonged upper airway obstruction. The resultant reduced airflow presents the classic symptoms of snoring, apnea, and open mouth. The most common causes of OSAS are nasal obstruction, adenotonsillar hypertrophy, body mass, cleft palate, craniofacial disorders, low tongue posture, and genetic basis.[12,13] Studies evaluating pediatric obstructive sleep apnea have shown that abnormal narrowing of the naso, oro, and hypopharynx can lead to abnormal air exchange during sleep and can lead to clinical signs.[14] It has been shown that many children with OSAS also have class II skeletal pattern and retrognathic mandible.[9] Studies have shown that children with a vertical growth pattern and a class II skeletal pattern have statistically significant smaller pharyngeal airway spaces than normal growers.[15,16,17,18,19,20,21]

The importance of a patent airway is becoming more and more recognized in proper craniofacial development in children. It may be beneficial to recognize these symptoms in patients at a younger age. Children with a retrognathic mandible are more susceptible to a narrowing of the pharyngeal airway space. Children with a vertical growth pattern have been shown to have more of a constricted airway than patients with a horizontal or normal growth pattern in linear and volumetric measurements as well as airflow based upon fluid-mechanical simulation tests.[14,16,17] In addition to the vertical growth patterns, studies show a significant decrease in pharyngeal airway space measurements in skeletal class II patients compared to class I and class III.[18,19,20,21,22,23]

Orthodontic Treatment Options and Effect on PAS

For years, orthodontists have been utilizing removable functional appliances such as the Frankel Appliances, Bionators, and Twin Block Appliances to treat skeletal class II patients by advancing the mandible.[24,25] Studies have been performed on adolescents measuring the antero-posterior distance of the pharyngeal airway space on lateral cephalograms after the use of removable functional appliances such as the twin-block appliance, cervical headgear, and other removable mandibular advancement appliances. Findings have shown an increase in the antero-posterior PAS after treatment with these appliances.[26,27,28,29] Increasing the length of the PAS may improve the airway in these patients.

It has been proposed by some authors that the use of a fixed functional appliance may also improve the airway in patients with a skeletal class II pattern and decreased PAS.[30,31] Iwasaki et al showed the airway changes after use of a Herbst appliance in twenty-four Class II subjects compared to a control group of twenty Class I subjects of the same age. They measured Cone-Beam Computed Tomography (CBCT) images to show a positive effect in the total pharyngeal, oropharyngeal, and laryngopharyngeal airway volume.[32]

The Mandibular Anterior Repositioning Appliance (MARA) is a tooth-borne functional appliance for use in correction of Class II skeletal and dental patients that moves the jaw anteriorly. Research demonstrates that the MARA is effective in treating patients with skeletal Class II and a significant difference in the total mandibular unit length, ramus height, and corpus length, with a 47% skeletal change and 53% dental change. [33,34] [35]

The purpose of the current retrospective study, using head and neck CBCT images, was to measure and compare three-dimensional changes of the pharyngeal airway space produced by the MARA and Herbst Class II correction appliances.[36]

Materials and Methods

Patient Selection

This study was approved by the Institutional Review Board (IRB) of Loma Linda University (LLU), Loma Linda, CA. All patients involved in this study received comprehensive orthodontics treatment in the Graduate Orthodontic Clinic at Loma Linda University. The treatment group consisted of 26 MARA patients (19 males, 7 females) and 9 Herbst patients (4 males, 5 females). The inclusion criteria for the treatment group were between the age of 10-18, use of a MARA or Herbst appliance as a part of comprehensive orthodontic treatment, and available T1 and T2 CBCT records. Inclusion criteria for the control group included skeletal class I (1°<ANB<4°) and Angle dental class I, age and gender matched to the treatment group, and comprehensive treatment without mechanics to alter the position or posture of the mandible. Exclusion criteria for the treatment and control group were:

- no phase 1 only treatment
- no orthognathic surgery
- no syndromic craniofacial abnormalities

CBCT Image Acquisition and Data Collection

All CBCT images were taken at LLU using the NewTom 3G^{TM} or NewTom 5G^{TM} (Verona, Italy). Images were taken with a 15 cm x 18 cm field of view (FOV) and a pulsed exposure time of 5 seconds set to 110kV. All patients were instructed to occlude into maximum intercuspation, hold their tongue in resting position, and avoid swallowing, breathing or moving their head or tongue during image acquisition. Images captured were exported in Digital Imaging and Communications in Medicine (DICOM) format then imported into Dolphin 3D™ 11.7 (Dolphin Imaging Solutions, Chatsworth, CA, USA) for three-dimensional evaluation of volumetric, cross-sectional area, and linear measurements of the pharyngeal airway space.[37] All patients also had a T1 and T2 lateral cephalogram taken on a Sirona Orthopos XG Plus™ machine (Dentsply Sirona, York, PA, USA) and imported into Dolphin Imaging™ software (Dolphin Image Solutions, Chatsworth, CA, USA).

All lateral cephalograms were digitized using Dolphin Imaging™ (Figure 1). Steiner Analysis landmarks utilized were Nasion, A point, B point, Tip of Maxillary Incisor, and Tip of Mandibular Incisor. The ANB was used to determine skeletal classification. Overjet was determined by the horizontal distance from the tip of the maxillary incisor and the tip of the mandibular incisor as determined in the Ricketts Analysis.[38]

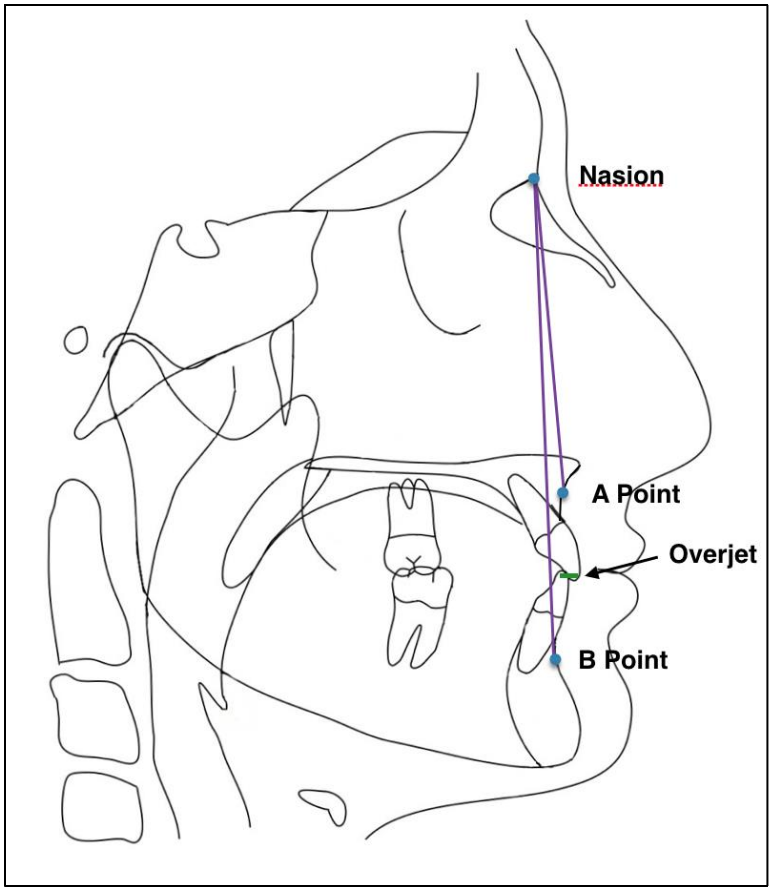


Figure 1. Steiner Analysis ANB Angle and Overjet Measurements.

Additional cephalometric landmarks were identified on each CBCT using Dolphin 3D^{TM} (Table 1). These landmarks were used to identify the upper and lower limits of the airway space as well as for references to the relevant planes for calculation of the cross-sectional area, length, and width at each plane (Table 2). A total of thirteen measurements were made on each patient at each time point (Table 3).

The 3D volume was first oriented so that the pitch, in the sagittal plane, of the palatal plane (ANS-PNS) was parallel to the bottom of the computer screen. The roll, in the frontal plane, was oriented to have the lower border of the orbits parallel with the bottom of the screen. The cephalometric landmarks were identified using the Multiplanar View

(MPR) (Figure 3). The cephalometric landmarks were identified using the axial and sagittal views of the MPR of the software viewer. On the sagittal view, ANS was marked as the most anterior tip of the hard palate using the Landmark Tool. The marked point on the sagittal view was then adjusted to fit on the axial view for ANS. PNS was identified as the most posterior tip of the hard palate on the sagittal view and marked using the Landmark Tool. It was then adjusted in the axial view. Palate point (P point) was identified as the most inferior tip of the soft tissue palate from the sagittal view after scrolling through all sagittal sections. P point was marked using the Landmark Tool and adjusted as necessary from the axial view. The locations of the tip of epiglottis point was identified as the most superior point of the epiglottis and V point was identified as the most anterior inferior point of the third cervical vertebrae bone marked on the sagittal view and adjusted accordingly on the axial views.

Table 1. *Cephalometric Landmarks*

Cephalometric Landmark		**Definition**
Anterior nasal spine	ANS	The most anterior point of the anterior nasal spine
Posterior nasal spine	PNS	The most posterior point of the posterior nasal spine
Palate point	P	The most inferior tip of the soft palate
Tip of epiglottis	Et	The most superior point of the epiglottis
C3 point	V	The most anterior inferior point of the third cervical vertebrae

Table 2. *Cephalometric Planes*

Planes	**Definitions**
Plane A	Plane extending from PNS to PPW*, parallel to palatal plane
Plane B	Plane extending from P Point to PPW, parallel to palatal plane
Plane C	Plane extending from Et Point to PPW, parallel to palatal plane
Plane D	Plane extending from V Point to APW**, parallel to palatal plane

*Posterior Pharyngeal Wall
**Anterior Pharyngeal Wall

Table 3. *Airway Measurements*

Measurements	Definition
Volume	Volume of airway, upper limit defined at the level of the palatal plane, lower limit defined by Plane D, lateral limits defined by interior soft tissue wall of pharynx and airway space
A Area	Cross-sectional area of airway at Plane A, limits defined by interior soft tissue wall of pharynx and airway space
A Length	Longest anteroposterior distance along Plane A
A Width	Widest lateral width distance along Plane A
B Area	Cross-sectional area of airway at Plane B, limits defined by interior soft tissue wall of pharynx and airway space
B Length	Longest anteroposterior distance along Plane B
B Width	Widest lateral width distance along Plane B
C Area	Cross-sectional area of airway at Plane C, limits defined by interior soft tissue wall of pharynx and airway space
C Length	Longest anteroposterior distance along Plane C
C Width	Widest lateral width distance along Plane C
D Area	Cross-sectional area of airway at Plane D, limits defined by interior soft tissue wall of pharynx and airway space
D Length	Longest anteroposterior distance along Plane D
D Width	Widest lateral width distance along Plane D

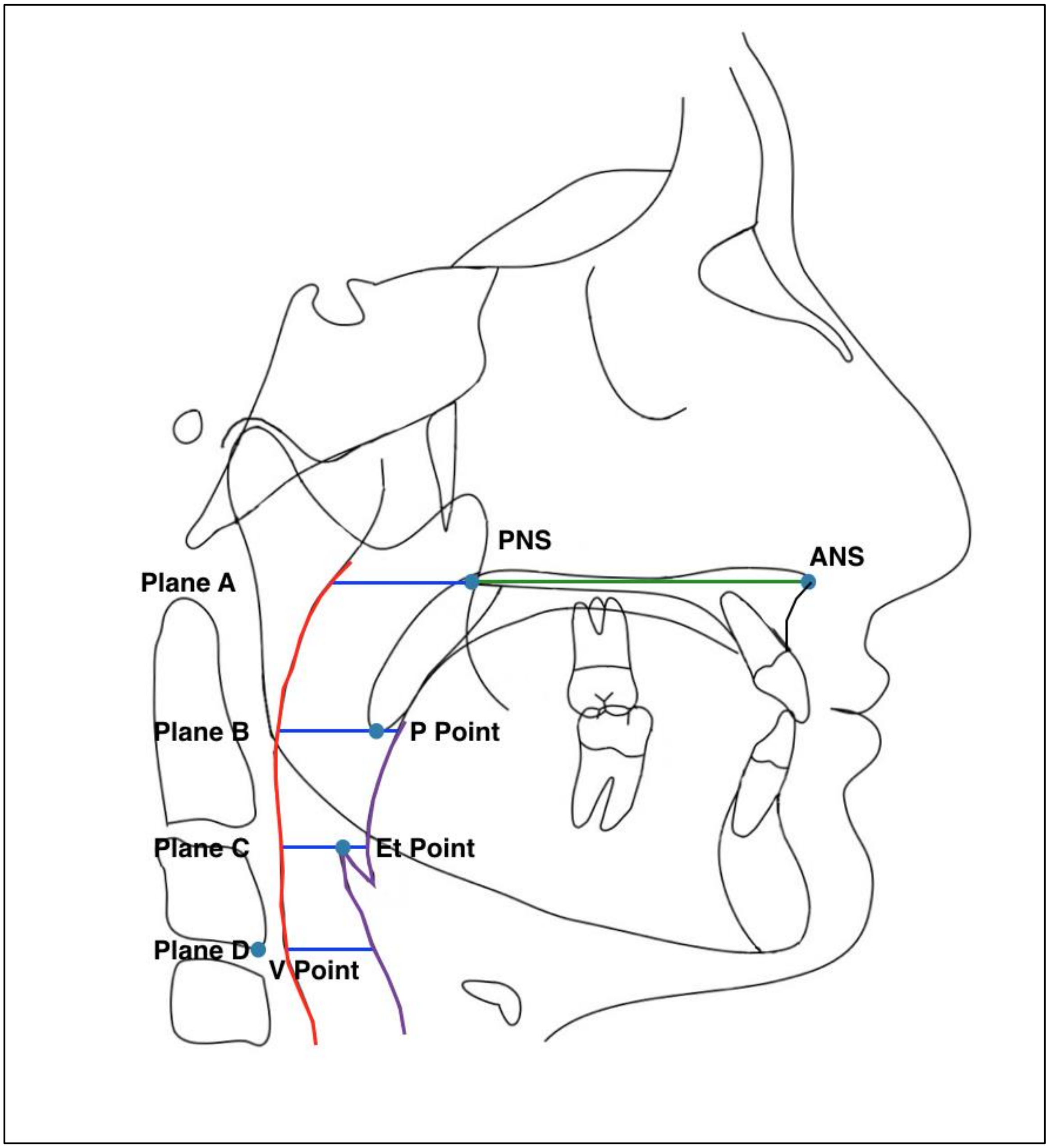


Figure 2. Cephalometric landmarks and pharyngeal airway planes.

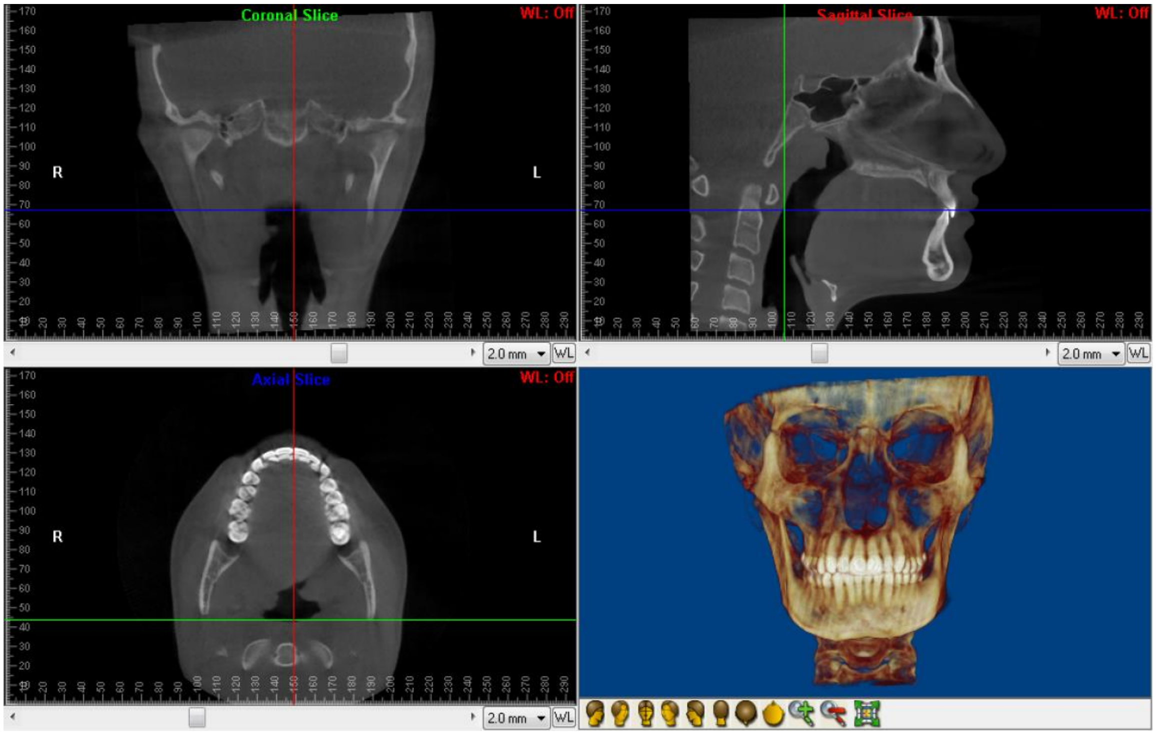


Figure 3. Multiplanar View. Upper left depicts coronal view, upper right depicts sagittal view, lower left depicts axial view, and lower right depicts 3D view.

The palatal plane (ANS-PNS) is a plane that connects ANS and PNS. This plane was used as our reference plane as it is a consistent hard-tissue reference (Figure 2).

Five reference planes were constructed to measure the cross-sectional areas, lengths, and widths along the airway (Table 2). Plane A represents the upper boundary of the velopharynx. Plane B represents the boundary between the velopharynx and the oropharynx. Plane C represents the boundary between the oropharynx and the hypopharynx, and plane D represents the lower boundary of the hypopharynx.

Volume acquisition was made using the Dolphin 3D^{TM} Sinus Airway Tool. This program required boundary points enclosing the desired airway to be measured. Boundary points were marked first at PNS, along A Plane, posterior to the PPW, and continued down to the most inferior limit of the airway at Plane D. The airway boundary line was then extended along Plane D anterior to the anterior pharyngeal wall, back up to the level of Plane B to P point and along the soft palate back to PNS. (Figure 4) Five seed points were marked along the entire airway for the desired radiolucent airway recognition. (Figure 5) The best-fit volume was then rendered by adjusting the Volume Sensitivity Tool and then was calculated in mm^3 using Dolphin 3D^{TM} program. (Figure 6)

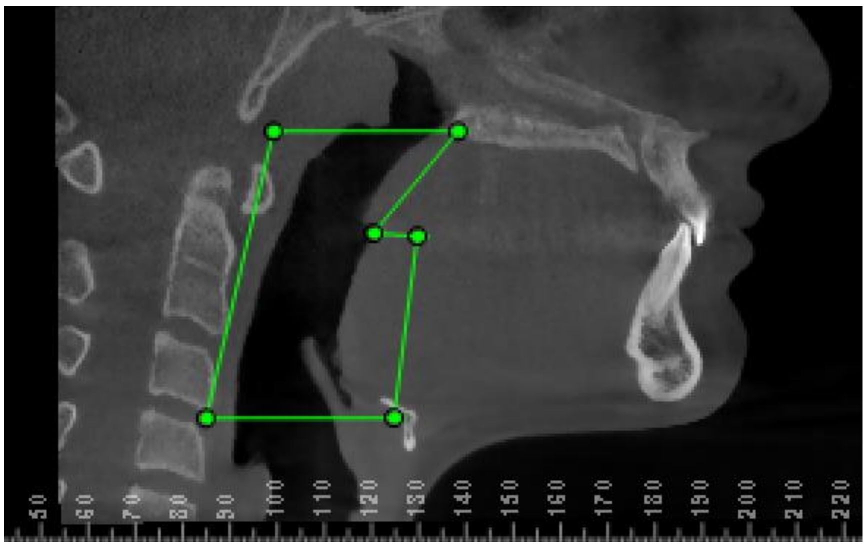


*Figure 4***.** Airway Volume Boundary. Boundary points depicted in green

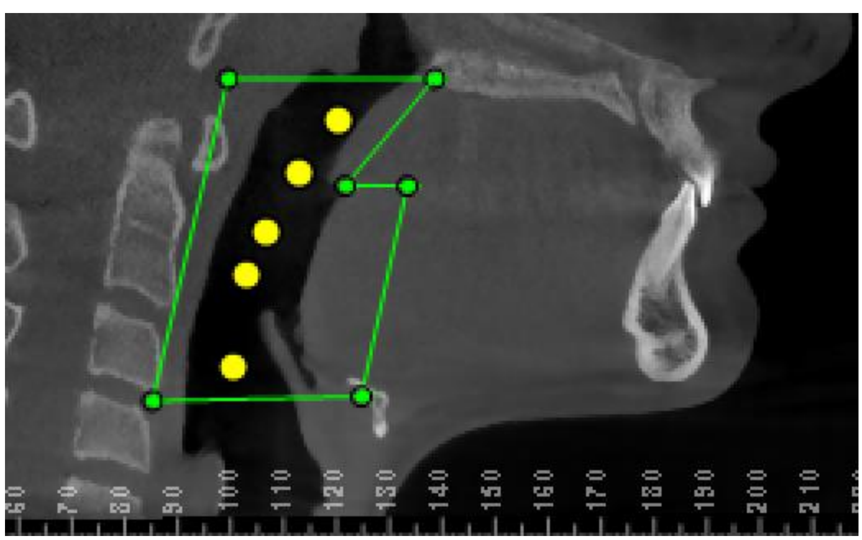


Figure 5. Airway Volume Seed Points.

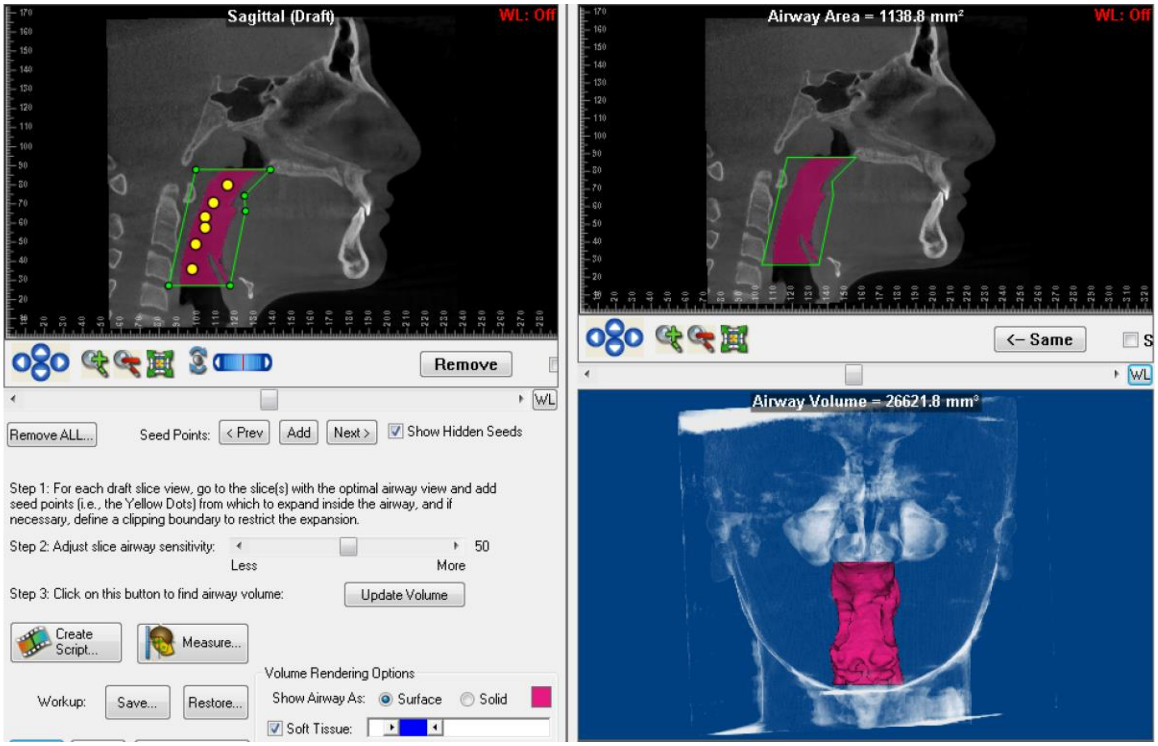


Figure 6. 3D Sinus/Airway Tool. Tool used to digitize and measure the airway volume. Upper left depicted boundary limits and placement of seed points. Upper right depicts sagittal view of volume rendered. Lower right displays region of volume in 3D view.

Cross-sectional area acquisition was made using the Dolphin 3D™ Slice Area Tool. Each of the Planes, A, B, C, and D was identified in the axial view by identifying the cephalometric landmark points made earlier. At Plane A, the ANS and PNS markers were located in the axial view and the Slice Area Tool was chosen. Using this tool, a point was placed along the border of the radiolucent pharyngeal airway and the boundary was outlined in a continuous series of points until the first initial point was reached and the area calculated in mm^2. The same steps were carried out for each of the areas A, B, C, D, and E. (Figure 7)

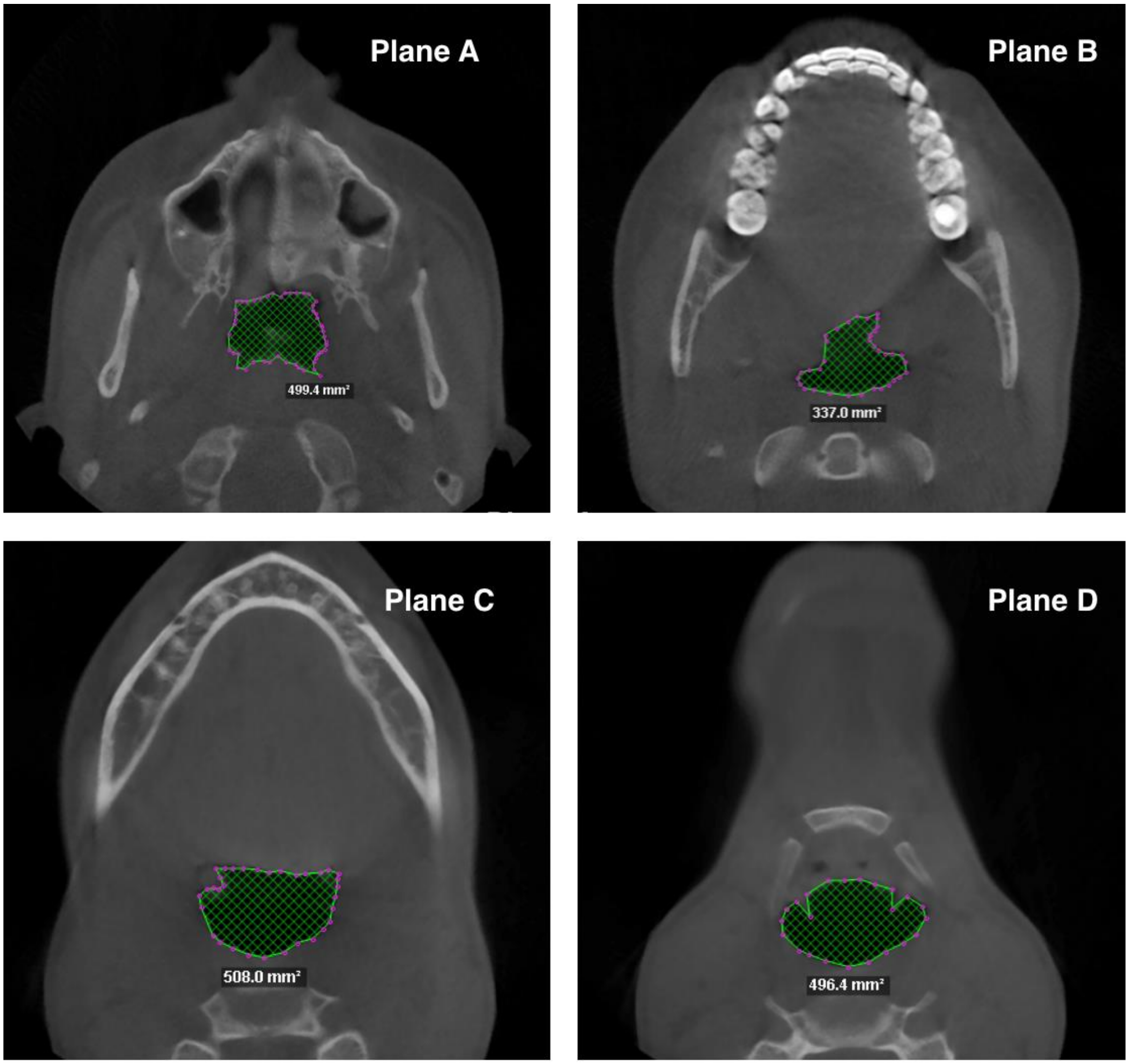


Figure 7. Cross-sectional Areas. Lateral boundary points depicted in purple and cross-sectional area depicted in green.

Length and width measurements at each plane were carried out using the Dolphin Line Tool. Length was defined as the largest distance on the anterior border of the pharyngeal wall to the posterior border of the wall perpendicular to the bottom of the screen. Width was defined as the distance between the largest points of the lateral walls of the pharyngeal airway space parallel to the bottom of the screen. (Figure 8)

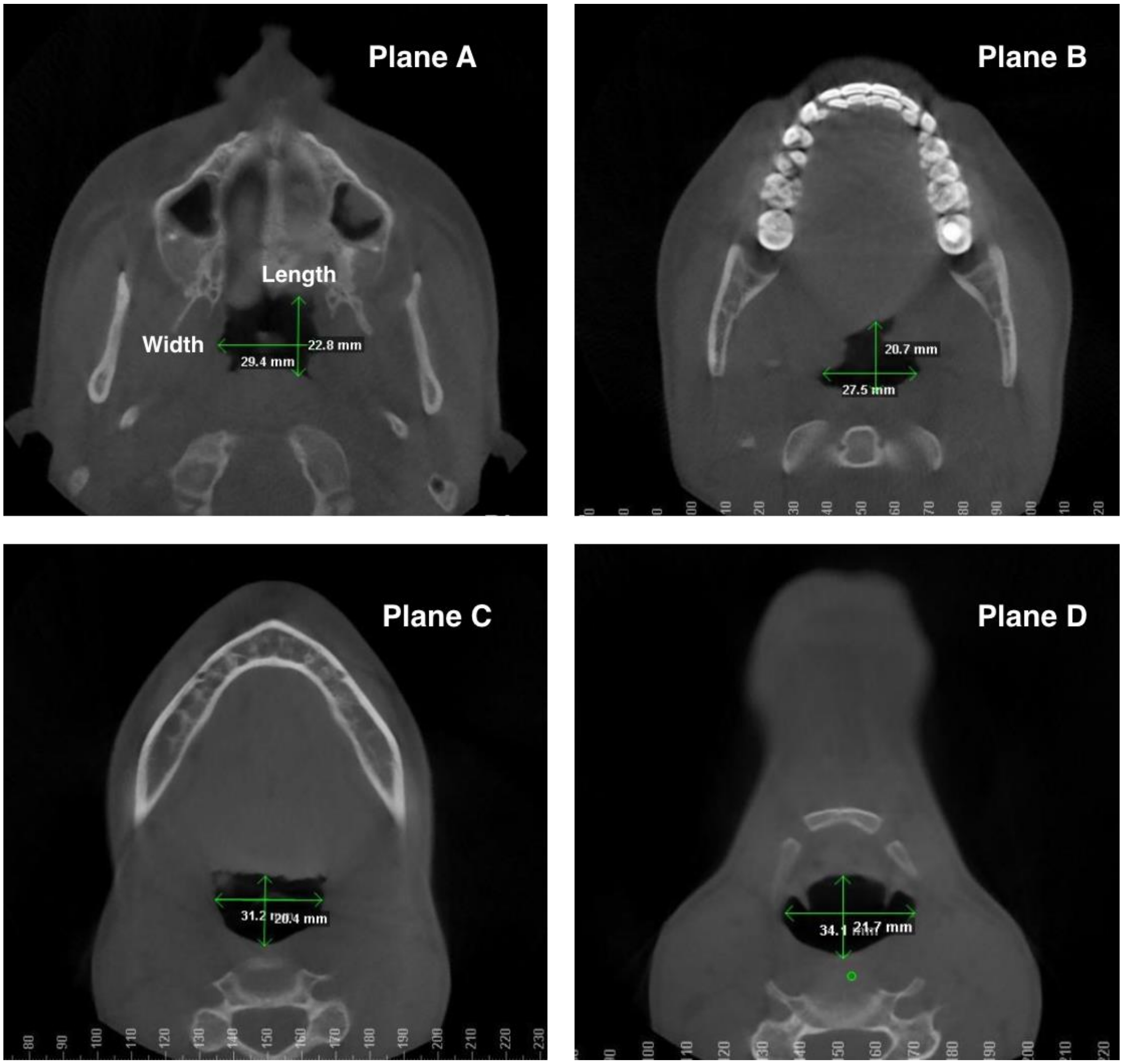


Figure 8. Cross-sectional Length and Width.

Statistical Analysis

SPSS^{TM} 23.0 software (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. In each group means and standard deviations were determined for age, treatment time, gender, ANB, OJ, volumetric, area, and linear measurements of the airway. The Kolmogorov-Smirnov tests were performed to determine the normality of the data and Kruskal-Wallis non-parametric test was performed to determine any significant changes ($p<0.05$) between any of the groups in each of the categories. Further analyses of covariance (ANCOVA) were performed to determine any statistically significant ($p<0.05$) independent factors on the different groups. Multiple covariates (age, gender, ANB, expansion, skeletal class) were used to determine any independent contributing factors in the data. Given a significant ANCOVA, a pairwise comparison Scheffe post-hoc test was performed to determine the source of the difference.

One examiner performed all measurements. Linear and angular measurements were rounded to the nearest 0.1 mm and 0.1° respectively. To determine reliability, all airway measurements on twenty percent of the patients were measured again by the same operator at least one week after the initial measurements. The calculated intraclass correlation coefficient (ICC) was between 0.87 and 0.93. This ICC shows very high reliability in all measurement.

Results

The mean age of the subjects at the beginning of treatment in the control, MARA, and Herbst groups were 13.2±1.77, 13.33±1.66, and 12.12±.67 respectively. (Table 4) The average treatment time of the control, MARA, and Herbst groups were 2.67 yrs, 3.04 yrs, 3.2 yrs respectively.

Table 4. *Sample ages*

T1	Control	MARA	Herbst	Total
Subject	25	26	9	60
Age (year)(mean ±SD)	13.2±1.77	13.33±1.66	12.12±0.67	13.11±1.65
Range (year)	10 - 17	10 - 16	11 - 13	10 - 17

Table 5. *Changes in the ANB and OJ at T1 and T2.*

Group	Measurement	Changes between T1 and T2 Mean ± SD		
		T1	**T2**	**T2-T1**
MARA	ANB (degrees)	5.9±2.18	4.26±2.25	-1.68±1.54
	OJ (mm)	6.16±2.44	3.30±0.60	-2.86±2.49
Herbst	ANB (degrees)	4.44±1.53	2.57±1.16	-1.79±.81
	OJ (mm)	5.6±2.30	3.03±1.06	-2.6±2.72
Control	ANB (degrees)	2.27±0.79	2.11±1.24	-.16±1.32
	OJ (mm)	3.65±1.64	2.77±1.11	-.88±2.10

The changes in ANB and OJ at T1 and T2 are shown in Table 5. The MARA and Herbst group had moderately more decrease in the ANB (-1.68°±1.54, -1.79°±.81) and OJ (-2.86mm±2.49, -1.79mm±.81) compared to the Control group (-.16°±1.32, -.88mm±2.1) (Table 5).

The ANCOVA showing the changes between T2 and T1 of the different groups are shown in Table 6. All three groups had an increase in the volumetric airway changes before and after treatment. There was a positive increase in all pharyngeal areas of the MARA, Herbst, and Control groups except a decrease in the Herbst group at the C Plane. The length and width increased for all groups in all the planes except a decrease in the length at the C plane in the Herbst group and a small decrease in the D length in the MARA group. The change in the length at the B plane among the groups was statistically significant (p=0.001). The Scheffe Post-Hoc test showed that there was a statistically significant change between the MARA and Control (p=0.019) and the Herbst and Control (p=0.003) (Table 7). There was no difference in the change in B Length between the MARA and Herbst Groups (p=0.622) between T1 and T2.

An additional ANCOVA including the age, gender, expansion, skeletal or dental class II, showed that when these additional independent factors were taken into consideration, there were no significant changes in any volumetric, area, or linear measurements.

Table 6. *ANCOVA showing the change (T2-T1) of each group.*

Measurement	**Changes between T1 and T2 Mean±SD**			**P-Value**
	MARA	**Herbst**	**Control**	
Volume (mm^3)	2195.00±4878.35	2455.33±3657.21	2055.56±4096.23	0.905
A Area (mm^2)	81.14±159	75.69±65.59	53.52±109.87	0.857
A Length (mm)	2.50±5.18	3.24±4.45	1.76±3.93	0.905
A Width (mm)	1.78±5.00	1.84±4.40	0.76±4.46	0.604
B Area (mm^2)	29.83±78.76	25.42±132.09	41.90±68.64	0.811
B Length (mm)	0.05±3.27	-2.56±2.53	2.17±3.36	0.001
B Width (mm)	2.61±5.93	5.12±7.92	1.54±4.39	0.371
C Area (mm^2)	56.68±90.33	-17.62±101.62	33.51±107.95	0.696
C Length (mm)	1.00±3.06	-0.29±3.44	0.89±3.80	0.846
C Width (mm)	2.44±5.40	0.60±7.78	1.30±3.61	0.915
D Area (mm^2)	26.77±99.17	5.88±77.60	28.41±86.26	0.855
D Length (mm)	-0.01±3.46	0.72±3.93	0.85±4.17	0.631
D Width (mm)	1.88±4.65	1.93±7.19	2.57±5.37	0.850

Table 7. *Post Hoc showing the comparison between individual groups at Length B.*

Measurement	**Changes between T1 and T2 Estimated Marginal Mean±SEM**				**P-Value**
	MARA	**Herbst**	**Control**	**Delta**	
B Length (mm)	-0.34±.62	---	2.09±.59	2.42±0.85	0.019
	---	-1.80 ±.95	2.09±.59	3.89±1.12	0.003
	-0.34±.62	-1.80 ±.95	---	-1.46±1.15	0.622

Discussion

As children age there is considerable variability in their airways. Scammon's growth curve demonstrates that the lymphoid tissue typically peaks to about 200% the normal adult size around the age of 10.[45] The adenoids and tonsils gradually decline to a fairly constant size in adulthood, although studies show they can also vary throughout life.[46] The treatment and control group in the current study include children of the same age of this high variability of adenoid and tonsillar change, which can have an effect on the dimensions of the pharyngeal airway.[47]

In addition to the variability of the airway in this age population due to the lymphoid tissues, the surrounding soft tissue of the airway can also have an effect on the measurements. Patients with OSA have been shown to have a narrowing of the length of oropharyngeal airway space when placed in a supine position.[48] Cartwright showed that patients sleeping in a supine position had twice as many apneic episodes than when they slept on their backs.[49] Pae et al observed that the pharynx became considerably longer in apneic patients that were placed in a supine position.[50] Patients in the current study were placed in a similar supine position for the CBCT acquisition, which may have had an effect on the measured airway dimensions.

As Harvold demonstrated, the body will adapt and make alterations in order to obtain the necessary oxygen. One simple example is the human nasal cycle. The normal nasal cycle shows the body makes small adaptations in order to receive sufficient oxygen.[51] If the constriction of the airflow is beyond the body's ability to adapt, it can lead to positional and skeletal changes, which may include a retrognathic mandible.[9,44] Our study shows that there were no changes in the dimensions of the airway even after advancement of the mandible in the skeletal class II patients. The change in the skeletal structure and airway may need to be made before the body is forced to adapt, which could alter the skeletal growth pattern of the child. An example of an early change was shown by Zettergren et al. They showed that children (mean age 5.8 years) diagnosed with OSAS had significantly different cephalometric measurements compared to a control group of healthy children. The treatment group received adenotonsillectomies and five years later their growth had an almost complete normalization of dentofacial morphology compared to the control group except in the anterior cranial base and length of nose.[7]

The current study shows that even after advancing the mandible with a MARA and Herbst appliance in class II patients there wasn't any significant increase in the pharyngeal airway space compared to the control group. We were unable to reject our null hypothesis that there were no changes in the pharyngeal airway after fixed functional appliance therapy. There was a statistically significant decrease in the length of the airway at the level of the oropharynx at the soft palate. A further ANCOVA showed that there was no independent factor (e.g. gender, age, expansion, skeletal class) that had a significant effect on the oropharyngeal airway.[52] It appears to be multifactorial and can't be attributed to one or two factors causing this decrease in the length. Our findings differ from that of Iwasaki et al who found a significant increase in the change of the volume of the Herbst treatment group as well as the length of the oropharyngeal and laryngopharyngeal airway.[32] Our study included a larger sample size of MARA patients and a smaller sample size of Herbst patients. The differences in our study to Iwasaki's may be due to the slightly different mechanics of the MARA compared to the Herbst appliance. Also, the measurements were taken at different levels along the pharyngeal airway, which may have an effect on the results.

Fixed functional appliances have been shown to have varying effects on the mandible versus the maxilla and the effects on the airway. It has been shown that the Herbst and MARA appliance have a headgear effect, restricting the maxilla, which may have an influence on the airway.[25] A study by Pirila-Parkkinen et al showed that patients with OSAS using a cervical headgear, which restricts the maxilla like a Herbst or MARA, had significantly more apnea/hypopnea periods while wearing the headgear compared to the healthy control group as well as the control group of children with OSAS and no headgear treatment. The oxygen desaturation index was also increased in the treatment group.[54]

Sleep apnea has been treated effectively by advancing the mandible into a protruded position.[55,56,57] The advancement of the mandible has shown to improve the degree of OSA according to the apnea-hypopnia index in some patients, but it has also has been shown to not have any cephalometric changes in the pharyngeal airway.[56] As this was a retrospective study, a rhinomanometric airway evaluation and/or polysomnography were unable to be obtained but should be included in a future prospective study. Therefore, the current study's patient pool were not diagnosed previously for OSA or screened for OSA symptoms such as snoring. Schwab et al showed that patients who snored or were diagnosed with OSA had significantly smaller area in the retropalatal area and narrowed airway laterally.[41] The pharyngeal airway, shape, size and adaptability has been shown to vary between compromised and non-compromised airway subjects.[41] Due to these differences, the results of this study may have been affected by not taking into account the airflow and shape of the airways in our control and treatment groups.

Conclusions

1. There was a significant decrease in the length of the pharyngeal airway space at the oropharynx from T1 to T2 (P = 0.019 and P = 0.003).
2. The significant change was multifactorial and was not significantly influenced by one of the following: age, gender, expansion, and skeletal or dental classification.
3. Overall, there were no significant changes in the pharyngeal airway volume, area, or linear measurements between the control and Herbst and MARA groups. In this study, the functional appliances did not appear to have an effect on the parameters measured.
4. We were unable to reject our null hypothesis.

CHAPTER THREE

EXTENDED DISCUSSION

Limitations of Study and Recommendations for Future Studies

This study was limited to measuring the length, width, and area of each of the planes. A more accurate way of determining changes in the airway may include a morphometric analysis of each plane to determine exactly where changes are occurring instead of linear measurements alone. Using different software, like the Anatomage software, (Anatomage Inc., San Jose, California) in the future would allow a systematic method of evaluating the most constricted section of the volumetric airway. The software would be able to show if the most constricted area improved or moved along the pharyngeal airway before and after treatment.

One of the limitations of measuring the airway in patients is the accuracy of the three-dimensional analysis of the software. In determining the overall volume of the airway, the sensitivity tool is adjusted to fill the desired radiolucent airway space with the volumetric model. One point difference in the sensitivity can give a change over 100 mm^3 in the overall volume. Weissheimer et al showed that the measurements of the pharyngeal airway in 33 growing patients compared to an oropharynx acrylic phantom had high reliability for the Dolphin3D™ (Dolphin Imaging & Management Solutions, Chatsworth, California). Although they did have an error of about 2% compared to the gold standard phantom.[53] The varying density of the soft tissue surrounding the pharyngeal airway can have an effect on the overall calculated volumetric measurements of the airway and may have had an effect in our study, especially taking into consideration that images were taken from the NewTom 3G™ as well as the NewTom 5G™.

A future study should include controls with a class I and class II group not being treated with functional appliances to determine if the growth pattern is similar to the treatment groups. The controls should also be matched in their vertical pattern of growth. [16,17,18]

A future prospective study that utilizes rhinometry or another fluid-mechanical simulation model to determine airflow changes before and after treatment would be a better determination as to whether an improvement had been made in the breathing of the patients. As this study was retrospective, it only evaluated the volume, area, and linear measurements.

Presence or absence of adenoids and tonsils were not directly evaluated as this was a retrospective study. A prospective study, including direct evaluation by an otolaryngologist, would allow the investigator to evaluate the subjects that have more comparable adenoids and tonsils. [7]

Body Mass Index (BMI) has been identified has a key indicator of OSAS. Including the BMI before and after treatment may also be beneficial in determining any effects it may have on the different groups.[12,13]

The current study had an adequate sample size to create sufficient power. However, a larger sample size may give a better analysis of the control and experimental groups in a future study.

References

1. Ceylan I, Okta, H. A study on the pharyngeal size in different skeletal patterns. Am J Orthod Dentofac Orthop. 1995; 108: 69-75

2. Mergen DC, Jacobs,MR. The size of nasopharynx associated with normal occlusion and Class II malocclusion. Angle Orthod. 1970; 40: 342-346

3. Harvold EP, Tomer BS, Vargervik K, Chierici G. Primate experiments on oral respiration. Am J Orthod Dentofac Orthop. 1981; 79: 359-372

4. Guilleminault C, Eldridge FL, Simmons FB, Dement WC. Sleep apnea in eight children. Pediatrics. 1976; 58: 23-30

5. McNamara JA. Influence of respiratory pattern on craniofacial growth. Angle Orthod. 1981; 51: 269-300

6. Martin SE, Mathur R, Marshall I, Douglas NJ. The effect of age, sex, obesity and posture on upper airway size. Eur Respir J. 1997;10: 2087-2090

7. Zettergren-Wijk L, Forsberg CM, Linder-Aronson S. Changes in dentofacial morphology after adeno-/tonsillectomy in young children with obstructive sleep apnoea--a 5-year follow-up study. Eur J Orthod. 2006; 28: 319-326

8. Yamada T, Tanne K, Miyamoto K, Yamauchi K. Influences of nasal respiratory obstruction on craniofacial growth in young Macaca fuscata monkeys. Am J Orthod Dentofacial Orthop. 1997; 111: 38-43

9. Beebe DW, Gozal D. Obstructive sleep apnea and the prefrontal cortex: towards a comprehensive model linking nocturnal upper airway obstruction to daytime cognitive and behavioral deficits. J Sleep Res. 2002; 11: 1-16

10. de Carlos Villafranca F, Cobo Plana J, Díaz-Esnal B, Fernández-Mondragón P, Macías Escalada E, Puente Rodríguez M. Chronic snoring and obstructive sleep apnea-hypopnea syndrome in children. Orthod Fr. 2003; 74: 431-457

11. Guilleminault C. The Sleep Apnea Syndromes. Annu. Rev. Med. 1976; 27: 465-484

12. Mora R, Salami A, Passali FM, Mora F, Cordone MP, Ottoboni S, Barbieri M. OSAS in children. International Journal of Pediatric Otorhinolaryngology. 2003; 67: 229-231

13. Brouilette R, Hanson D, David R, Klemka L, Szatkowski A, Fernbach S, Hunt C. A diagnostic approach to suspected obstructive sleep apnea in children. J Pediatr. 1984; 105:10-4

14. Kawashima S, Niikuni N, Chia-hung L, Takahasi Y, Kohno M, Nakajima I, Akasaka M, Sakata H, Akashi S. Cephalometric comparisons of craniofacial and upper airway structures in young children with obstructive sleep apnea syndrome. Ear Nose Throat J. 2000; 79: 499-502, 505-506

15. Schwab TJ, Gupta KB, Gefter WB, Metzger LJ, Hoffman EA, Pack AI. Upper airway and soft tissue anatomy in normal subjects and patients with sleep-disordered breathing. Significance of the lateral pharyngeal walls. Am J Respir Crit Care Med. 1995; 152: 1673-1689

16. de Freitas MR, Alcazar NM, Janson G, de Freitas KM, Henriques JF. Upper and lower pharyngeal airways in subjects with Class I and Class II malocclusions and different growth patterns. Am J Orthod Dentofacial Orthop. 2006; 130: 742-745

17. Kaur S, Rai S, Kaur M. Comparison of reliability of lateral cephalogram and computed tomography for assessment of airway space. Niger J Clin Pract. 2014; 17: 629-636

18. Wang T, Yang Z, Yang F, Zhang M, Zhao J, Chen J, Li Y. A three dimensional study of upper airway in adult skeletal Class II patients with different vertical growth patterns. PLoS One. 2014; 22:9(4)

19. Iwasaki T, Saitoh I, Takemoto Y, Inada E, Kanomi R, Hayasaki H, Yamasaki Y. Evaluation of upper airway obstruction in Class II children with fluid-mechanical simulation. Am J Orthod Dentofacial Orthop. 2011; 139: 135-145

20. Zheng ZH, Yamaguchi T, Kurihara A, Li HF, Maki K. Three-dimensional evaluation of upper airway in patients with different anteroposterior skeletal patterns. Orthod Craniofac Res. 2014; 17: 38-48

21. Claudino LV, Mattos CT, Ruellas AC, Sant' Anna EF. Pharyngeal airway characterization in adolescents related to facial skeletal pattern: a preliminary study. Am J Orthod Dentofacial Orthop. 2013; 143: 799-809

22. Grauer D, Cevidanes LS, Styner MA, Ackerman JL, Proffit WR. Pharyngeal airway volume and shape from cone-beam computed tomography: relationship to facial morphology. Am J Orthod Dentofacial Orthop. 2009; 136: 805-814

23. Oh KM, Hong JS, Kim YJ, Cevidanes LS, Park YH. Three-dimensional analysis of pharyngeal airway form in children with anteroposterior facial patterns. Angle Orthod. 2011; 81: 1075-1082

24. Bishara SE, Ziaja RR. Functional appliances: a review. Am J Orthod Dentofacial Orthop. 1989; 95: 250-258

25. Siara-Olds NJ, Pangrazio-Llbersh V, Berger J, Bayirli B. Long-term dentoskeletal changes with the Bionator, Herbst, Twin Block and MARA functional Appliances. Angle Orthod. 2010; 80: 18-29

26. Ghodke S, Utreja AK, Singh SP, Jena AK. Effects of twin-block appliance on the natomy of pharyngeal airway passage (PAP) in class II malocclusion subjects. Prog Orthod. 2014; 23;15:68

27. Jena AK, Singh SP, Utreja AK. Effectiveness of twin-block and Mandibular Protraction Appliance-IV in the improvement of pharyngeal airway passage dimensions in Class II malocclusion subjects with a retrognathic mandible. Angle Orthod. 2013; 83: 728-734

28. Han S, Choi YJ, Chung CJ, Kim JY, Kim KH. Long-term pharyngeal airway changes after bionator treatment in adolescents with skeletal Class II malocclusions. Korean J Orthod. 2014; 44: 13-19

29. Kirjavainen M, Kirjavainen T. Upper airway dimensions in Class II malocclusion. Effects of headgear treatment. Angle Orthod. 2007; 77: 1046-1053

30. Schüt TC, Dominguez GC, Hallinan MP, Cunha TC, Tufik S. Class II correction improves nocturnal breathing in adolescents. Angle Orthod. 2011; 81: 222-228

31. Itzhaki S, Dorchin H, Clark G, Lavie L, Lavie P, Pillar G. The effects of 1-year treatment with a herbst mandibular advancement splint on obstructive sleep apnea, oxidative stress, and endothelial function. Chest. 2007; 131: 740-749

32. Iwasaki T, Takemoto Y, Inada E, Sato H, Saitoh I, Kakuno E, Kanomi R, Yamasaki Y. Three-dimensional cone-beam computed tomography analysis of enlargement of the pharyngeal airway by the Herbst appliance. Am J Orthod Dentofacial Orthop. 2014; 146: 776-785

33. Pangrazio MN, Pangrazio-Kulbersh V, Berger JL, Bayirli B, Movahhedian A. Treatment effects of the mandibular anterior repositioning appliance in patients with Class II skeletal malocclusions. Angle Orthod. 2012; 82: 971-977

34. Al-Jewair TS. Meta-analysis on the mandibular dimensions effects of the MARA appliance in patients with Class II malocclusions. Angle Orthod. 2015; 85: 706-714

35. Pangrazio-Kulbersh V, Berger JL, Chermak DS, Kaczynski R, Simon ES, Haerian A. Treatment effects of the mandibular anterior repositioning appliance on patients with Class II malocclusion. Am J Orthod Dentofacial Orthop. 2003; 123: 286-295

36. Ghoneima A, Kula K. Accuracy and reliability of cone-beam computed

tomography for airway volume analysis. European Journal of Orthodontics. 2013; 35: 256-261

37. Mattos CT, Cruz CV, da Matta TC, Pereira LA, Solon-de-Mello PA, Ruellas AC, Sant'anna EF. Reliability of upper airway linear, area, and volumetric measurements in cone-beam computed tomography. Am J Orthod Dentofacial Orthop. 2014; 145: 188-197

38. Sayinsu K, Isik F, Arun T. An evaluation of the errors in cephalometric measurements on scanned cephalometric images and conventional tracings. Eur J Orthod. 2007; 29: 105-108

39. Ferguson KA, Ono T, Lowe AA, Ryan CF, Fleetham JA. The relationship between obesity and craniofacial structure in obstructive sleep apnea. Chest. 1995; 108: 375-81

40. Hoffstein V, Mateika S. Differences in abdominal and neck circumference in patients with and without obstructive sleep apnea. Eur Respir J. 1992; 5: 3773-3778

41. Schwab J. Sex differences and sleep apnoea. Thorax.1999; 54: 284-285

42. Eikermann M, Jordan AS, Chamberlin NL, Gautam S, Wellman A, Lo YL, White DP, Malhotra, A. The influence of aging on pharyngeal collapsibility during sleep. Chest. 2007; 131: 1702-1709

43. McNamara. Influence of respiratory pattern on craniofacial growth. Angle Orthod. 1981; 51: 269-300

44. Harari D, Redich M, Miri S, Hamud T, Gross M. The effect of mouth breathing versus nasal breathing on dentofacial and craniofacial development in orthodontic patients. The Laryngoscope. 2010: 120; 2089-2093

45. Scammon RD. The measurement of the body in childhood. In: Harris JA, ed. The Measurement of Man. Minneapolis: University of Minnesota Press; 1930

46. Hollender AR, Szanto PB. Lymphoid hyperplasia in the nasopharynx; a study of 131 autopsy specimens. Arch Otolaryngol. 1945; 41: 291-294

47. Arens R, McDonough J, Costarino A, Mahboubi S, Tayag-Kier E, Maislin G, Schwab R, Pack AI. Magnetic Resonance Imaging of the Upper Airway Structure of Children with Obstructive Sleep Apnea Syndrome. Am J Respir Crit Care Med. 2001; 164: 698-703

48. Ingman T, Nieminen T, Hurmerinta K. Cephalometric comparison of pharyngeal changes in subjects with upper airway resistance syndrome or obstructive sleep

apnoea in upright and supine positions. The European Journal of Orthodontics. 2004; 26: 321-326

49. Cartwright RD. Effect of sleep position on sleep apnea severity. Journal of Sleep Research & Sleep Medicine. 1984; 7: 110-114

50. Pae E, Lowe AA, Fleetham JA. A role of pharyngeal length in obstructive sleep apnea patients. Am J Orthod Dentofac Orthop. 1997; 111: 12-17

51. Hasegawa M, Kern EB. The human nasal Cycle. Mayo Clinic Proceedings. 1977; 52: 28-34

52. Gordon JM, Rosenblatt M, Witmans M, Carey JP, Heo G, Major PW, Flores-Mir C. Rapid palatal expansion effects on nasal airway dimensions as measured by acoustic rhinometry. A systematic review. Angle Orthod. 2009; 79: 1000-1007

53. Weissheimer A, Macedo de Menezes L, Sameshima GT, Pham J. Imaging software accuracy for 3-dimensional analysis of the upper airway. Am J Orthod Dentofac Orthop. 2012; 142: 801-813

54. Pirila-Parkkinen K, Perttiniemi P, Nieminen P, Lopponen H, Tononen U, Uotila R, Huggare J. Cervical headgear therapy as a factor in obstructive sleep apnea syndrome. Pediatric Dentistry. 1999; 21: 39-45

55. Yoshida K. Effect of a prosthetic appliance for treatment of sleep apnea syndrome on masticatory and tongue muscle activity. J Prosthet Dent. 1998; 79: 537-544

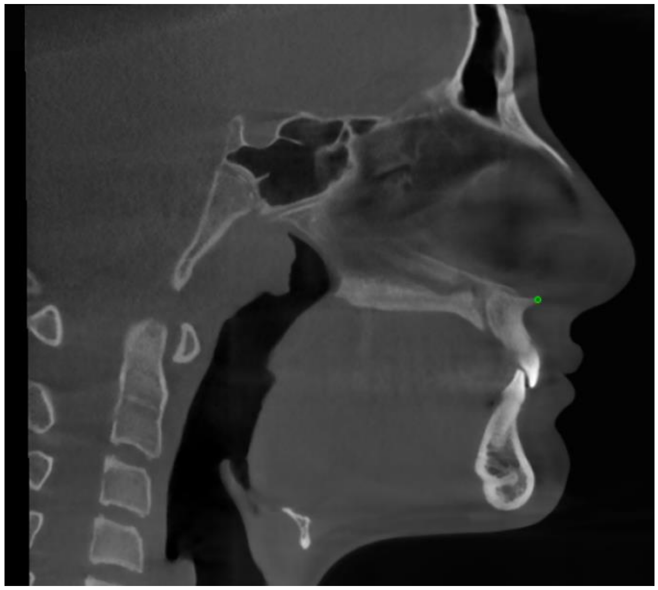
56. O'Sullivan RA, Hillman DR, Mateljan R, Pantin C, Finucane KE. Mandibular advancement splint: an appliance to treat snoring and obstructive sleep apnea. Am J Respir Crit Care Med 1995; 151: 194-198

57. Nakazawa Y, Sakamoto T, Yasutake R, Yamaga K, Kotorii T, Miyahara Y, Ariyoshi Y, Kameyama T. Treatment of sleep apnea with prosthetic mandibular advancement (PMA). Sleep. 1992; 15: 499-504

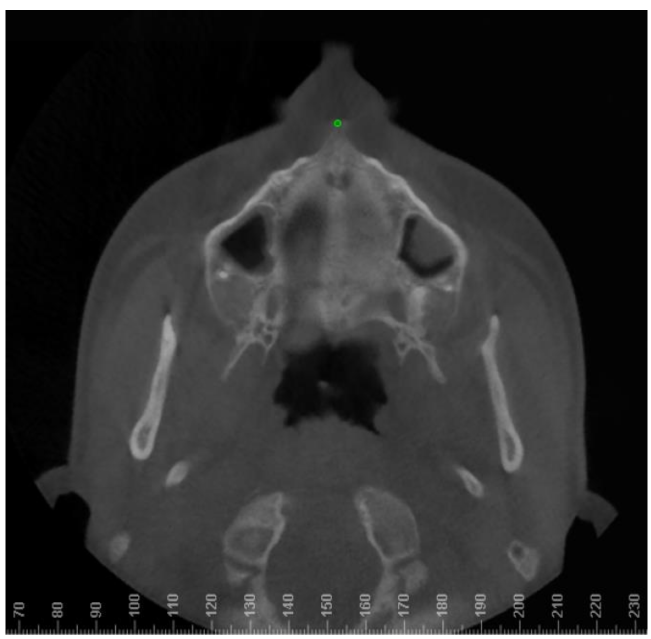
58. Eveloff SE, Rosenberg CL, Carlisle CC, Millman RP. Efficacy of a Herbst mandibular advancement device in obstructive sleep apnea. Am J Respir Crit Care Med. 1994; 149: 905-909

APPENDIX A

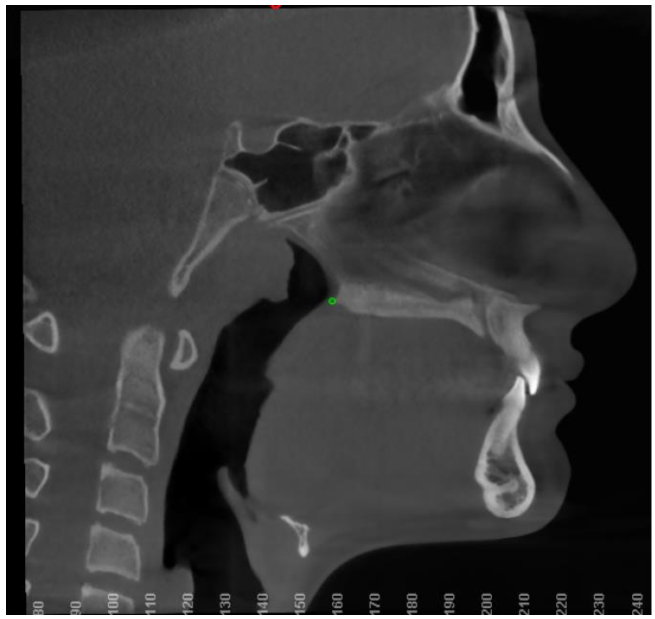
LANDMARK IDENTIFICATION



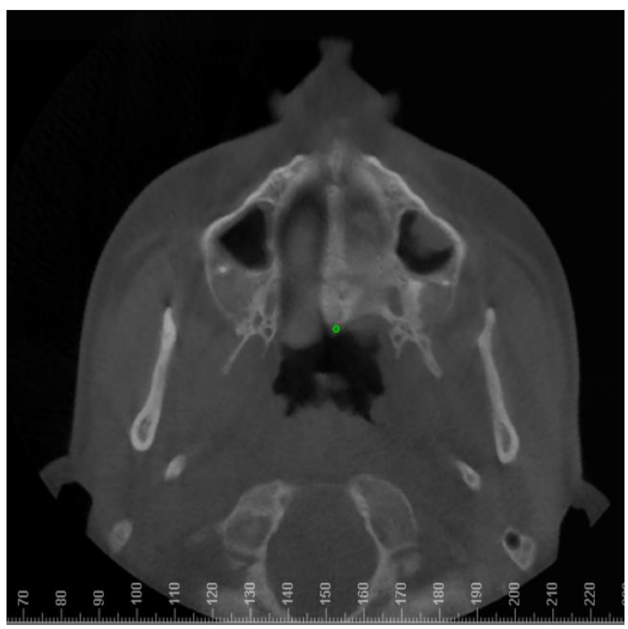
Appendix A-1. ANS Sagittal. CBCT sagittal view. ANS, most anterior point of the anterior nasal spine, depicted in green.



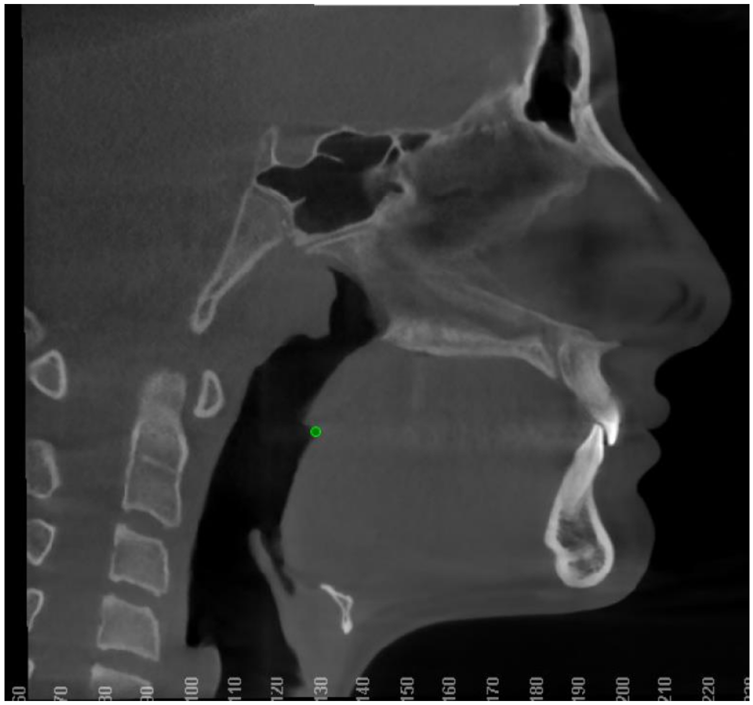
Appendiz A-2. ANS Axial. CBCT axial view. ANS, most anterior point of the anterior nasal spine, depicted in green.



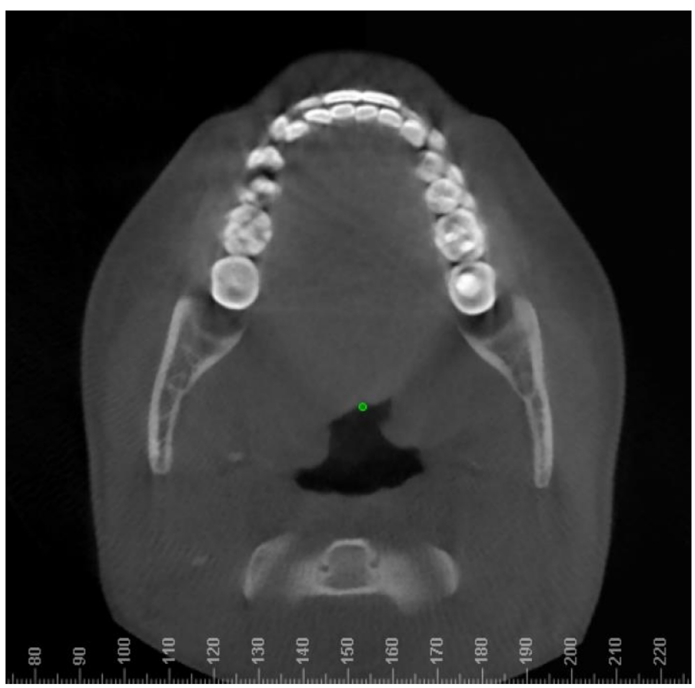
Appendiz A-3. PNS Sagittal. CBCT sagittal view. PNS, the most posterior point on the posterior nasal spine, depicted in green



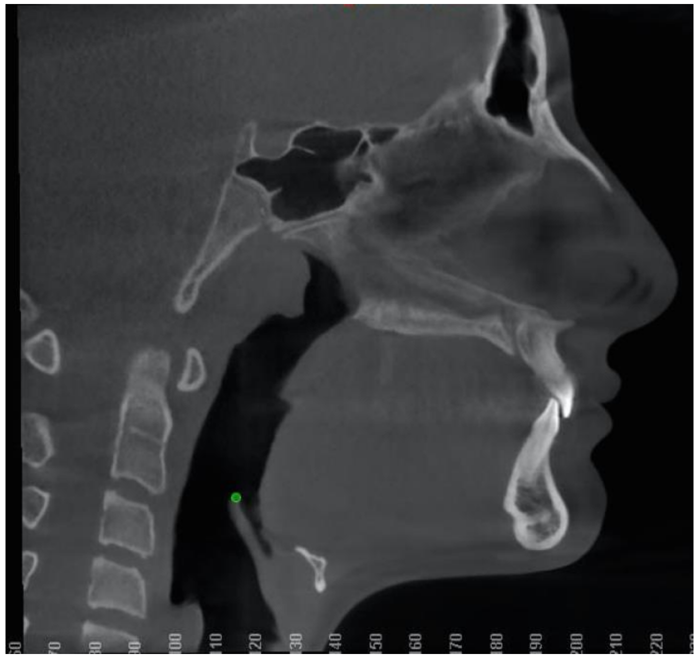
Appendix A-4. PNS Axial. CBCT axial view. PNS, the most posterior point on the posterior nasal spine, depicted in green.



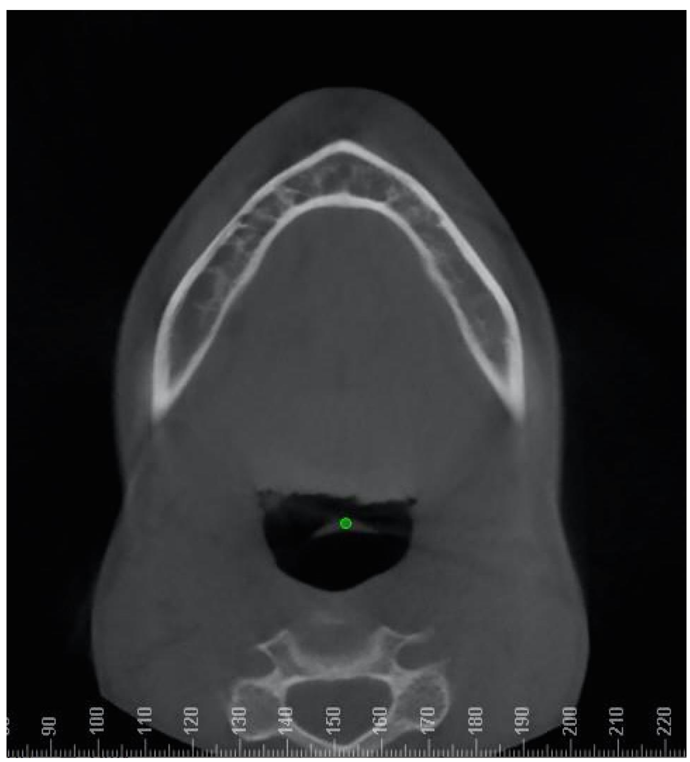
Appendix A-5. P Point Sagittal. CBCT Sagittal view. P point, the most inferior tip of the soft palate, depicted in green



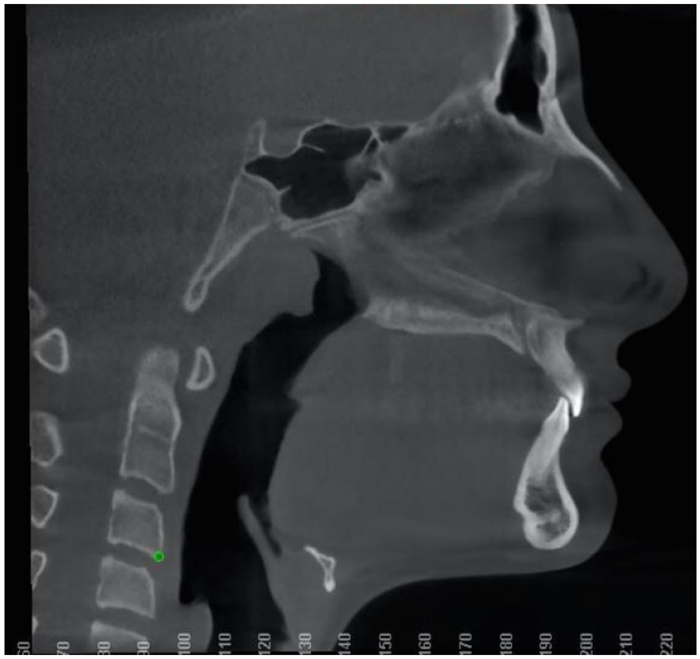
Appendix A-6. P Point Axial. CBCT axial view. P point, the most inferior tip of the soft palate, depicted in green.



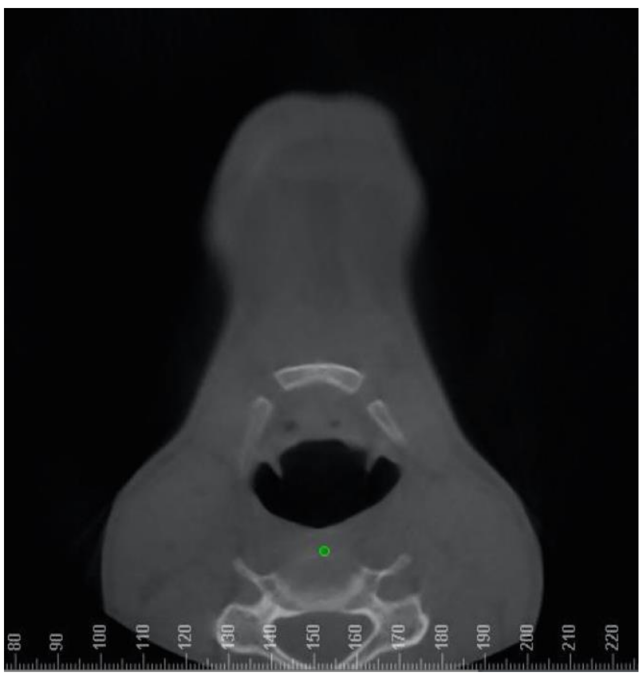
Appendix A-7. Et Point Sagittal. CBCT sagittal view. Et point, the most superior point of the epiglottis, depicted in green.



Appendix A-8. Et Point Axial. CBCT axial view. Et point, the most superior point of the epiglottis, depicted in green.



Appendix A-9. V Point Sagittal. CBCT sagittal view. V point, the most anterior inferior point of the third cervical vertebrae, depicted in green.



Appendix A-1-. V Point Axial. CBCT axial view. V point, the most anterior inferior point of the third cervical vertebrae, depicted in green.

APPENDIX B

RAW DATA

MARA	Sex	T1 ANB	T1 OJ	T2 ANB	T2 OJ	T1Volume mm3	T1 A area mm2	T1 A length mm	T1 A width mm	T1 B area mm2
1	M	10.2	11.8	8.2	3.7	9,102.60	171.30	12.50	17.70	138.20
2	M	4.6	5.3	2	3.5	15,846.30	421.40	19.10	26.80	124.10
3	M	9.1	7.7	7.5	2.3	12,899.20	172.60	17.30	12.40	211.40
4	M	4.3	4.1	3.2	2.1	6,638.70	242.30	16.90	19.10	90.50
5	M	6.2	5.4	5.7	3	13,455.80	233.40	9.30	22.10	184.90
6	F	6.2	8.9	5.6	3.2	12,167.50	277.00	15.50	21.70	187.60
7	M	5	6.6	3.6	2.3	12,610.20	99.70	5.60	19.40	230.00
8	F	2.5	4.3	1.7	3.2	25,184.60	492.40	19.40	29.90	271.80
9	M	9.3	6.5	9.3	4.5	10,251.30	226.00	13.70	19.40	224.10
10	M	3.5	5.9	2.1	3.6	11,020.50	353.70	18.50	24.00	153.80
11	M	3.8	4.1	4.3	3.7	8,511.40	191.20	11.50	25.00	62.60
12	M	4.4	4.6	1.9	3.6	13,850.90	334.60	17.90	27.40	169.90
13	M	3.6	3.4	3.3	4.5	7,571.90	273.00	16.00	18.90	132.50

MARA	T1 B length mm	T1 B width mm	T1 C area mm2	T1 C length mm	T1 C width mm	T1 D area mm2	T1 D length mm	T1 D width mm
1	22.80	11.60	175.90	16.40	17.00	260.50	15.40	26.30
2	15.30	11.50	285.50	14.30	27.40	303.90	13.40	30.60
3	11.50	29.00	98.60	7.30	23.90	104.80	5.50	23.30
4	9.60	12.70	119.90	7.70	22.60	156.60	9.30	26.80
5	9.80	21.80	252.20	12.60	27.80	153.80	9.00	30.60
6	14.70	17.20	255.00	13.00	27.70	421.30	17.10	32.10
7	11.50	29.00	266.60	14.50	23.00	326.70	14.20	36.10
8	13.50	24.30	326.10	12.30	32.60	420.10	17.40	32.40
9	10.90	24.80	262.00	10.90	28.30	199.20	8.60	30.90
10	10.20	18.20	136.70	8.30	27.40	229.80	10.90	31.80
11	9.20	6.70	134.30	8.70	24.90	190.30	8.90	28.70
12	12.40	17.20	234.30	12.10	26.50	246.00	18.80	27.70
13	7.50	19.30	145.50	9.10	19.70	144.40	8.50	26.20

MARA	Sex	T1 ANB	T1 OJ	T2 ANB	T2 OJ	T1Volume mm3	T1 A area mm2	T1 A length mm	T1 A width mm	T1 B area mm2
14	M	8.3	8	7.4	3.2	11,335.40	231.90	18.60	15.40	192.70
15	F	7.7	3.3	6.2	2.5	7,730.90	236.70	15.20	23.30	152.60
16	F	2.9	8.7	3.6	3	8,667.00	311.70	18.50	23.80	102.50
17	F	7.1	7.2	2.7	3.1	11,907.00	399.00	17.90	27.00	202.50
18	M	7.2	5.1	2.6	3.2	9,952.40	279.90	16.30	22.60	127.10
19	M	2.7	4.8	3.6	2.7	16,626.80	352.00	16.00	27.30	274.80
20	F	7.6	3.4	5.1	3.3	12,840.60	143.90	10.00	18.50	253.20
21	M	6.3	4.2	1.8	3.7	15,262.80	481.40	24.10	26.40	207.20
22	M	6.9	7	4.6	3.4	6,406.20	179.20	12.50	19.10	112.30
23	F	5.6	12.5	1.6	3.5	11,273.20	378.10	19.50	24.70	279.10
24	M	4.5	7.8	1.8	3.7	15,879.20	389.80	20.40	26.00	201.60
25	M	6.5	3.8	4.4	3.3	8,624.40	455.10	19.60	34.20	246.00
26	M	8.5	5.7	6.9	3.9	9,331.40	335.00	15.90	27.10	102.90

MARA	T1 B length mm	T1 B width mm	T1 C area mm2	T1 C length mm	T1 C width mm	T1 D area mm2	T1 D length mm	T1 D width mm
14	10.20	20.00	103.00	7.40	21.70	92.80	8.20	16.90
15	11.10	19.00	167.50	8.10	31.40	269.90	11.40	32.80
16	8.90	15.70	109.10	7.50	22.50	180.10	11.40	27.80
17	13.60	17.30	219.20	13.30	23.90	146.20	14.00	17.30
18	17.50	12.00	253.70	16.90	20.90	312.30	16.90	27.70
19	14.90	24.00	338.50	12.60	36.30	443.80	16.20	36.00
20	13.60	26.60	249.10	10.90	27.00	266.70	12.80	27.00
21	15.20	18.50	339.70	16.50	29.00	350.20	19.10	32.70
22	12.50	12.70	176.90	12.30	24.00	192.10	11.40	28.70
23	13.60	31.70	250.90	13.50	30.10	98.70	11.40	11.70
24	12.80	18.90	318.30	13.50	33.60	282.00	12.70	34.80
25	16.00	21.10	78.90	5.70	23.60	161.30	8.60	28.20
26	12.70	15.00	170.90	10.50	25.50	270.10	12.10	32.50

MARA	T2 Volume mm3	T2 A area mm2	T2 A length mm	T2 A width mm	T2 B area mm2	T2 B length mm	T2 B width mm
1	10,224.70	195.80	15.50	17.50	131.20	16.50	15.50
2	12,478.40	433.40	21.60	27.00	96.80	12.60	10.90
3	5,640.00	166.10	13.20	12.50	112.20	8.60	18.40
4	11,097.40	456.90	22.60	23.60	176.40	11.40	18.60
5	19,010.20	495.00	19.80	29.80	294.40	11.50	25.70
6	12,403.30	374.90	20.60	24.00	207.90	14.00	19.20
7	20,887.10	489.20	19.80	29.00	326.40	12.70	35.50
8	26,253.00	606.40	23.00	31.60	314.10	13.90	31.80
9	16,418.10	239.50	14.90	19.50	433.40	14.70	33.60
10	14,519.90	399.30	19.10	24.40	174.30	14.20	17.20
11	11,786.80	248.50	14.70	20.20	101.30	13.20	11.50
12	15,414.30	369.70	18.50	27.00	167.70	12.50	15.60
13	11,194.80	255.20	15.30	24.60	204.80	13.10	19.10

MARA	T2 C area mm2	T2 C length mm	T2 C width mm	T2 D area mm2	T2 D length mm	T2 D width mm
1	323.40	16.90	25.40	332.60	19.80	25.40
2	167.60	9.30	25.10	146.30	8.50	27.60
3	81.60	7.30	17.10	78.80	6.50	15.60
4	162.20	9.20	26.90	139.40	7.40	21.10
5	401.30	15.40	35.50	170.50	7.40	31.80
6	271.70	11.70	27.70	248.00	10.90	34.00
7	335.30	12.50	34.70	335.30	12.20	32.00
8	354.90	15.20	28.20	400.40	17.90	31.50
9	441.20	16.30	33.60	507.80	17.90	37.70
10	202.40	10.20	27.10	202.40	11.20	34.30
11	335.10	13.40	32.90	331.30	12.60	36.80
12	308.80	15.60	27.50	395.50	16.60	35.00
13	275.00	12.80	29.70	218.60	10.50	36.00

MARA	T2 Volume mm3	T2 A area mm2	T2 A length mm	T2 A width mm	T2 B area mm2	T2 B length mm	T2 B width mm
14	9,798.80	249.40	14.20	22.70	197.60	11.20	23.60
15	11,931.60	320.40	18.20	25.80	283.30	13.90	21.80
16	10,104.00	162.40	14.50	20.60	158.70	12.80	17.70
17	12,119.00	297.50	16.40	21.50	197.10	12.40	16.00
18	28,457.80	751.00	26.60	33.30	318.70	17.00	27.40
19	17,287.10	436.90	19.20	27.80	282.00	13.90	28.50
20	16,940.20	532.10	20.60	31.70	249.90	10.90	28.90
21	11,292.70	366.70	18.30	26.30	146.50	9.40	10.00
22	7,141.90	235.90	14.60	20.90	117.90	10.30	14.10
23	7,221.70	267.10	14.80	20.00	124.00	8.90	18.50
24	16,756.30	557.50	24.10	28.00	207.80	10.60	23.50
25	9,906.20	372.30	19.20	27.20	256.60	14.90	19.50
26	15,732.90	492.90	23.30	28.90	130.40	17.80	15.60

MARA	T2 C area mm2	T2 C length mm	T2 C width mm	T2 D area mm2	T2 D length mm	T2 D width mm
14	177.60	9.10	27.90	88.90	7.60	20.00
15	312.30	12.10	32.70	316.60	14.20	34.60
16	171.50	10.60	22.10	147.30	9.60	25.00
17	285.80	15.20	24.80	293.60	14.20	28.20
18	467.00	17.40	32.60	464.40	18.50	35.20
19	322.50	11.30	37.40	397.40	18.90	37.10
20	293.80	13.20	29.20	302.00	13.40	28.60
21	226.00	10.00	32.90	304.20	11.50	32.30
22	155.40	10.60	24.70	190.40	9.50	32.50
23	135.50	10.00	18.90	95.80	11.50	14.10
24	345.80	12.90	35.70	333.90	12.90	38.40
25	109.60	7.70	23.50	156.70	6.60	30.60
26	278.70	15.90	28.10	321.40	15.20	31.10

Herbst	Sex	T1 ANB	T1 OJ	T2 ANB	T2 OJ	T1 Volume mm3	T1 A area mm2	T1 A length mm	T1 A width mm	T1 B area mm2	T1 B length mm	T1 B width mm
1	F	4.8	11.3	1.8	2	14,418.50	88.20	3.80	17.80	130.10	15.90	11.10
2	M	2.9	3.8	1.1	2.6	7,303.60	336.80	19.00	22.00	126.30	9.30	17.60
3	F	2.9	3.8	1.8	2.2	7,728.80	150.70	13.70	14.30	103.90	10.90	11.10
4	F	5.2	5.8	4.3	2.3	9,785.20	259.90	12.60	26.10	142.80	16.60	12.90
5	F	3.5	5.4	2.4	5.5	11,241.80	330.70	16.10	28.80	348.00	18.50	23.30
6	M	7.4	5.1	4.5	2.9	11,494.50	233.00	14.10	20.20	129.30	17.80	10.20
7	M	4.6	5.8	2.3	3.4	11,251.10	365.20	20.30	24.00	247.60	16.90	18.40
8	F	5.7	5.8	3	3.5	13,755.40	284.60	15.40	25.70	192.80	12.30	19.60
9	M	3	3.8	1.9	2.9	16,104.40	482.60	21.60	30.10	250.90	15.70	23.90

Herbst	T1 C area mm2	T1 C length mm	T1 C width mm	T1 D area mm2	T1 D length mm	T1 D width mm
1	360.20	16.30	29.30	426.90	20.60	31.20
2	170.50	11.90	23.70	151.30	9.90	28.40
3	150.00	9.60	21.70	126.30	8.30	25.50
4	327.70	16.30	26.60	300.50	14.30	29.70
5	321.80	15.50	26.40	334.60	17.30	23.30
6	328.40	17.00	27.40	383.90	16.60	32.70
7	289.80	15.00	25.90	350.10	16.20	31.50
8	231.70	10.80	26.50	368.90	16.70	31.90
9	399.40	14.90	30.40	327.90	16.50	28.60

Herbst	T2 Volume mm3	T2 A area mm2	T2 A length mm	T2 A width mm	T2 B area mm2	T2 B length mm	T2 B width mm
1	10,848.50	223.50	17.20	11.30	74.00	13.70	9.10
2	13,265.10	300.90	17.00	21.50	165.40	9.50	21.20
3	9,379.00	264.60	18.00	21.60	153.90	11.20	16.50
4	15,099.80	376.10	17.60	32.60	443.20	12.30	37.50
5	9,879.10	320.70	18.90	26.90	172.20	11.40	20.90
6	15,662.50	374.10	16.70	23.60	200.20	16.40	15.50
7	18,719.50	424.90	19.30	29.00	336.90	16.50	24.40
8	6,731.70	247.50	13.70	18.90	126.60	8.90	16.60
9	18,744.70	521.90	22.70	32.70	199.00	10.90	26.40

Herbst	T2 C area mm2	T2 C length mm	T2 C width mm	T2 D area mm2	T2 D length mm	T2 D width mm
1	213.20	23.70	11.90	284.90	30.40	14.80
2	290.00	12.50	32.50	253.50	13.00	36.30
3	176.10	9.80	25.10	132.00	7.10	30.40
4	306.60	13.70	29.20	275.70	12.00	31.50
5	169.80	10.90	22.90	322.10	16.90	28.90
6	348.10	16.50	26.90	333.80	15.50	35.10
7	409.30	15.70	33.10	450.20	18.40	33.60
8	133.30	10.70	17.00	96.10	11.10	14.10
9	271.10	11.50	30.30	394.80	16.00	34.80

Control	Sex	ANB T1	OJ T1	ANB T2	OJ T2	Volume mm3	T1 A area mm2	T1 A length mm	T1 A width mm	T1 B area mm2	T1 B length mm	T1 B width mm
1	M	2.5	2.2	1.6	1.9	15,607.90	245.00	11.70	26.40	193.50	8.50	26.00
2	F	2	2.8	1.5	3.1	14,520.10	227.50	12.40	22.00	335.50	19.70	19.70
3	M	1.2	3.9	1.2	2.7	3,872.40	108.90	11.00	12.30	64.70	8.50	9.10
4	F	3.6	4.4	2.3	2	9,465.90	275.40	13.40	25.50	70.60	9.20	8.30
5	M	2.3	2.9	2.1	3.2	9,200.80	227.30	14.40	21.90	123.50	10.10	13.80
6	F	2.2	3.6	2	2.8	16,858.30	289.10	13.40	24.90	197.70	13.10	15.90
7	F	3.5	1.7	3.7	2.3	7,917.40	382.30	20.40	27.20	83.30	6.70	14.00
8	M	2.4	3.6	4.4	3.2	11,055.40	227.50	15.10	17.80	153.10	17.00	10.20
9	F	2.9	4.7	3.3	2.8	10,061.80	226.60	15.20	21.60	142.00	12.10	16.00
10	F	3.6	4	3.6	4.9	8,281.90	268.00	16.80	20.60	140.30	9.70	16.30
11	M	2.7	2.6	1	2.8	32,022.30	437.80	19.20	27.90	605.80	21.20	34.60
12	F	2.2	3.2	3	2.5	13,198.20	75.30	4.50	17.90	250.80	15.30	20.10
13	M	2.3	2.9	0.4	3.4	26,621.80	499.40	22.80	29.90	337.00	20.80	27.50

Control	T1 C area mm2	T1 C length mm	T1 C width mm	T1 D area mm2	T1 D length mm	T1 D width mm
1	300.60	11.00	34.20	354.30	14.90	29.20
2	415.30	21.80	28.30	493.70	24.80	28.10
3	78.60	8.50	11.60	74.10	7.50	13.20
4	154.30	8.00	25.80	308.50	13.40	35.00
5	231.70	13.30	27.10	189.80	10.20	29.90
6	300.20	13.70	27.40	223.40	15.60	19.10
7	115.00	6.40	20.70	169.60	11.30	24.20
8	268.40	14.40	27.20	201.00	12.10	31.40
9	176.00	11.60	21.40	271.20	16.50	28.60
10	136.70	7.40	24.20	90.80	10.90	10.90
11	668.50	21.90	39.00	487.50	18.50	38.70
12	315.20	14.40	28.00	234.60	12.80	29.30
13	497.40	20.40	31.40	468.60	21.40	34.10

Control	S ex	ANB T1	OJ T1	ANB T2	OJ T2	Volume mm3	A area mm2	A length mm	A width mm	B area mm2	B length mm	B width mm
14	F	2.7	3.8	1.7	4.1	6,601.10	192.20	15.00	20.60	30.40	5.40	9.30
15	M	1.7	5.9	0.8	3.6	11,635.00	399.40	18.00	28.30	142.30	9.40	17.20
16	F	2.9	2.5	0.9	2.9	19,830.80	618.50	26.40	28.20	329.30	17.40	25.50
17	M	3.4	3.2	1.3	3	9,170.60	412.50	18.40	29.90	92.90	7.30	21.00
18	M	1.4	0.4	0.1	3	13,320.60	416.20	23.30	23.00	187.10	16.50	13.30
19	M	2.7	6.7	3.8	3.2	16,418.70	244.20	16.90	22.40	297.00	17.20	20.60
20	M	1.5	3.5	1.7	2.6	8,195.50	203.20	14.80	18.00	120.40	10.60	17.30
21	M	1.3	3.5	2.1	2	11,996.80	471.10	22.00	29.10	162.50	15.80	14.50
22	M	1.7	6	0.3	4.6	9,515.40	444.00	20.70	26.10	129.50	10.90	13.30
23	M	1.1	7.9	2.8	0.6	9,384.10	120.90	11.00	14.60	253.00	16.50	16.50
24	M	2	1.7	3.5	2.6	13,144.10	257.20	14.30	23.60	248.00	20.00	18.50
25	M	1	3.7	3.7	0.7	14,327.80	500.10	26.10	28.60	270.10	17.70	24.00

Control	T1 C area mm2	T1 C length mm	T1 C width mm	T1 D area mm2	T1 D length mm	T1 D width mm
14	133.20	15.90	15.00	188.20	13.30	25.00
15	103.10	5.70	22.60	222.20	11.40	29.50
16	334.60	16.70	25.00	286.70	17.90	25.80
17	107.40	8.90	23.50	186.30	12.80	31.10
18	293.60	16.70	24.80	247.90	19.70	20.00
19	344.90	17.00	26.60	391.50	19.40	32.10
20	233.00	13.80	26.10	114.30	9.20	18.40
21	182.10	12.50	20.80	275.10	15.80	33.60
22	92.70	7.80	20.70	116.00	10.60	14.00
23	265.40	15.00	22.40	223.90	16.10	28.70
24	303.90	14.80	27.50	404.00	21.50	27.50
25	295.40	16.60	27.90	280.80	17.30	15.80

Control	T2 Volume mm3	T2 A area mm2	T2 A length mm	T2 A width mm	T2 B area mm2	T2 B length mm	T2 B width mm
1	11,277.70	239.60	10.90	25.50	190.90	11.40	21.80
2	12,178.80	267.20	15.70	22.90	240.80	14.60	19.70
3	7,785.10	196.70	13.70	19.40	122.70	13.00	12.40
4	20,469.20	366.00	17.50	27.50	213.10	16.60	19.70
5	8,490.30	225.00	12.80	22.80	142.60	11.40	16.40
6	16,581.50	352.30	17.20	24.50	220.10	14.50	17.80
7	14,222.50	452.60	23.10	24.20	179.50	12.10	22.10
8	19,736.40	256.20	16.70	17.90	308.80	20.10	21.60
9	8,604.30	79.70	11.00	11.30	124.50	13.20	13.90
10	13,591.70	305.60	17.30	23.60	223.40	11.40	22.20
11	35,618.20	679.60	21.30	33.20	724.00	23.30	34.90
12	12,909.40	315.70	14.80	20.30	241.50	14.80	21.50
13	29,954.00	512.10	21.50	28.90	402.60	23.50	23.20

Control	T2 C area mm2	T2 C length mm	T2 C width mm	T2 D area mm2	T2 D length mm	T2 D width mm
1	252.70	9.70	30.90	280.60	12.90	41.50
2	239.70	14.70	21.70	336.10	18.90	26.30
3	143.50	13.00	14.40	143.50	14.70	18.40
4	333.90	15.80	28.90	466.80	19.20	35.50
5	258.30	15.30	27.40	150.00	8.20	24.60
6	246.80	11.40	28.30	232.20	14.00	18.50
7	231.00	10.30	26.30	240.90	12.10	28.50
8	528.90	23.30	30.20	355.00	17.90	32.80
9	171.10	10.40	21.90	322.20	16.70	30.90
10	205.50	9.00	29.50	186.60	13.10	20.10
11	461.00	16.90	35.50	314.40	12.00	38.30
12	274.80	15.50	23.60	188.70	12.10	25.40
13	590.60	20.90	36.60	591.40	22.90	35.20

Control	T2 Volume mm3	T2 A area mm2	T2 A length mm	T2 A width mm	T2 B area mm2	T2 B length mm	T2 B width mm
14	6,775.50	291.90	19.60	20.30	129.60	17.40	12.50
15	14,037.80	480.90	21.50	31.50	171.90	11.50	18.60
16	16,061.00	440.30	19.80	26.30	257.00	13.90	20.60
17	7,831.80	298.60	16.10	25.10	75.60	5.40	18.40
18	13,385.70	411.20	20.30	24.80	203.60	17.80	13.00
19	13,767.30	288.40	18.70	20.20	244.30	18.70	16.80
20	10,810.40	441.30	23.10	26.40	148.70	11.00	15.70
21	16,069.00	456.50	23.90	22.90	223.40	17.50	17.80
22	9,781.70	404.60	19.40	25.40	136.70	12.40	13.40
23	10,484.80	273.60	18.10	22.10	282.90	20.80	17.70
24	20,494.50	419.50	20.20	23.70	391.00	25.10	22.60
25	22,695.20	652.50	26.90	36.70	408.70	19.40	26.80

Control	T2 C area mm2	T2 C length mm	T2 C width mm	T2 D area mm2	T2 D length mm	T2 D width mm
14	249.60	14.40	21.70	259.40	14.60	27.60
15	172.10	9.00	27.70	266.40	12.90	32.90
16	282.90	14.00	25.20	272.30	15.70	20.90
17	137.20	9.40	24.80	188.80	13.00	27.80
18	317.40	21.30	24.10	312.20	22.60	28.30
19	244.70	13.50	25.40	353.00	15.30	36.30
20	220.20	11.70	26.40	233.60	18.70	23.40
21	216.60	15.60	17.50	288.00	16.50	33.40
22	152.00	8.10	23.30	95.30	9.90	15.20
23	327.20	18.70	24.50	351.10	25.50	30.40
24	477.00	18.70	33.90	443.60	21.90	31.10
25	450.30	15.90	32.10	342.30	14.80	34.20