CASE WESTERN RESERVE UNIVESRITY
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THE RELATIONSHIP BETWEEN THE HYOID BONE AND THE UPPER AIRWAY

by

ADRIANO FARINA, D.M.D.

Submitted in partial fulfillment of the requirements for
the degree of Master of Science in Dentistry

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~~[December 11, 2014]~~January 16, 2015

DEDICATION

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My parents, Frank and Mary, and my brother Sasha, for always being there and encouraging me to do something that I love. Without your support over the years, I would have never made it this far. You've been instrumental in molding me into the person I am today, and for that, I can never thank you enough.

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Thank you Dr. Palomo for helping bring this project to life. You continued to challenge me and make this project the best it could possibly be. Your extensive knowledge of the airway and imaging proved to be invaluable throughout this process. Without your guidance this project would have never turned out the way it did. Most importantly, I want to thank you for choosing to accept me into what I believe is the best orthodontic program in the world.

Thank you Dr. Hans, not only for accepting me into the program, but being a pivotal figure throughout my research. Thank you for helping me bridge the gap between the research I conducted and its clinical application. It never ceases to amaze me how one person can be so knowledgeable about so many different topics.

Dr. Venkat, I want to thank you for all the time you spent helping me understand the airway. Thank you for replying to my hundreds of emails and meeting me at all hours of the day and night. I, along with the whole department of orthodontics, are incredibly lucky to have the privilege to have worked with such a caring and excellent physician. Because of all the contributions you've made with my project, ~~we (need to reprase possibly~~ the orthodontic department ~~will~~ is looking forward to

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collaborating with your department for many years to come.

Finally I would like to thank all of my classmates. It's been an incredible experience that I will never forget. The bonds we've formed will last forever. When I moved to Cleveland over two years ago, not only did I gain many new friends, but I feel that I've become part of a very special family. You will all be greatly missed.

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ABSTRACT

THE RELATIONSHIP BETWEEN THE HYOID BONE AND THE UPPER AIRWAY

by

ADRIANO FARINA

The objective of this study was to investigate if there is an association between the 3-dimensional position and width of the hyoid bone, and the morphology of the upper airway (oropharyngeal volume, nasopharyngeal volume, total volume and minimum axial area). Forty-seven (47) patients from CWRU's Core orthodontic clinic having pre-treatment CBCT radiographs were examined: 28 female and 19 male. CBCT radiographs visibly demonstrated all appropriate landmarks in order to examine the hyoid bone and the upper airway. Exclusion criteria included patients with evidence of congenital craniofacial deformities, detectable pharyngeal pathology through inspection of the images, nasal obstruction, scans showing incomplete imaging of the airway, and extreme mandibular plane measurements (FMA <19 or >31). All measurements were conducted using Dolphin imaging software. Oropharyngeal (OP) volumes and nasopharyngeal (NP) volumes were measured and summed to provide the total upper airway volume. In addition, the most constrictive

axial area (MinAx) was also recorded. Hyoid bone position was recorded in three dimensions, along with the inter-greater horn distance.

Vertical markers of hyoid bone position were shown to have no significant correlation with the morphology of the upper airway. However, both the sagittal position of the hyoid bone and width of the hyoid bone were found to be significantly correlated with the OP volume, and consequently the total airway volume ($p < 0.05$). Additionally, the MinAx was found to be significantly correlated with the sagittal position of the hyoid bone ($p < 0.05$). 32.3% of the variability in the OP volume could be predicted using the hyoid bone's 3D position and width.

We conclude that the vertical and mediolateral position of the hyoid bone doesn't seem to influence the airway parameters studied in this project. The sagittal position of the hyoid bone has a significant positive correlation with the OP volume and the MinAx, while the width of the hyoid bone has a significant positive correlation with the OP volume.

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LITERATURE REVIEW~~reg~~REVIEW ~~no underline~~

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A critical step in orthodontic diagnosis and treatment planning involves the taking of radiographic images. In the past, the lateral cephalogram and panoramic radiograph were considered to be the gold standard. As research in the field of radiology has progressed, new methods of imaging have entered into the arena of orthodontics. Cone-beam computed tomography (CBCT) provides a three-dimensional view of the hard and soft tissue structures of the head and neck. As we transition from two to three dimensional imaging, there are more opportunities to investigate the anatomical characteristics of our patients.

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Imaging in Orthodontics

Because a lateral cephalogram is a 2D image of a complex 3D structure, it has numerous limitations, including "distortion, differences in magnifications, superimposition of the bilateral craniofacial structures, and in addition, a low reproducibility as a result of difficulties in landmark identification" (Lenza 2010). Sagittal linear measurements of the airway have been found to have a weak correlation with transverse linear measurements, most cross-sectional areas and most partial

volumes of the upper airway. Additionally, the upper airway cannot be accurately described using a single linear measurement obtained from a 2D image. Furthermore, reporting the total airway volume doesn't tell the investigator anything about the 3D morphology of the airway. Magnetic resonance imaging has shown that the difference in airway caliber between apneic and normal subjects is due more to the size and thickness of the lateral pharyngeal walls, than the anteroposterior measurements of the airway (Schwab 1995). This illustrates how sagittal and vertical measurements of the airway may be misleading when there is a restriction in the transverse dimension.

Although a single linear measurement cannot accurately describe the morphological characteristics of the airway, the area of most constricted region at the base of the tongue in the axial view (MinAx), is the variable that demonstrates the best correlation with the oropharyngeal volume. (El Hakan and Palomo, 2011, 2013)

Despite the fact that airway size may predispose individuals to pharyngeal collapse, the morphology and elliptical orientation of the airway may be more important. Leiter et al (1996) found that people with obstructive sleep apnea (OSA) tend to have airways that are elliptically shaped along the anteroposterior

direction. This elliptical orientation may negatively affect the activity of the upper airway musculature.

Because of its ability to obtain fast and complete images at a reasonable cost, CBCT imaging has become a viable way to examine the upper airway instead of MRI and conventional CT scans (Osorio 2008). Various investigators have shown that by adjusting various settings, CBCT imaging allow us to see the intricate details of the upper airway while limiting the radiation dose the individual is subjected to (Osorio 2008, Palomo 2007)

In orthodontics, most investigations of the airway have primarily revolved around 2D lateral cephalograms. While the airway is a complex 3D structure, lateral cephalograms are only able to provide the investigator with linear and angular measurements (El Hakan and Palomo ~~bring this up possibly take out some spaces above2010~~2010). ~~).~~

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Airway volumes can be calculated through automatic or manual segmentation. Segmentation of the airway involves the demarcation and removal of adjacent structures to highlight the region of interest. Manual segmentation is a time consuming process, whereby the investigator must delineate the airway region on each

slice of the CBCT, and then combine these measurements to produce a volume. Automatic segmentation relies upon the soft tissues surrounding the airway having higher density values than the airway itself. By identifying the density of the airway voxels, one can then differentiate the airway from the neighboring soft tissue structures and calculate the airway volume in a quicker fashion. Although manual segmentation provides a more accurate measurement of airway volumes compared to automatic segmentation, it's time consuming nature make its clinical applicability impractical. El Hakan and Palomo (2010) demonstrated that measuring the airway using automatic segmentation was very reliable, but was less accurate when compared to manual segmentation. Systematic errors introduced during the segmentation process tend to overestimate or underestimate the airway volumes.

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Pharyngeal Morphology and Growth

The pharynx consists of three principal regions; the nasopharynx, oropharynx and hypopharynx. Because of its intimate association with the oral and nasal cavity, the pharynx plays a pivotal role in speech, respiration and deglutition. Inferiorly the pharynx divides into an anterior and posterior segment. The anterior division becomes the larynx of the respiratory

tract, and the posterior division becomes the esophagus of the digestive tract (Donner, 1985).

Prior to examining if there is a relationship between the hyoid bone and the upper airway, one must understand how the hard and soft tissue structures of the oropharyngeal region change over time. Taylor et al (1996) examined healthy, orthodontically untreated children in order to elucidate the pattern of bony and soft tissue growth of the oropharynx. Lateral cephalograms of thirty-two patients were examined at the ages of 6, 9, 12, 15 and 18 years of age. Hard and soft tissue tracings were compiled at different ages in order to generate tracing templates. Pharyngeal soft tissues exhibited two periods of accelerated change (6-9 years and 12-15 years) and two periods of quiescence (9-12 years and 15-18 years). Beginning at age 9, the soft palate increased in both length and thickness. The increase in airway size that occurs from ages 6-9 is thought to occur due to continued growth of the pharyngeal region, surgical removal of adenoid tissue and the natural involution of adenoid tissue, either alone or in combination with one another. The same three mechanisms are suspected to play a role in the increase of the airway during the 12-15 year old time period. Moreover, inferior regions of the airway located below

the tonsils and adenoids also demonstrated these periods of growth and quiescence.

Hyoid Bone Position and Morphology

The hyoid bone is the only bone in the head and neck region without a bony articulation. It lies freely suspended by muscles that are integrally related to the pharyngeal region. Its muscle attachments can be described as belonging either to the suprahyoid or infrahyoid groups. Arising from the cartilages of the 2nd and 3rd branchial arches, the hyoid bone consists of a central body which then projects posteriorly as a left and right greater horn. Attaching to the superior surface of the hyoid bone are the left and right lesser horns (Moore 2007). Papadopoulos et al (1989), used the hyoid bones from 76 cadavers to demonstrate their lack of symmetry. Among their sample, almost 50% of hyoid bones were found to be asymmetric in the transverse dimension. Nearly 60% of the hyoid bones examined displayed some difference in the extension of the greater horns.

A combination of linear and angular measurements show that the hyoid bone descends and moves slightly anteriorly up to age 18. Anterior movement of the hyoid bone is postulated to be related to the forward translation of the mandible that occurs during

cephalocaudal skeletal growth. The descent of the hyoid bone may be explained by the growth of the cervical vertebrae. The combined anterior and downward displacement results from the hyoid bone being suspended between the cervical vertebrae and the mandible (Taylor, 1996).

The hyoid bone position is determined by the combined activity of the suprahyoid and infrahyoid muscle groups, with the upper airway (UA) dilator muscles being of great importance. It is believed that an increase in upper airway resistance occurs when the contractile properties of these muscle groups change, and there is a loss in the compensatory muscular mechanisms designed to establish upper airway patency, also resulting in a change in hyoid bone position (Verin, 2002)

Behlfelt et al (1990) concluded that age was positively correlated with linear measurements of sagittal and vertical posture of the hyoid bone. Enlarged tonsils can impinge on the upper airway, leading to a restricted passage and smaller airway volumes. They observed that children with enlarged tonsils had a more caudally positioned hyoid bone with respect to the mandibular plane (H-MP). When comparing the sagittal position of the hyoid bone, either in relation to the cervical spine or to gnathion, no significant differences

were found between controls and subjects with enlarged tonsils. Cohen et al (1976) found that during growth and development, the tongue increases in size and becomes larger with respect to the intermaxillary space, especially in males. This disproportionate increase in tongue mass relative to the oral cavity may lead to the tongue moving downwards an as individual grows. This descent of the tongue may play a role in the inferior and anterior movement of the hyoid bone that occurs as one ages.

Just like Taylor et al, Nelson et al (2003) found that the H-MP distance increased over time, irrespective if the person was a snorer or not. Their study demonstrated that there was a trend for snorers to have a greater H-MP distance during the prepubertal and pubertal period ($P < 0.10$). Likewise, adult snorers displayed a significantly larger H-MP distance ($P < 0.05$) compared to nonsnoring controls. Hyoid bone position can potentially be influenced by anatomic variables, neuromuscular control and even deposition of fat in the neck region. Sforza et al (2000) hypothesized that excessive submental fat deposition in obese patients could be responsible for moving the hyoid bone further inferiorly.

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Airway Function and Hyoid Bone Position

An effective approach to decreasing upper airway collapsibility involves decreasing the resistance to airflow along the airway. Patients with a maxillary transverse deficiency often have a smaller cross-sectional area of the airway, contributing to their increased nasal airway resistance. Surgical and orthopedic expansion of the maxilla has been shown to significantly increase the nasal airway volume and minimal cross sectional area, thus decreasing the resistance to nasal airflow.

Upon examining lateral cephalograms, Sforza et al (2000) showed that differences in the position of the hyoid bone and measurements of the posterior airway space exist between control subjects and snorers. They proposed that the pharyngeal critical pressure (Pcrit), which represents the minimal airway pressure required to allow airflow to pass through the upper airway, plays a central role in pharyngeal collapsibility. Upon examining male patients w/ OSA, it was found that Pcrit had a

significant correlation with the distance from the hyoid bone to the posterior pharyngeal wall ($r = 0.29$, $p = 0.03$) and the vertical position of the hyoid bone ($r = 0.32$, $p = 0.02$). A lower hyoid position was theorized to predispose a subject to pharyngeal collapse by influencing their Pcrit, thus somewhat contributing to their OSA.

Verin et al (2002) demonstrated that segmental upper airway resistance (UAR) was correlated with the posterior airway space (PAS) and the distance from the hyoid bone to the mandibular plane and the distance from the hyoid bone to the posterior pharyngeal wall (H-Ph) ($P < 0.05$). Patients with OSA displayed a greater UAR which was linked to various anatomical variables, especially the position of the hyoid bone. A more downward and anterior position of the hyoid bone was demonstrated in OSA subjects compared to both snorers and normal subjects.

Van de Graaff et al (1984) conducted a study on anesthetized dogs, and observed how the hyoid arch and the muscles that attach to it can act to maintain and increase the patency of the upper airway and can affect upper airway resistance. They demonstrated that moving the hyoid arch ventrally, via wire traction or by stimulating hyoid muscles, significantly decreased the UA resistance during the inspiratory and expiratory phases.

Additionally the ventral movement of the hyoid arch also resulted in expansion the airway. The muscles of the hyoid arch, which play a crucial role in establishing the UA morphology, demonstrated changes in muscle activity in response to chemical, vagal and negative pressure stimuli.

Influence of RME on Hyoid Bone Position and Airway Volumes

Links between hyoid position and airway resistance have been demonstrated in the literature. Because maxillary transverse deficient patients receiving orthopedic maxillary expansion experience a decrease in nasal airway resistance, Phoenix et al (2011), investigated if rapid maxillary expansion (RME) had any association with the position of the hyoid bone relative to the mandibular plane. When comparing controls to patients who received RME to treat a transverse maxillary deficiency, the group receiving RME was found to have a larger H-MP distance prior to orthodontic intervention. After orthodontic treatment, the RME group experienced a decrease in the H-MP distance, while the H-MP distance increased in the non-RME group. The pretreatment difference in H-MP distance between the two groups was eliminated, thus illustrating that RME tends to normalize

hyoid bone position.

The changes in hyoid bone position as a result of RME have been clearly described. In their study, El Hakan and Palomo (2013), revealed that patients with a maxillary transverse discrepancy receiving RME experienced a significant increase in the volume of the nasopharynx. The mean increase in the volume of the NP region was more than twice as large in the RME group compared to the control group (1719.9 ± 1510.7 vs. 813.6 ± 1006.7, p=0.006). However, a significant increase in the OP volume wasn't detected in the RME patients compared to the controls.

Upper Airway Volume

Various airway parameters can be significantly different among subjects with different maxillary and mandibular positions. In an attempt to describe how sagittal jaw position could affect the upper airway, El Hakan and Palomo (2011) compared different airway properties among patients with various sagittal skeletal relationships. The OP volume was significantly smaller in Class II patients compared to Class I and Class III patients. As the mandible assumed a more anterior position the OP volume became larger, while a more posteriorly positioned mandible was assumed to position

the tongue and soft palate backwards into the oropharynx thereby decreasing its volume. The NP volume only showed statistically significant differences between the Class II and Class I groups, whereby the NP volume was smaller when the mandible assumed a more retruded position. In 2013, El Hakan and Palomo, further distinguished patients with different sagittal jaw relationships by examining whether the maxilla or mandible was responsible for the skeletal imbalance. The PAS, the MinAx and the OP volume were found to be the smallest in Class II patients with mandibular retrognathism and highest in Class III patients with mandibular prognathism. Compared to Cl II subjects with mandibular prognathism, Cl I patients had a significantly larger NP volume. This illustrates both the role of mandibular positioning on the configuration of the upper airway, as well as the importance of segmenting the upper airway into oropharyngeal and nasopharyngeal compartments when conducting airway measurements.

Likewise, Grauer et al (2009) examined whether vertical or sagittal jaw position affected airway volumes. The upper airway was divided into a superior and inferior compartment and combined to provide a total volume measurement. They observed a significant difference in the inferior compartment volume between different A-P skeletal relationships. No significant

difference in the superior compartment volumes was found for different A-P skeletal relationships. Additionally, no significant differences in the inferior, superior and total airway volumes among the long, normal and short faced groups were demonstrated in this study. Conflicting results between various studies may be explained by the use of different anatomical boundaries in order to segment the airway into various compartments.

Peters-Schuster et al (2009) set out to determine if there was any significant difference in the NP and OP volumes between males and females who were 12 and 13 years old. Using CBCT radiographs obtained for orthodontic diagnosis, they concluded that there was no significant difference in the OP or NP volumes between males and females at 12 nor 13 years old. Because of the lack of difference between sexes, the male and female samples were combined to examine if there was any difference in airway volumes between 12 and 13 year old subjects. Once again, no significant difference was found. Interestingly, BMI didn't account for significant differences in NP nor OP volumes.

Although a population of subjects may demonstrate a large range of possible airway volumes, Sullivan et al (2010), obtained airway volumes from the CBCTs of 50 patients under 18 years old undergoing orthodontic

treatment. Among their sample, the OP volume increased 0.98 ±1.17 CC/year and NP volume increased 1.05 ±0.89 CC/year. No significant difference in the rate of volume change was observed for age, gender, ethnicity, treatment duration nor use of RME.

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STATEMENT OF THE THESIS

The objective of this study was to examine if a relationship existed between the three-dimensional position and width of the hyoid bone, and the morphology of the upper airway, utilizing CBCT imaging. Forty-seven subjects had airway volumes and the most constricted area obtained through automatic segmentation of the airway. The same subjects then had the position of the hyoid bone recorded in three

dimensions, as well as the hyoid bone width, from CBCT images.

It was hypothesized that no relationship existed between the hyoid bone position and width, and airway volumes and most constricted axial area. If rejected, patients with a particular hyoid position and width would have a tendency to have larger airway volumes and minimum cross sectional area.

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MANUSCRIPT

The Relationship Between the Hyoid Bone and the Upper Airway

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ABSTRACT

THE RELATIONSHIP BETWEEN THE HYOID BONE AND THE UPPER AIRWAY

by

ADRIANO FARINA

The objective of this study was to investigate if there is an association between the 3-dimensional position and width of the hyoid bone, and the morphology of the upper airway (oropharyngeal volume, nasopharyngeal volume, total volume and minimum axial area). Forty-seven (47) patients from CWRU's Core orthodontic clinic having pre-treatment CBCT radiographs were examined: 28 female and 19 male. CBCT radiographs visibly demonstrated all appropriate landmarks in order to examine the hyoid bone and the upper airway. Exclusion criteria included patients with evidence of congenital craniofacial deformities, detectable pharyngeal pathology through inspection of the images, nasal obstruction, scans showing incomplete imaging of the airway, and extreme mandibular plane measurements (FMA <19 or >31). All measurements were conducted using Dolphin imaging software. Oropharyngeal (OP) volumes and nasopharyngeal (NP) volumes were measured and summed to provide the total upper airway volume. In addition, the most constrictive axial area (MinAx) was also recorded. Hyoid bone position was recorded in three dimensions, along with the inter-greater horn distance.

Vertical markers of hyoid bone position were shown to have no significant correlation with the morphology of the upper airway. However, both the sagittal position of the hyoid bone and width of the hyoid bone were found to be significantly correlated with the OP volume, and consequently the total airway volume ($p < 0.05$). Additionally, the MinAx was found to be significantly correlated with the sagittal position of the hyoid bone ($p < 0.05$). 32.3% of the variability in the OP volume could be predicted using the hyoid bone's 3D position and width.

We conclude that the vertical and mediolateral position of the hyoid bone doesn't seem to influence the airway parameters studied in this project. The sagittal position of the hyoid bone has a significant positive correlation with the OP volume and the MinAx, while the width of the hyoid bone has a significant positive correlation with the OP volume.

INTRODUCTION

Imaging as always been a key concept in orthodontic diagnosis and treatment planning. Cone-beam computed tomography (CBCT) provides a three-dimensional view of the hard and soft tissue structures of the head and neck, allowing us to examine areas, volumes and complex hollow structures, including the airway, all while being able to modulate the radiation dose[6,11,12]. Though the relationship between the hyoid bone and the airway remains controversial, both structures are readily identifiable on routine CBCT images. Lenza et al[9] showed that the "upper airway cannot be accurately expressed by single linear measurements as performed on cephalograms". Furthermore, reporting the total airway volume doesn't tell the investigator anything about the 3D morphology of the airway. 2D imaging fails to examine the transverse dimension of the airway which often has a large implication on the airway morphology and function[16]. Although a single linear measurement cannot accurately describe the morphological characteristics of the airway, the most constricted area at the base of the tongue in the axial view (MinAx), is the variable that demonstrates the best correlation with the oropharyngeal volume [4, 5].

Airway volumes can be measured on CBCT images through a variety of methods. Automatic segmentation of the airway has been shown to be a reliable way to report the oropharyngeal (OP) and the nasopharyngeal (NP) volume, while being much more time efficient compared to manual segmentation[6].

Prior to examining if there is a relationship between the hyoid bone and the

upper airway, one must understand how the hard and soft tissue structures of the oropharyngeal region change over time. Taylor et al[17] examined healthy orthodontically untreated children in order to elucidate the pattern of bony and soft tissue growth of the oropharynx. Airway size was found to increase due to continued growth of the pharyngeal region, surgical removal and natural involution of adenoid tissue, either alone or in combination with one another. Additionally it was show that the hyoid bone descends and moves slightly anteriorly up to age 18. Many studies[1,2,10] have reported that the hyoid bone descends and moves anteriorly during growth and development.

The hyoid bone position is determined by the combined activity of the suprahyoid and infrahyoid muscle groups, with the upper airway (UA) dilator muscles being of great importance. It is believed, that an increase in upper airway resistance (UAR) occurs when the contractile properties of these muscle groups change, and there is a loss in the compensatory muscular mechanisms designed to establish UA patency, also resulting in a change in hyoid bone position[18]. Moreover, it has been demonstrated that segmental UAR was correlated with the posterior airway space (PAS), the distance from the hyoid bone to the mandibular plane (H-MP) and the distance from the hyoid bone to the posterior pharyngeal wall (H-Ph) ($P < 0.05$). Additional investigations have also shown that subjects with enlarged tonsils[1] or excessive submental fat deposition[15], both of which can affect airway morphology, may have changes in the vertical position of the hyoid bone, and occasionally the sagittal position.

Links between hyoid position and airway resistance have been demonstrated in the literature. An effective approach to decreasing upper airway collapsibility involves decreasing the resistance to airflow along the airway. Patients with a maxillary transverse deficiency have a smaller cross-sectional area of the airway, contributing to increased nasal airway resistance. Rapid maxillary expansion (RME) has been shown to significantly increase the nasal airway volume and minimal cross sectional area, thus decreasing the resistance to nasal airflow. Phoenix et al[14], investigated if RME had any association with the position of the hyoid bone relative to the mandibular plane. When comparing controls to patients who received RME to treat a maxillary transverse deficiency, the group receiving RME was found to have a larger distance from the H-MP prior to orthodontic intervention. After orthodontic treatment, the RME group experienced a decrease in the H-MP distance, while the H-MP distance increased in the non-RME group. The pretreatment difference in H-MP between the two groups was eliminated, thus illustrating that RME tends to normalize hyoid bone position.

As the changes in hyoid bone position as a result of RME have been clearly outlined, it has been proven that RME also causes a significant increase in the volume of the nasopharynx. El Hakan and Palomo[7] demonstrated that the mean increase in the volume of the NP region was more than twice as large in the RME compared to the control group (1719.9 ± 1510.7 vs. 813.6 ± 1006.7, $p=0.006$). However, a significant increase in the OP volume wasn't detected in the RME patients compared to controls.

The influence of mandibular and maxillary sagittal position on airway morphology has been clearly illustrated[4,5,8]. The posterior airway space, the MinAx and the OP volume were found to be the smallest in Class II patients with mandibular retrognathism and highest in Class III patients with mandibular prognathism. A more posteriorly positioned mandible is assumed to position the tongue and soft palate backwards into the oropharynx, thereby decreasing its volume. The NP volume showed statistically significant differences between the Class II and Class I groups, whereby the NP volume was smaller when the mandible assumed a more retruded position. Because of its intimate involvement of the tongue, it's postulated that the hyoid bone position would change in patients with different skeletal jaw relationships. It seems plausible that a relationship may exist between the 3D position of the hyoid bone and the upper airway morphology, yet no study to date has examined this relationship using CBCT imaging.

MATERIALS AND METHODS

Sample Selection

70 patients were randomly selected from Case Western Reserve University's Core teenage clinic. All patients to be included in the study had a pre-operative CBCT taken for diagnostic purposes. All CBCTs needed to demonstrate the appropriate landmarks necessary to perform the appropriate measurements. In addition patients were required to have completed medical history forms and online dental charts. Exclusion criteria included patients with evidence of congenital

craniofacial deformities, detectable pharyngeal pathology through inspection of the CBCT images, visible nasal obstruction/masses, scans with incomplete imaging of the airway, poor demarcation of the airway-soft tissue interface of the pharynx, scans showing incomplete imaging of the airway, and extreme vertical mandibular plane measurements (FMA <19 or >31). After applying the inclusion and exclusion criteria, 47 patients (28 female, 19 male) comprised the sample group.

Data Collection

Descriptive information on each patient was obtained from the completed dental history forms and online dental charts. CBCT images were attained using a Hitachi CB Mercuray Scanner (Hitachi Medical Systems America, Twinsburg, Ohio). All radiographs were taken prior to the commencement of this study for diagnostic purposes. The radiographs were taken with a 2mA, 120kVp and 12-in field of view (F mode) setting. Every radiograph was comprised of 512 slices, with a slice thickness of 0.3777 mm, a resolution of 1024 x 1024 pixels, and 12 bits per pixel (4096 gray scale).

All DiCOM files were loaded to a computer with a Xeon (Intel, Santa Clara, Calif) processor, running Windows 7 Professional (Microsoft, Redmond, Wash) operating system. Measurements were then made using Dolphin 3D (version 11.8, Dolphin Imaging & Management Solutions, Chatsworth, Calif). All CBCTs were oriented according to the protocol outlined by Wu et al[19]. Orientation of the CBCT in the coronal view was achieved by aligning the axial plane with the center of the left

and right optical foramina. In the axial view, the CBCT was rotated until the coronal plane was aligned with the center of the left and right foramen ovale. The sagittal plane was placed to pass through the foramen cecum, serving as a midsagittal marker. In the sagittal view, the pitch of the head was altered until the axial plane passed through McRae's line (Basion-Opisthion). Following proper orientation, a lateral cephalogram was created in order to gather linear and angular cephalometric measurements. Sagittal and vertical position of the hyoid bone was calculated by first identifying the most anterosuperior point on the hyoid bone (Hyoidale, H). Vertical position was recorded as the perpendicular distance from Hyoidale to the mandibular plane (Gonion-Menton). The sagittal position of the hyoid bone was recorded as the distance from Hyoidale to the most anteroinferior point on the third cervical vertebrae (C3), parallel to Frankfurt Horizontal (Porion-Orbitale). Angular and linear measurements were obtained using a digitized tracing of each rendered image after applying a customized tracing analysis.

Airway volumes were calculated using the sinus/airway feature in Dolphin 3D imaging. The OP volume was defined as the pharyngeal volume located between a plane passing through the palatal plane (PNS-ANS) and a parallel plane passing through the most anteroinferior point of the second cervical vertebrae (C2). Both planes were extended to pass through the anterior and posterior pharyngeal walls (figure 1). The superior limit of the OP volume served as the inferior limit of the NP volume. The NP volume was defined as being the pharyngeal volume located between the palatal plane and a parallel plane passing through the last axial slice

before the nasal septum fused with the posterior pharyngeal wall (figure 2).

Once boundaries were outlined in the sagittal plane, additional boundaries outlining the respective airway were made in the axial and coronal planes (figure 3 and 4). Four seed points were placed within the confines of the OP airway region and five within the NP region, in order to identify airway voxels and their respective density. The region that would be calculated as the airway volume was to be marked in pink. The airway sensitivity scale was set to its maximum (100), and then scaled back until it was determined that no region outside of the airway was being identified by the pink marker. Once the sensitivity was selected, the airway volumes were calculated and recorded.

The minimal cross section area of the OP volume in the axial plane (MinAx) was calculated using the "enable minimum axial area" feature. Superior and inferior limits were identified in the sagittal plane and were moved until they passed through both anterior and posterior airway-soft tissue boundaries (figure 5).

The most lateral extension of the left and right greater horns of the hyoid bone were identified in all 3 planes of space (figure 6). Distances from the lateral most point on the greater horn perpendicular to the mid sagittal line were calculated in the coronal plane. The combined distances from the right and left greater horn were summed to determine the width of the hyoid bone (figure 7). The geometric center point between the two greater horns was also recorded in reference to the midsagittal plane (centered, right or left). The absolute value of the perpendicular distance from the center point to the midsagittal plane was recorded as the mediolateral position of

the hyoid bone.

Data Analysis

Data from the 47 subjects were entered into an Excel™ (Microsoft Corporation – Redmond, WA) spreadsheet and then statistical analyses were performed using Excel™ and SPSS statistical software (SPSS Inc. – Chicago, IL). All measurements were repeated on 10 randomly selected patients and intra-rater reliability was reported using intra-class correlation coefficients. A Shapiro-Wilks test was performed to assess for normality. Pearson Correlation Coefficient tests (r) were performed to examine the degree of association between the respective airway and hyoid bone variables, with significance accepted for analysis set at $p < 0.05$. (Table 3). Patients were then grouped according to their sagittal jaw relationships (Class I ($0 < ANB < 4$), Class II ($4 \leq ANB$), Class III ($0 \geq ANB$), illustrated in table 4. No significant differences were found in the hyoid bone position, width, airway volumes and areas between Cl I and II individuals.

RESULTS

Intra-rater reliability on the 10 randomly selected subjects ranged from 0.893-0.998, indicating good reliability among the sample measurements (Table 1). Descriptive statistics describing the sample population are illustrated in Table 2. After performing Pearson Correlation Coefficient tests, no airway volumes nor the MinAx were found to have any significant correlations with the vertical position of the hyoid bone (Table 3). The OP volume ($8{,}349 \pm 3164$ $mm^{3)}$ and the total volume

(15, 047 ± 4,952 mm^3) were both found to be significantly associated with the sagittal position of the hyoid bone (r = 0.399, p =0.006) and the width of the hyoid bone (r = 0.325, p = 0.026). The NP volume (6,699± 2,853 mm^3) was not found to have any significant correlation with any measurements of the hyoid bone positions nor the hyoid width. The MinAx (148.2 ± 70.2 mm^2) showed a positive association with the sagittal hyoid position (r = 0.445, p = 0.002). Consistent with previous studies[4,5], significant positive correlations were observed between most of the upper airway variables measured (Table 3).

Table 4 illustrates the means and standard deviations among Class I subjects (12 females, 8 males), Class II subjects (14 females, 8 males) and Class III subjects (2 females, 3 males).

Multiple linear correlations were performed to look at how much of the variability in airway volumes and the MinAx could be predicted by the different hyoid positions and the hyoid width (Tables 5-8). The R^2 value for the OP model was 0.323, with the sagittal position of the hyoid bone and the width of the hyoid bone being significant independent variables ($p < 0.05$). The MinAx model had the highest R^2, with a value of 0.361. The sagittal position was found to be a significant variable (p = 0.001), but not the hyoid width (p = 0.252). Consequently, in the MinAx model, the hyoid mediolateral position seemed to be the independent variable with the strongest predictive value. Hyoid position and width were the worst at being able to predict the variability of the NP volume. It was found that the only significant independent variable for the NP volume model was the hyoid width (p = 0.048).

DISCUSSION

CBCT imaging allows for the 3D investigation of hollow structures, including the airway. Thus with 3D imaging, studies are examining volumes and areas rather than lengths and angles[6]. Various studies examining the airway have already been conducted utilizing CBCT imaging. Because of its reliability, automatic segmentation was chosen to sculpt the upper airway[6]. Though the reported volumes may be overestimates or underestimates of the true volumes, these reproducible measurements are sufficient to test for correlations in a time efficient manner.

Different theories regarding positional changes in the hyoid bone exist. Aside from growth and development, it has been postulated that the hyoid bone is an indicator of head and neck muscle tone. Others believe that the vertical change in hyoid bone position may be part of a neuromuscular response, whereby patients with a small NP volume experience a change in their H-MP distance as part of a compensatory mechanism to increase their NP volume[14].

Despite numerous studies examining hyoid bone position, our current study appears to be one of the first to describe the hyoid bone position in 3D using CBCT imaging. Furthermore, this study was able to report norms for the inter-greater horn distance.

A recent study[3], looked at inter-greater horn distance, however no mention of

the transverse position of the hyoid bone was made. Additionally they failed to examine the nasopharynx and only reported which variables could describe the variability among OP volumes. However, this study did find a positive correlation when comparing the various airway volumes and areas. The high correlation between the total volume and the MinAx has been reported by others[4, 5].

Differences in hyoid bone shape, as well as asymmetries and anisometries, make it crucial to examine the hyoid bone in 3D. A previous study examining 76 human cadavers, found that 47.4% of hyoid bones were asymmetric (40% to the right, 60% to the left) and 59.0% had greater horns that were anisometric[13]. Our findings are in agreement, where we found that fewer than 5% of our sampled subjects had greater horns equidistantly positioned from the mid-sagittal plane. When locating the lateral most extensions of the greater horns, deviations in the sagittal and vertical position were also noted.

Among our sample population, no significant correlations were found between the vertical position of the hyoid bone and any airway variable. Phoenix et al[14] illustrated that RME causes the hyoid bone to move superiorly compared to controls. One would expect that as the NP volume increased, the H-MP distance would decrease, yet this relationship wasn't observed among our sample.

The classification of subjects into the different angle classifications was done solely by using ANB, with Class I being defined as O < AND < 4. Had a different range of ANB angles, or additional variables such as overjet or mandibular length been used to stratify the sample, the distribution within each angle group could have

been vastly different. It's entirely possible that significant differences between hyoid bone position and width, and airway measurements could exist among the various angle groups had different criteria been used to define these groups.

The MinAx has a significant influence on airway functioning, and is strongly correlated with the OP volume. Despite 3D evaluation of the airway being more valuable, many orthodontists are still taking lateral cephalograms as part of their orthodontic records. We showed that the hyoid bone's sagittal position was positively correlated with the MinAx. Because the distance of the hyoid bone to C3 can be easily measured on 2D images, while the MinAx cannot, the hyoid bone-C3 distance could be used as part of a diagnostic workup to assess airway function in new patients. Extreme posterior positioning of the hyoid bone could alert clinicians to patients with possible airway issues, and could be used as a preliminary screening tool for airway function. When searching for information about the hyoid bone position, lateral cephalogram studies are still relevant because the sagittal position of the hyoid bone seems to be the most important. However, CBCT studies are required when one wants to investigate the morphology of the upper airway.

A thorough examination of the sample population used in this study is required. Because patients were randomly sampled, an unequal distribution of Class I, II and III patients was obtained. The effect of sagittal jaw position on airway volumes and constrictive regions may have biased our results when examining the collective sample. The small number of Class III subjects reflects the predominance of Class I and II patients among the orthodontic seeking population.

The airway is a structure constantly changing as we breathe throughout the day. CBCT images provide only a small snapshot of this dynamic process. A single CBCT image may not accurately reflect the anatomic relationships of the pharyngeal region that truly exists in an individual. However, one would expect that as the configuration of the upper airway were to change, the position of the hyoid bone would also change accordingly. As the field of diagnostic imaging is constantly evolving, we may one day be able to investigate the dynamic interplay between the hyoid bone and the airway throughout the inspiration and expiration process.

Future studies should examine how the relationship between the hyoid bone and the airway is affected in patients with different sagittal jaw positions. Moreover, as our study has a cross-sectional design, we have yet to examine how the relationship between the airway and the hyoid bone changes longitudintally.

When evaluating the airways of our patients, it is crucial for us as clinicians to assess their airway function. Flow volume loops obtained from spirometry tests can be used to demonstrate the presence of extrathoracic obstructions and evaluate airway function. Furthermore, pulse oximetry can be used to measure oxygen saturation in an individual's blood. Investigating how the position and width of the hyoid bone could influence these objective measurements of airway function seems like the next logical step if we are to use radiographs as a screening tool for airway problems.

~~Conclusions~~CONCLUSIONS

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1) The vertical and mediolateral position of the hyoid bone doesn't seem to influence the airway parameters studied in this project.
2) The sagittal position of the hyoid bone has a significant positive correlation with the OP volume and the MinAx.
3) The width of the hyoid bone has a significant positive correlation with the OP volume.

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List of Figures

~~Figure caps~~

1. -- OP VOLUME SUPERIOR AND INFERIOR LIMITS IN SAGITTAL SLICE.

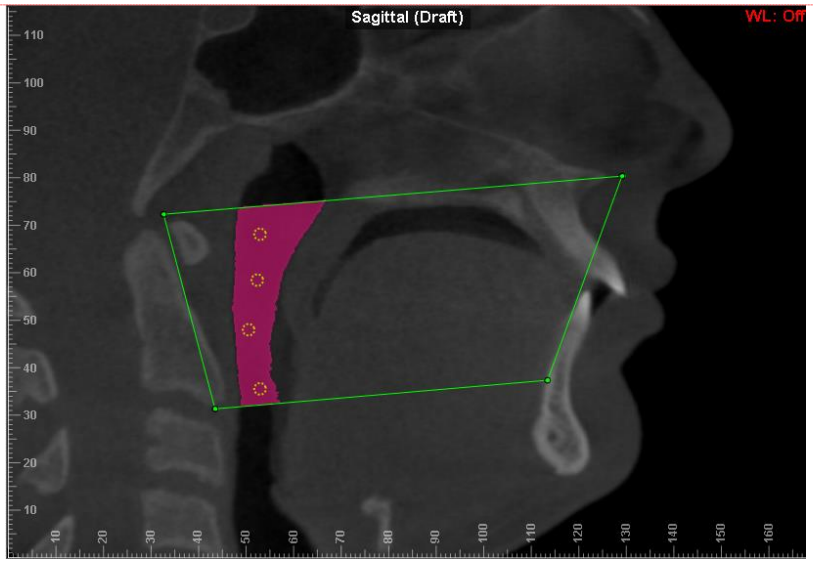
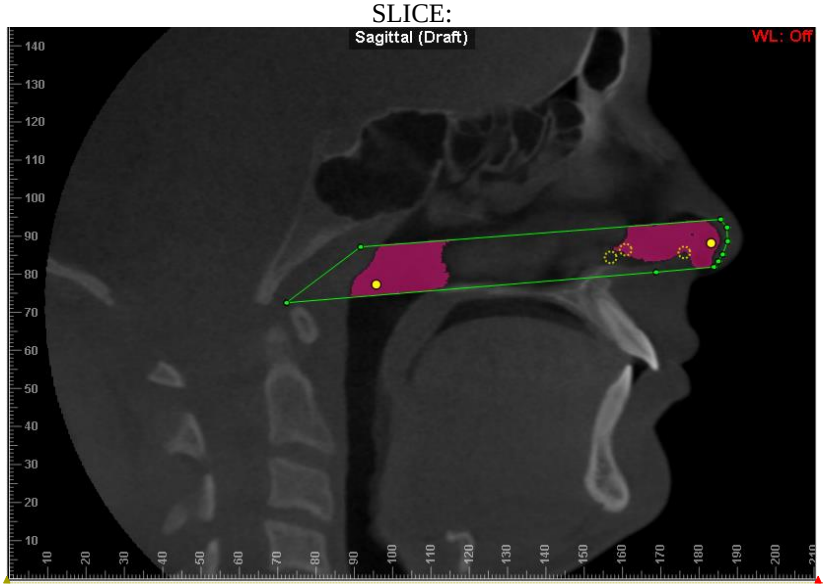


FIGURE 2. -- NP VOLUME SUPERIOR AND INFERIOR LIMITS IN SAGITTAL SLICE:



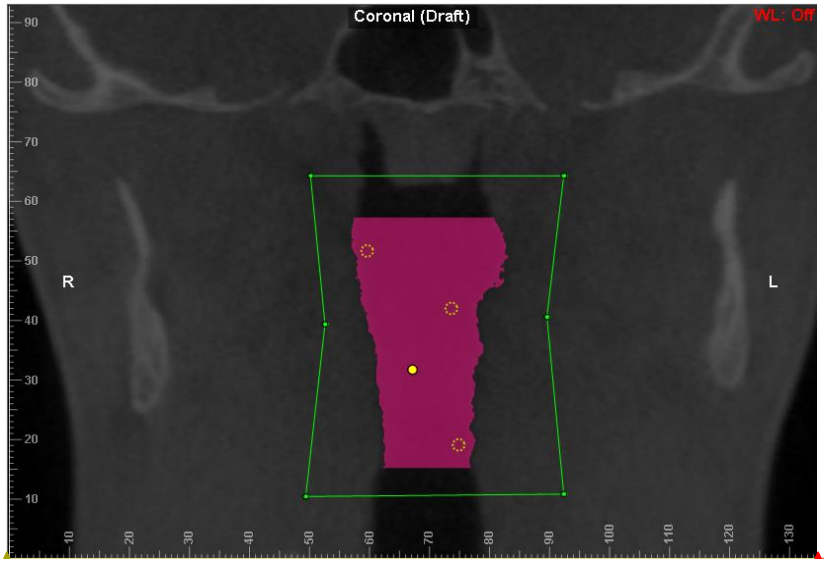
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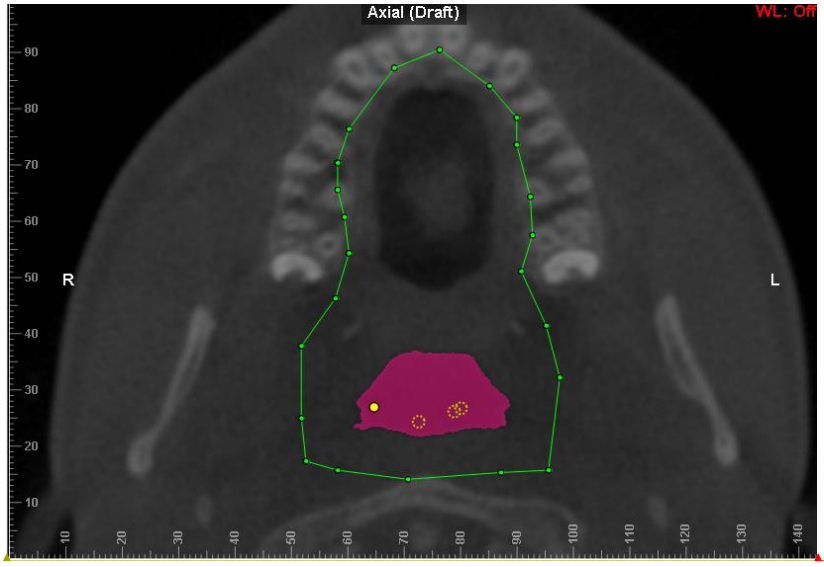
FIGURE 3. -- OP VOLUME BOUNDARY TRACING AND SEED POINTS IN CORONAL SLICE:



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FIGURE 4. -- OP VOLUME BOUNDARY TRACING AND SEED POINTS IN AXIAL SLICE.



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FIGURE 5. -- MEASUREMENT OF THE MINAX.

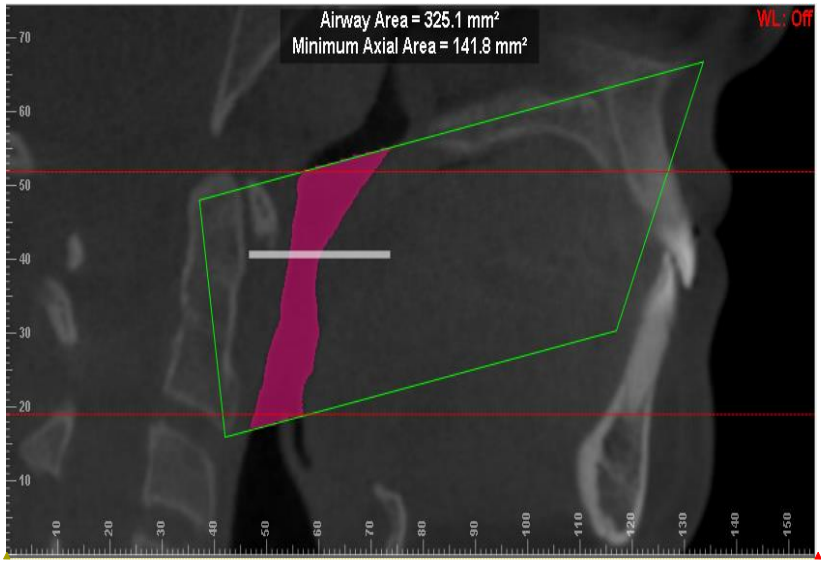
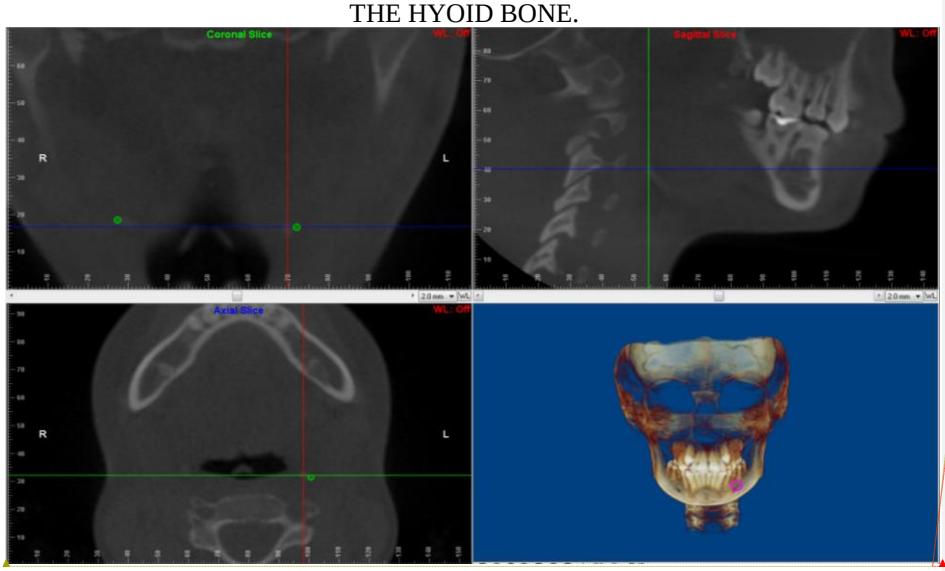


FIGURE 6. -- LOCALIZATION OF OUTER CONTOUR OF GREATER HORN OF THE HYOID BONE.



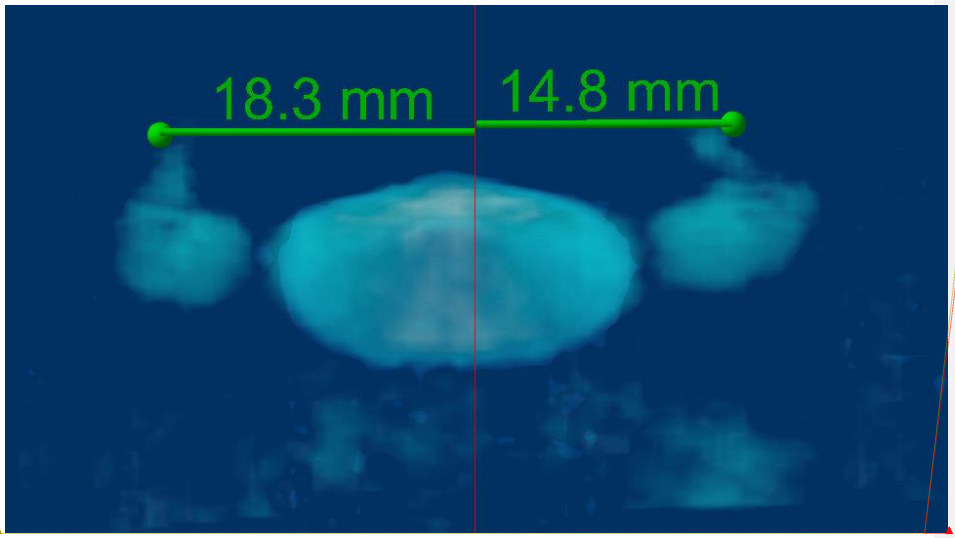
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FIGURE 7. -- INTER-GREATER HORN DISTANCE MEASURED AS THE PERPENDICULAR DISTANCE FROM LATERAL-MOST EXTENSION OF THE GREATER HORN TO THE MID-SAGITTAL PLANE.



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TABLE 1. -- RELIABILITY OF MEASUREMENTS.

Variable	Intraclass Correlation Coefficient
Hyoid Width	0.893
Hyoid Vertical Position	0.996
Hyoid Sagittal Position	0.988
OP Volume	0.998
NP Volume	0.994
Total Volume	0.996
MinAx	0.995
SNA	0.937
SNB	0.942
ANB	0.987
FMA	0.983
Maxillary Length	0.994
Mandibular Length	0.995

TABLE 2. --DESCRIPTIVE STATISTICS OF SAMPLE (N =47).

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	Maximum (years)	Minimum (years)	Mean (years)	S.D. (years)
Age	11.1	16.1	13.1	1.4
Female Age (n = 28)	11.1	15.9	13.0	1.4
Male age (n = 19)	11.2	16.1	13.2	1.4

	OP Volume (mm^3)	NP Volume (mm^3)	Total Volume (mm^3)	MinAx (mm^2)	Hyoid Vertical Position (mm)	Hyoid Sagittal Position (mm)	Hyoid Mediolateral Position (mm)	Hyoid Width (mm)
Mean	8,349	6,699	15,047	148.2	12.0	33.8	1.5	39.9
S.D.	3,164	2,853	4,952	70.2	4.1	4.3	1.3	4.1

	SNA (°)	SNB (°)	ANB (°)	FMA (°)	Maxillary Length - Co-A (mm)	Mandibular Length – Co-Gn (mm)
Mean	81	77	4.0	25	86.5	116.7
S.D.	3.0	3	2.0	3	6.4	8.7

TABLE 3. -- PEARSON CORRELATION COEFFICIENTS OF OVERALL SAMPLE (N =47).

Correlations

		OPVOL	NPVOL	TotalVol	MinAx	HyoidVertical	HyoidSagittal	HyoidMediolateral	HyoidWidth
OPVOL	Pearson Correlation	1	.353*	.842**	.830**	.147	.399**	-.177	.325*
	Sig. (2-tailed)		.015	.000	.000	.323	.006	.235	.026
	N	47	47	47	47	47	47	47	47
NPVOL	Pearson Correlation	.353*	1	.802**	.244	-.188	.105	-.204	.278
	Sig. (2-tailed)	.015		.000	.098	.205	.482	.169	.059
	N	47	47	47	47	47	47	47	47
TotalVol	Pearson Correlation	.842**	.802**	1	.671**	-.014	.315*	-.230	.368*
	Sig. (2-tailed)	.000	.000		.000	.925	.031	.119	.011
	N	47	47	47	47	47	47	47	47
MinAx	Pearson Correlation	.830**	.244	.671**	1	.228	.445**	-.297*	.133
	Sig. (2-tailed)	.000	.098	.000		.123	.002	.043	.371
	N	47	47	47	47	47	47	47	47
HyoidVertical	Pearson Correlation	.147	-.188	-.014	.228	1	.306*	.111	-.002
	Sig. (2-tailed)	.323	.205	.925	.123		.036	.458	.988
	N	47	47	47	47	47	47	47	47
HyoidSagittal	Pearson Correlation	.399**	.105	.315*	.445**	.306*	1	.128	.006
	Sig. (2-tailed)	.006	.482	.031	.002	.036		.392	.968
	N	47	47	47	47	47	47	47	47
HyoidMediolateral	Pearson Correlation	-.177	-.204	-.230	-.297*	.111	.128	1	.033
	Sig. (2-tailed)	.235	.169	.119	.043	.458	.392		.824
	N	47	47	47	47	47	47	47	47
HyoidWidth	Pearson Correlation	.325*	.278	.368*	.133	-.002	.006	.033	1
	Sig. (2-tailed)	.026	.059	.011	.371	.988	.968	.824	
	N	47	47	47	47	47	47	47	47

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

TABLE 4. --DESCRIPTIVE STATISTICS FOR CL I, II AND III GROUPS.

	Class I (n=20)		Class II (n=22)		Class III (n =5)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
OP Vol (mm^3)	8,367	3,598	8,499	2,957	7619	2640
NP Vol (mm^3)	6,957	3,275	6,262	2,502	7584	2726
Total Vol (mm^3)	15,324	6,256	14,761	3,757	15203	4596
MinAx (mm^2)	149.6	81.0	148.7	64.8	139.9	58.3
Hyoid Vertical (mm)	12.4	4.2	11.4	4.2	12.5	4.0
Hyoid Sagittal (mm)	32.8	5.4	34.7	3.3	34.0	2.9
Hyoid Width (mm)	40.7	4.3	39.4	4.0	39.2	4.8
Hyoid Mediolateral (mm)	1.7	1.4	1.4	1.4	1.5	0.9
SNA (°)	81	3	81	2	79	4
SNB(°)	78	3	76	2	80	3
ANB (°)	3	1	5	1	-1	1
FMA (°)	24	3.6	25	3	24	3
Maxillary Length - Co-A (mm)	84.8	6.3	88.8	6.0	83.6	6.8
Mandibular Length - Co-Gn (mm)	116.4	9.6	116.5	7.9	118.7	10.2

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TABLE 5. --MULTIPLE LINEAR REGRESSION MODEL FOR OP VOLUME:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.568[a]	.323	.258	2725.64247

a. Predictors: (Constant), HyoidWidth, HyoidVertical, HyoidMediolateral, HyoidSagittal

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-11647.942	5022.994		-2.319	.025
	HyoidVertical	37.647	103.064	.049	.365	.717
	HyoidSagittal	305.872	99.290	.413	3.081	.004
	HyoidMediolateral	-592.402	309.558	-.246	-1.914	.062
	HyoidWidth	252.800	97.165	.331	2.602	.013

a. Dependent Variable: OPVOL

TABLE 6. --MULTIPLE LINEAR REGRESSION MODEL FOR NP VOLUME:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.431[a]	.186	.108	2694.17517

a. Predictors: (Constant), HyoidWidth, HyoidVertical, HyoidMediolateral, HyoidSagittal

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3043.222	4965.004		-.613	.543
	HyoidVertical	-156.191	101.874	-.225	-1.533	.133
	HyoidSagittal	133.296	98.144	.200	1.358	.182
	HyoidMediolateral	-465.018	305.984	-.214	-1.520	.136
	HyoidWidth	195.390	96.044	.283	2.034	.048

a. Dependent Variable: NPVOL

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TABLE 7. -- MULTIPLE LINEAR REGRESSION MODEL FOR TOTAL VOLUME:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.569[a]	.323	.259	4263.42908

a. Predictors: (Constant), HyoidWidth, HyoidVertical, HyoidMediolateral, HyoidSagittal

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-14691.164	7856.929		-1.870	.068
	HyoidVertical	-118.544	161.212	-.098	-.735	.466
	HyoidSagittal	439.168	155.309	.379	2.828	.007
	HyoidMediolateral	-1057.420	484.208	-.280	-2.184	.035
	HyoidWidth	448.190	151.985	.375	2.949	.005

a. Dependent Variable: TotalVol

TABLE 8. --MULTIPLE LINEAR REGRESSION MODEL FOR MINAX:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.601[a]	.361	.300	58.75824

a. Predictors: (Constant), HyoidWidth, HyoidVertical, HyoidMediolateral, HyoidSagittal

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-196.767	108.284		-1.817	.076
	HyoidVertical	2.246	2.222	.131	1.011	.318
	HyoidSagittal	7.421	2.140	.452	3.467	.001
	HyoidMediolateral	-19.969	6.673	-.374	-2.992	.005
	HyoidWidth	2.435	2.095	.143	1.162	.252

a. Dependent Variable: MinAx

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AIRWAY VOLUMES, AREAS, AND HYOID BONE POSITION MEASUREMENTS:

Subject #	sex	OP Volume (mm^3)	NP Volume (mm^3)	Total Airway Volume (mm^3)	MinAx (mm^2)	Hyoid Mediolateral Position (mm)	Hyoid Vertical Position (mm)
1	F	6659.4	5309.1	11968.5	141.8	4.9	13.3
2	F	7340	10624.6	17964.6	112.2	0.15	12.6
3	F	7214.1	6020.8	13234.9	147.6	1.55	10.6
4	F	7835.7	5915.5	13751.2	62.3	2.4	9
5	M	12826.6	4197.7	17024.3	184.2	3.55	11.1
6	M	4092.4	9024.4	13116.8	66.7	0.35	4.8
7	F	6882.5	3732.2	10614.7	178.2	0.4	19.4
8	M	8984.1	10179.5	19163.6	137.3	2.15	18.5
9	F	5306.5	3585.1	8891.6	91.6	3.15	10.3
10	F	9780.1	10936.3	20716.4	187.5	0.4	11.1
11	M	9816.3	4722.7	14539	142.5	0.2	5.6
12	F	5724.1	4636.3	10360.4	130.1	0.3	8.4
13	F	3161	5197.1	8358.1	42.9	2.1	9.2
14	F	13245.8	8981.8	22227.6	388.1	0	14.1
15	M	10045.1	6962.6	17007.7	149.5	1.75	14
16	M	5938.6	3998.5	9937.1	100.5	2.6	15.9
17	F	6217.2	5644.5	11861.7	101.3	0.55	15
18	M	6249.9	9910	16159.9	69.4	0.35	10.5
19	F	7982.4	3669.5	11651.9	155.8	0.75	12.7
20	F	6170.4	7364.7	13535.1	72.2	3.85	2.9
21	F	6587	6125.1	12712.1	102.6	0.25	15.1
22	F	8144.7	4554.9	12699.6	232.6	0.15	10.7
23	M	11215	6249.5	17464.5	153.7	2.1	12.5
24	M	3360.1	7444	10804.1	84.7	4.05	12.1
25	M	8506.9	3151	11657.9	193.4	0.25	6.7
26	F	12343.7	7829.1	20172.8	239.1	1	13.7
27	F	7316.7	2560.7	9877.4	115.7	0.7	9.8
28	F	8170.8	3124	11294.8	124.9	0.7	18.6
29	M	6315.4	9444.5	15759.9	103	0.75	6.7
30	M	7590.8	3321.2	10912	125.9	2.1	19.8
31	M	12630.1	9873.1	22503.2	216.3	1.45	7.7
32	F	7442.4	2748.9	10191.3	125.4	3.1	20.4
33	F	12162.3	7849.4	20011.7	228.2	1.5	12.5

~~34~~	~~F~~	~~5551.2~~	~~6110.3~~	~~11661.5~~	~~68~~	~~1.1~~	~~10.3~~
Subject #	Sex	OP Volume (mm^3)	NP Volume (mm^3)	Total Airway Volume (mm^3)	MinAx (mm^2)	Hyoid Mediolateral Position (mm)	Hyoid Vertical position (mm)
34	F	5551.2	6110.3	11661.5	68	1.1	10.3
35	F	8844.7	5077.4	13922.1	139.3	4.15	11.3
36	F	8520.1	8928.7	17448.8	169.8	1.25	15.4
37	M	18626.9	14717.5	33344.4	304.8	0.25	11.7
38	F	5382.7	3940.3	9323	116.5	1.6	9.8
39	M	8187.2	7818.8	16006	103.1	4.45	13
40	F	17765.7	6170.7	23936.4	332.3	0.7	15.6
41	F	6447.1	8586.8	15033.9	125.8	1.25	12.7
42	M	9439.5	5175.1	14614.6	127.5	1.05	12.3
43	M	5327.9	5240.5	10568.4	76.8	0.75	8.8
44	M	10072.4	12939.5	23011.9	128.8	1.15	5.1
45	F	7842.8	4889.3	12732.1	189.5	1.6	12.1
46	M	8062	10690.7	18752.7	180.3	0	8.7
47	F	9068	9661.3	18729.3	193.5	2.25	19.6
Mean		8348.857447	6698.621277	15047.47872	148.1531915	0.612766	11.95106383
S.D.		3164.453449	2852.964053	4951.982701	70.22246591	0.166559	4.107991805

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HYOID POSITION AND CEPHALOMETRIC MEASUREMENTS:

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Subject #	Sex	Hyoid Sagittal Position (mm)	SNA (°)	SNB (°)	ANB (°)	FMA (°)	Maxillary Length (mm)	Mandibular Length (mm)
1	F	37	80.7	77	3.7	29	81.3	109.7
2	F	26.4	79.7	77	2.8	21.6	76.1	105.5
3	F	33.5	81	80.6	0.3	22.4	82	115.1
4	F	26.6	74.9	71.9	3	27.5	86.1	117
5	M	38.2	81	75.8	5.2	25.9	84.5	116.2
6	M	35	78.4	73.8	4.6	21.7	83.2	113.8
7	F	34	76.6	75.6	1	25.5	80.3	118.4
8	M	37.2	76	76.2	-0.3	20.4	87.2	120.8
9	F	25.8	80.3	76.5	3.8	30.5	75.8	104.5
10	F	33.9	79.9	74.9	5	27	77.8	105.2
11	M	29.8	82.6	75	7.6	23.9	82.6	103.3
12	F	32.4	84.2	81.2	2.9	21	81	105.4
13	F	30.5	82.3	82.8	-0.5	25.1	71.5	101.6
14	F	34.5	82.4	80.5	1.9	25	77.6	107.2
15	M	34.3	76.6	79.1	-2.5	26.4	86.6	128.2
16	M	33.2	77.9	74.9	3	19.6	84.5	113.2

17	F	25.5	77.6	75.4	2.3	21.9	77	105.4
~~18~~	~~M~~	~~37.9~~	~~80.7~~	~~75.8~~	~~4.9~~	~~19.6~~	~~96.3~~	~~125.4~~
Subject #	Sex	Hyoid Sagittal Position (mm)	SNA (°)	SNB (°)	ANB (°)	FMA (°)	Maxillary Length (mm)	Mandibular Length (mm)
18	M	37.9	80.7	75.8	4.9	19.6	96.3	125.4
19	F	37	81.1	73.8	7.3	29.9	93.8	115.8
20	F	31.9	84.6	80	4.6	22.4	93.5	116.9
21	F	29.7	79.8	75.4	4.4	21.5	82.2	105.1
22	F	38.5	80.6	73.5	7	25.8	88.7	109.6
23	M	31.8	82.5	82.2	0.3	30.8	81.6	113
24	M	35	79.8	77.6	2.2	23	89.4	121.4
25	M	37.3	81.3	76.4	4.9	22.6	94.9	124
26	F	33.4	83.3	76.7	6.6	23.7	100.3	130.6
27	F	30.1	81.6	75.9	5.6	27.2	86.4	110.1
28	F	32.7	79.2	74.6	4.6	29.1	88.3	118.2
29	M	35	83.6	80.3	3.3	22.7	94.3	127.4
30	M	40.1	82.6	79	3.6	19.2	92.9	125.6
31	M	28.1	83.6	80	3.5	24.6	82.6	112.8
32	F	38.4	82.7	79.8	2.9	20	95	126.5
33	F	32.6	79	76.5	2.5	23	86	113.7
34	F	29.4	79.9	76.7	3.1	29.8	85.6	118.5
35	F	39.5	81.6	76.1	5.5	30.3	87.3	123.4
36	F	34.8	82.4	77.3	5.2	23.5	98.7	125.2
37	M	47.1	86.8	83.9	2.9	24.9	93	141.6
38	F	34.4	80.3	74.9	5.4	25.2	88.1	118.7
39	M	35.2	85.6	81.5	4.1	19.4	93.6	124.6
40	F	39.2	81.8	76.9	4.9	24.2	85.5	117.9
41	F	32.8	77.2	73	4.2	29.8	82.8	108.3
42	M	33.3	83.5	77	6.5	26.5	89.1	122.8
43	M	29.8	76.9	72.1	4.8	19.9	83	105.8
44	M	30.2	80	76.5	3.6	22.8	93	125.9
45	F	36.5	83.3	83.9	-0.6	21	87.8	123.9
46	M	31.7	76.6	78	-1.4	25.5	84.9	118.9
47	F	38.9	84.4	76.8	7.6	29.8	92	122
Mean		33.83191489	80.81702	77.24043	3.570213	24.51276596	86.50425532	116.6829787
S.D.		4.272770529	2.685251	2.943575	2.353066	3.43648057	6.439246427	8.712817124

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REPEATED MEASUREMENTS OF AIRWAY VOLUMES, AREAS, AND HYOID BONE POSITION:

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Subject #	sex	OP Volume (mm^3)	NP Volume (mm^3)	Total Airway Volume (mm^3)	MinAx (mm^2)	Hyoid Mediolateral Position (mm)	Hyoid Vertical position (mm)
27	F	7163.1	2988	10151.1	115.6	0.7	9.8
26	F	12537.3	7839.1	20376.4	253.5	1	13.7
25	M	8595	3349.4	11944.4	200.2	0.35	6.9
24	M	3568.6	7352.7	10921.3	80.2	3.75	11.9
23	M	11375	6223	17598	151.2	2.25	12.6
22	F	8406.8	4909.6	13316.4	226.7	0.15	10.1
34	F	5684.6	6786.9	12471.5	68	1.2	10.8
21	F	6345.8	5812.1	12157.9	101.4	0.05	14.8
43	M	5458.6	5201.5	10660.1	83.8	0.35	8.9
44	M	10352.9	12620.9	22973.8	122.6	1.2	5.1

REPEATED MEASUREMENTS OF HYOID POSITION AND CEPHALOMETRIC MEASUREMENTS:

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Subject #	Sex	Hyoid Sagittal Position (mm)	SNA (°)	SNB (°)	ANB (°)	FMA (°)	Maxillary Length (mm)	Mandibular Length (mm)
27	F	30.7	81.3	76.2	5.1	26.7	86	109.7
26	F	33.2	83.3	74.6	6.9	23.3	100	130.7
25	M	37.1	82.3	76.8	5.4	23.2	94.6	125.1
24	M	35.1	80.8	78.4	2.3	23.5	88.4	120.8
23	M	32	81.7	81.5	0.2	31.3	81.8	114.1
22	F	39	80.7	74.1	6.7	26.3	88.2	110.7
34	F	29	79.2	75.8	3.4	29.7	87.1	117
21	F	29.8	80.6	76	4.6	20.5	82.2	104.8
43	M	29.2	76.4	72	4.4	18.7	83.6	106.7
44	M	31.4	79.7	75.8	3.8	23.6	93	125.9