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Volumetric Velopharyngeal Space Modifications in Patients with and without Cleft Palate Undergoing Le Fort 1 Maxillary Advancement

par

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Résumé

Historique & Objectifs: Les effets de l'avancement maxillaire (AM) sur l'anatomie velopharyngée ont déjà été étudiés en utilisant la céphalométrie. Cette modalité ne permet toutefois pas de bien caractériser les tissus mous. Le but de cette étude est de comparer la configuration de l'espace vélopharyngé en pré- et post-opératoire, telle que mesurée par tomodensitométrie (TDM). De plus, notre objectif est d'analyser et de comparer les différences dans ces mesures chez les patients avec et sans fente palatine (FP).

Méthodologie: Ceci est une étude rétrospective portant sur 44 patients avec et sans FP, traités avec AM pour une hypoplasie maxillaire et une malocclusion dento-squelettique. Les TDM pré- et post-opératoires ont été comparés en se basant sur des repères préétablis. Des distances linéaires, des aires de sections transversales et des mesures volumétriques ont été mesurées en utilisant des reconstructions tridimensionnelles des TDM.

Résultats: Pour les distances linéaires mesurées, une différence statistiquement significative a été notée pour les mesures linéaires du nasopharynx et du palais mou (25.1 vs 28.5 mm p=0.001 et 6.5 vs 7.6 mm p=0.026, respectivement). Les aires des sections transversales au niveau du nasopharynx et du palais mou ainsi que l'évaluation volumétrique de l'espace vélopharyngé n'ont pas démontrées une différence statistiquement significative en comparant les mesures en pré- et post-opératoire (p>0,05). En comparant les patients avec et sans FP, une différence statistiquement significative n'a été notée que pour la distance linéaire et l'aire de la section transversale du nasopharynx (p=0.045 et p=0.04, respectivement). Un antécédent de réparation de FP n'était pas prédictif de différences de mesures pré- et post-opératoire.

Conclusion: Nos résultats confirment que, bien que certaines modifications structurelles de l'espace vélopharyngé soient inhérentes à l'AM chez les patients avec FP, leurs aires et volumes ne semblent pas changer de façon significative. Ces changements sont indépendants d'une histoire de FP réparée.

Mots-clés : Fente labiale, Fente palatine, Insuffisance velopharyngée, Chirurgie orthognathique, Avancement maxillaire, Le Fort, Tomodensitométrie, Céphalométrie, Anatomie

Summary

Background & Purpose: The effects of maxillary advancement (MA) on velopharyngeal anatomy have primarily been studied using lateral cephalometric radiographs. However, with recent advances in orthognathic surgery, there is an increased need for more detailed and precise imaging such as computerized tomographic (CT) scan reconstructions, to help in surgical planning and to measure outcomes. The purpose of this study is to compare the pre-and post-operative velopharyngeal space configuration modifications as measured on CT scans. The aim is also to assess differences in these airway measures between patients with and without history of prior repaired cleft palate (CP).

Methods: This is a retrospective cohort study of 44 patients with and without CP who were treated with MA for midface hypoplasia and secondary malocclusion at skeletal maturity. The pre-and post-operative CT scans were compared with respect to pre-established landmarks. Linear distances, cross-sectional areas, and volumes were measured using 3-dimensional (3D) CT scan reconstructions.

Results: For the linear distances measured, a statistically significant difference was found when comparing the pre-and post-operative measures of the narrowest part of the nasopharynx and the narrowest part of the retropalatal airway space (25.1 vs 28.5 mm $p=0.001$ and 6.5 vs 7.6 mm $p=0.026$, respectively). Retropalatal cross-sectional areas, nasopharyngeal cross-sectional areas and the volumetric assessment of the nasopharyngeal space showed no statistically significant differences when comparing pre-and post-operative scans ($p>0.05$). The main effect of palatal repair (CP vs. Non-CP) showed that there was only a statistically significant difference for the measures of the narrowest part of the nasopharynx and the nasopharyngeal cross-sectional area (p=0.045 and p=0.04, respectively). Mean changes in the measures did not differ over time (pre- and post-op) depending on whether there was prior history of CP repair.

Conclusion: Our results support the hypothesis that although structural modifications of the pharyngeal space are inherent to MA in patients with CP, its surface area and volume do not change significantly. These changes are also independent of history of previous CP repair.

Keywords: Cleft lip, Cleft palate, Velopharyngeal insufficiency, Orthognathic surgery, Maxillary advancement, Le Fort, Computed tomography, Cephalometric, Anatomy

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LEGEND

CLP: Cleft lip and palate

CL/P: Cleft lip and/or palate

CL: Isolated cleft lip

CPO: Isolated cleft palate

CP: Cleft palate

NAM: Nasoalveolar molding

VPF: Velopharyngeal function

VPD: Velopharyngeal dysfunction

VPI: Velopharyngeal insufficiency

PSA: Perceptual speech assessment

MA: Maxillary advancement

CT: Computed tomography

3D: 3-dimensional

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1 – Introduction

1.1 Cleft lip & palate

1.1.1 Epidemiology

Cleft lip and palate (CLP) are common congenital malformations affecting an excess of 10 million people worldwide.(1, 2) Cleft lip with or without a cleft palate (CL/P) and isolated cleft palate (CPO) are two distinct entities pathogenetically and epidemiologically. The overall incidence of oral clefts is 1 in 750 live births.(3) Forty-six percent are patients with CL/P, 33% with CPO, and 21% with isolated cleft lip (CL).(3) While CPO has a racial distribution that is equivalent among races, CL/P has the highest incidence among Asians, followed by Caucasians and then Africans.(4, 5) CL/P has a male to female ratio of 2:1 while CPO's distribution is the inverse of 1:2. Finally, the ratio of left to right to bilateral CL/P is 6:3:1, respectively.(6)

1.1.2 Embryology

The face is formed from five facial primordia. These include, the frontonasal prominence, the bilateral maxillary prominences and the bilateral mandibular prominences.(6) The frontonasal prominence eventually gives rise to the forehead, the midline of the nose, the philtrum, the middle portion of the upper lip and the primary palate. The paired maxillary prominences give rise to the upper jaw, the sides of the face and upper lip, and the secondary palate (figure 1). The bilateral mandibular prominences form the lower jaw and lower lip.(7)

The embryologic development of the lip begins during the 4th week of gestation when the aforementioned frontonasal prominence and bilateral maxillary prominences appear.(1) The formation of the upper lip at week 6 to 7 of gestation is the result of the meeting between the paired maxillary prominences with the medial and lateral nasal processes of the frontonasal prominence.(1) Failure of the medial nasal process to contact the maxillary process results in the formation of a cleft lip.(8)

The primary palate is made up of the lip, nostril sill, alveolus, and hard palate anterior to the incisive foramen. It develops from the fusion of the paired medial nasal processes with the maxillary prominence. This occurs between weeks 4 to 7 of gestation.(6) The hard palate posterior to the incisive foramen and the soft palate make up the secondary palate. The secondary palate is formed by the fusion of the lateral palatal processes of the maxillary prominences. This fusion begins during week 9 of gestation and moves in an anterior to posterior direction.(1) Any interruption in these processes may result in the presence of a cleft palate (CP).(6)

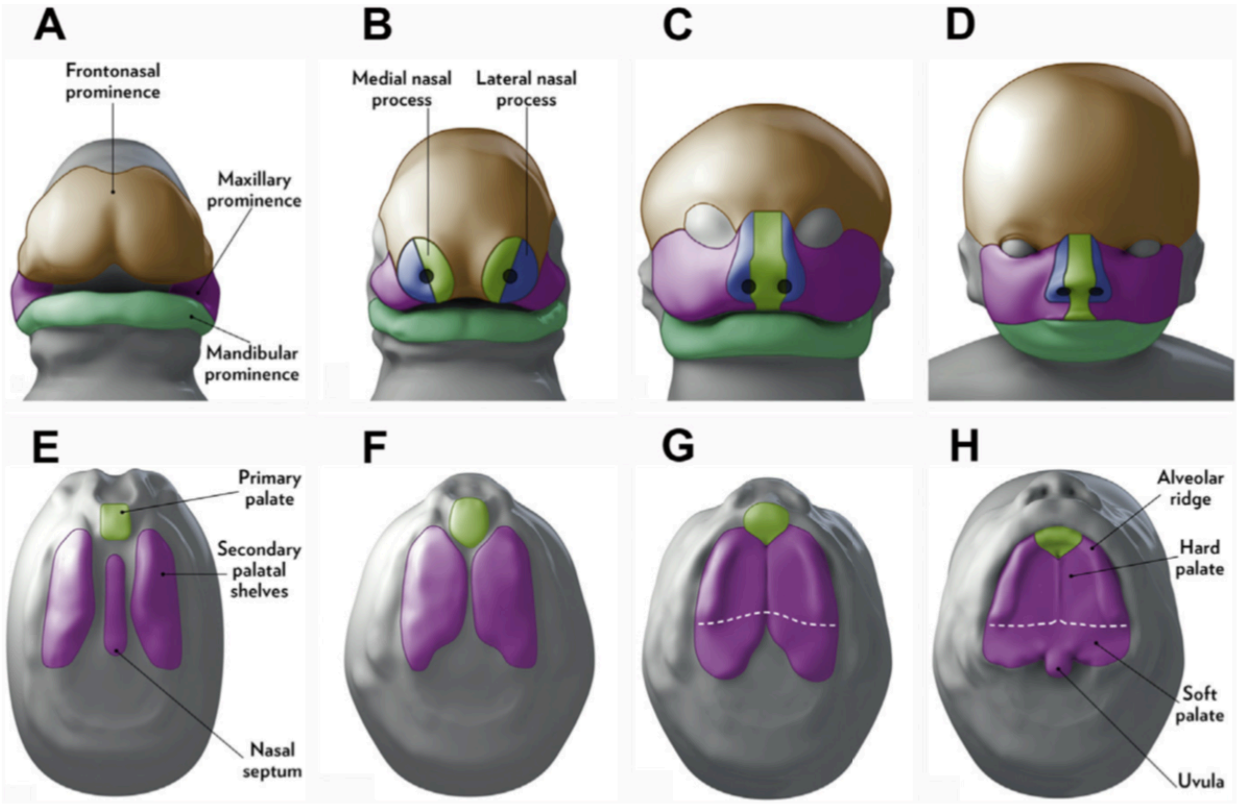

Figure 1. Adapted from Worley et al.(1) A-D, Development sequence of the upper lip.

E-H, Development sequence of the hard and soft palate.

1.1.3 Etiology

There are both genetic and epigenetic factors that play important roles in the etiology of CLP. The varying incidence of clefting based on ethnicity, geographic location and socio-economic status support this claim.(9-11) Further demonstrating the genetic predisposition to CL/P, twin studies have shown a 60% pairwise comparison in monozygotic twins as compared to a 10% concordance in dizygotic twins.(12, 13) While no one gene has been identified as the single one responsible for the presence of CL/P, there are clearly strong genetic components to the development of oral clefts.(1) Over 200 genetic syndromes have been associated with CL and over

400 syndromes with CP.(14) Despite this, most cases occur in an isolated fashion and are referred to as nonsyndromic clefts.(9) The data is inconsistent with respect to the frequency of other malformations in patients with CL/P. Rollnick and Pruzansky reported the presence of other malformations in 35% of patients with CL/P and 54% in patients with CPO.(15)

There are common congenital anomalies and genetic syndromes associated with CLP.(16) Congenital heart defects, hydrocephalus and urinary tract infections are all frequent anomalies that can be present in patients with CPO.(1) The most common associated anomaly is Robin Sequence which consists of a triad that includes micrognathia/retrognathia, glossoptosis and airway obstruction.(17) Common genetic syndromes include; Stickler syndrome accounting for 25% of syndromic CP(18), velocardiofacial syndrome accounting for 15% of syndromic CP(18) and Van der Woude syndrome accounting for 19% of syndromic CL/P and CP.(10)

In patients with nonsyndromic oral clefts, the genetic contribution is estimated to be between 20% and 50%.(19) In patients with nonsyndromic CP, the mode of inheritance is likely to be either a recessive single-gene model, several interacting loci, or both.(20, 21) However, nonsyndromic CL/P is likely secondary to a combination of multiple interacting major genes and has multifactorial inheritance.(22, 23)

This genetic component is also demonstrated in the higher recurrence rates seen in affected families.(1) Parents that are unaffected who have one child with CL/P have an estimated recurrence risk of 4%. This rises to 9% when there are two affected children. With one affected parent, the risk is of 4% and this rises to 17% with history of one affected parent and one affected child.(24)

Additionally, the risk of CL/P in siblings increases with the severity of the deformity. When a child has a unilateral CL/P, the risk of CL/P for the next child is 2.5% and this rises to 5.7% in the presence of a previous child with bilateral CL/P.(10)

Environmental factors also play a role in the development of orofacial clefts. While the data remains inconsistent, risk factors such as tobacco use, pregestational or gestational diabetes and alcohol use have been linked to the development of CL/P.(25-27) The use of anticonvulsants such as topiramate have been reported to increase the risk of developing CL/P by 5-fold when taken during the first-trimester.(28) Living in higher altitudes has also shown an increased risk of developing CL.(29) Finally, the role of multivitamin supplements has been shown to be beneficial in lowering the incidence of CL/P,(30) particularly when taken by woman with a positive family history.(31)

1.1.4 Anatomy and Classification

When a CL is present, there is a resulting projection and outward rotation of the premaxilla with a repositioning of the lateral maxillary segment. The lateral muscle fibres of the orbicularis oris end at the margin of the cleft and insert onto the alar wing. When a bilateral CL is present, the two deep clefts separate the prolabium from the lateral elements. The prolabium has no orbicularis oris and the fibres from the lateral elements run parallel to the cleft edges towards the alar bases.(6)

The classification of CL is based on the extent of the anatomical involvement. CLs can be classified as microform, incomplete or complete.(1) When a microform CL is present, there is a notch in the vermillion cutaneous junction but all of the lip tissues remain present.(1) In an incomplete CL, there is a dehiscence of the orbicularis oris with variable skin involvement. In patients with an incomplete CL, a Simonart band is the thin band of soft tissue that spans the superior aspect of the incomplete CL. Finally, in complete CL, there is an abnormal insertion of the orbicularis oris onto the ala and columella as the cleft extends through the length of the lip and directly into the nasal sill. As mentioned earlier, in the presence of bilateral CL, the intermaxillary segment is displaced anteriorly with complete absence of the orbicularis oris at that level (figure 2).(1)

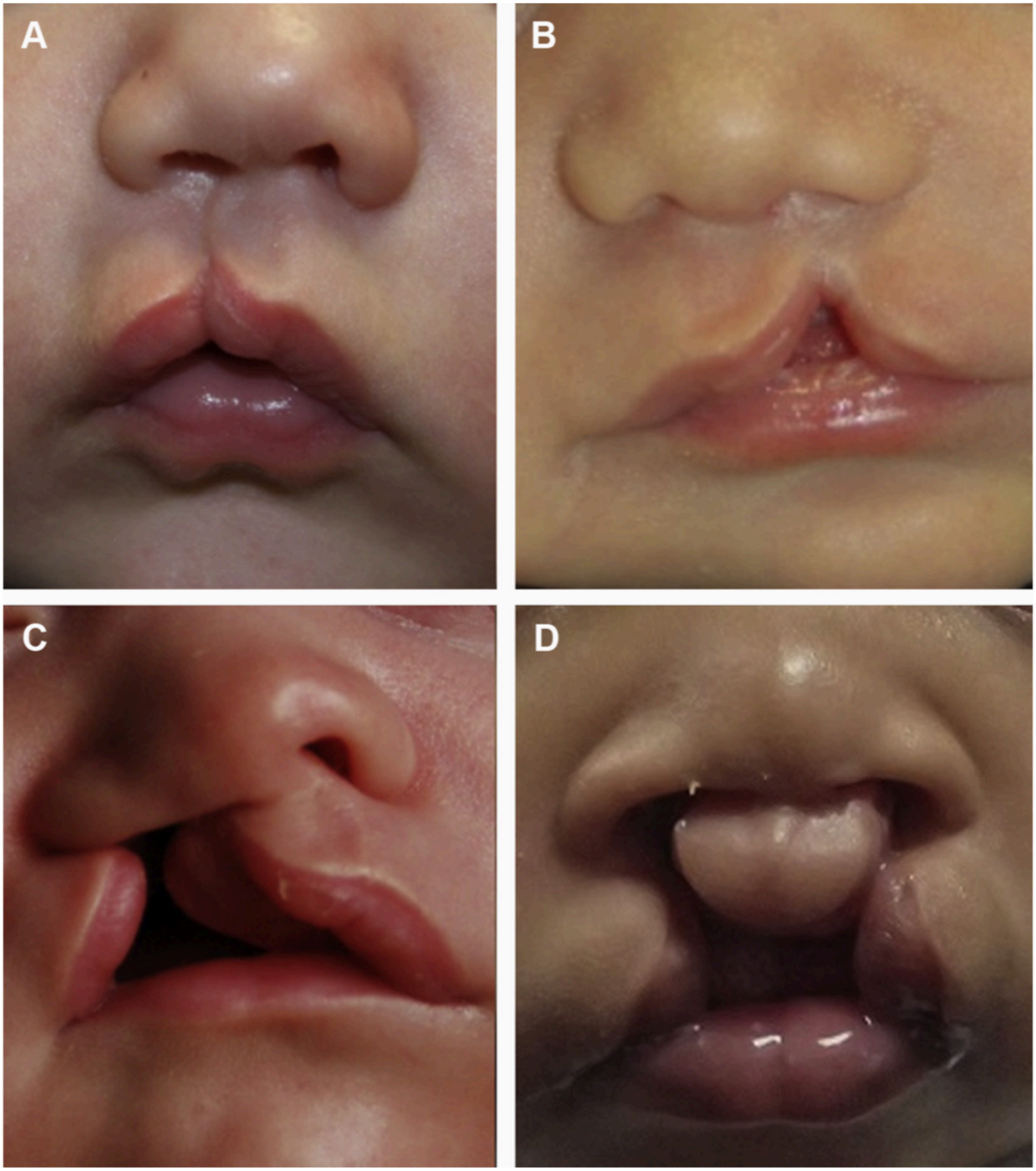

Figure 2. Adapted from Worley et al. (1) A) Microform CL B) Incomplete left CL C) Complete right CL D) Complete bilateral CL.

There is a wide spectrum of oral cleft anomalies that exist. They range from a bifid uvula to a complete bilateral cleft of the palate with associated alveolar and lip clefts.(32) Similar to CLs, CPs can be classified according to the extent of their anatomical involvement. In the case of submucosal clefts, there is an underlying dehiscence of the palatal musculature with no associated mucosal deficit. Clefts can involve the primary or secondary palate. As described earlier, these are defined based on their embryologic origins. A cleft of the secondary palate extends from the incisive foramen, posteriorly to the uvula. A cleft of the primary palate extends anteriorly from the incisive foramen to the alveolar arch. Finally, a complete CP involves both the primary and secondary palates.(1)

In order to create a uniform and simple way of reporting the varying degrees of CL/P, in 1971, Desmond Kernahan created the Y classification.(33) In his description, the dividing point between the primary and secondary palate was represented at the junction of the Y by a small circle. Anterior to this, each stem of the Y was divided numerically from 1 to 3 and from 4 to 6. The most anterior representing the lip, the middle representing the alveolus and the posterior representing the hard palate anterior to the incisive foramen. Posterior to this, the palate was segmented into 3 parts (7 to 9). In 1998, Smith et al. published a modification of the Y classification in order to more accurately describe the cleft varieties using an alphanumeric system.(34) This classification system clearly describes the region, the site and the degree of the cleft. It is largely accepted and used worldwide (figure 3).(2, 35)

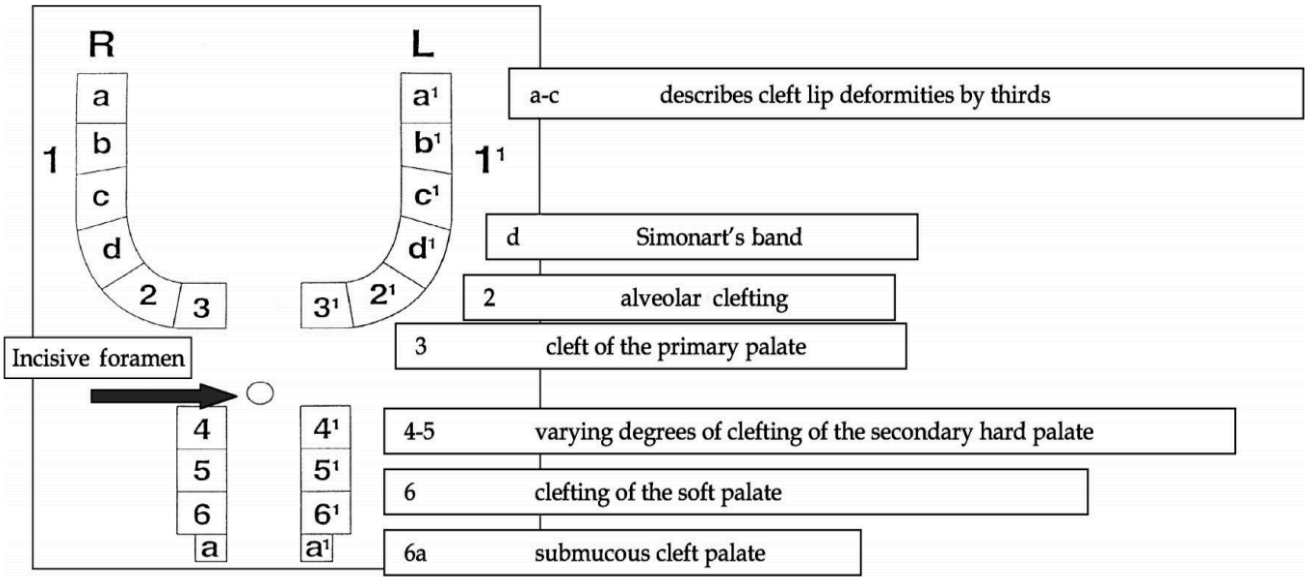

Figure 3. Adapted from Elahi et al.(2) The modified Y classification by Smith et al.

1.1.5 Diagnosis and Management

It can be a source of psychological distress for families birthing and raising a child with a CL/P.(36, 37) The use of prenatal diagnostic testing can assist families in preparing for care of their future child.(38, 39) CL/P can be detected by prenatal 2-dimensional (2D) or 3-dimensional (3D) ultrasounds. This is usually performed during the second trimester, between 18 to 20 weeks of gestation.(6) The accuracy however of these diagnostic tests have shown significant variability. A systematic review by Maarse et al. reported that the range of detection for all types of clefts using 2D ultrasound was between 0% and 73%.(40) A higher rate of detection was noted for CL as compared to CPO.(40) The use of 3D ultrasonography has improved diagnostic accuracy. Maarse et al. reported a detection rate of 100% for CL, 86% to 90% for CLP and 0% to 89% for CPO.(40) It is to be noted that the detection rate is likely dependent on multiple other factors such as technician experience and gestational age.(1)

A multidisciplinary team approach is of utmost importance when treating patients with orofacial clefts. This should be commenced during the first few days of life.(41) Depending on the presence of additional abnormalities, a full evaluation by a team consisting of an audiologist, a geneticist, a neurosurgeon, an otorhinolaryngologist, a pediatrician, a plastic surgeon, a speech language pathologist and a dentist may be required.(6) These families should be connected to a craniofacial team that will assist them in planning care for their child.

The management of patients with orofacial clefts can be long and arduous. It generally begins in the prenatal period with genetic and familial counselling and continues until early adulthood after completion of orthognathic surgery(table 1).(1, 6) The earliest steps of management for these patients and families includes a complete feeding evaluation by a speech-language pathologist who can assess the child and provide counselling. Feeding difficulties are common among patients with CL/P. While patients with CL can usually be fed by breast or regular bottle, the presence of a CP prevents the creation of an adequate suction and makes feeding more difficult.(6) Reid et al. compared the amplitude of suction in patients with varying degrees of clefts and found that babies with smaller clefts were more likely to generate normal levels of suction.(42) In order to ensure proper feeding there are multiple bottles made specifically for patients with CL/P. Some of these include the Haberman nipple, the squeezable cleft palate nurser (Mead Johnson) and the pigeon nipple.(6) These bottles have been classified into 2 subtypes; assisted delivery and rigid.(1) In a review by Bessell et al. of 292 babies, no difference was found in growth outcomes when comparing rigid versus squeezable bottle types.(43)

Procedure	Age
Cleft lip repair	3 mo
Tip rhinoplasty	
Tympanostomy tubes	
Palatoplasty	9-18 mo
T-tube placement	
Speech evaluation	3-4 yr
Velopharyngeal insufficiency workup and surgery	4-6 yr
Alveolar bone grafting	9-11 yr
Nasal reconstruction	12-18 yr
Orthognathic surgery	Completion of mandibular growth (>16 yr)

Table 1. Adapted from Janis. Essentials of Plastic Surgery (6) Steps in cleft care.

In order to reduce the severity of the CL/P, lip taping and nasoalveolar molding (NAM) can be applied in the pre-operative period.(1) The theoretical benefits of these techniques include improved nasal symmetry and decreased cleft width.(44-46) There is controversy however regarding their efficacy and utility.(47) Pool and Farnworth described their protocol for lip taping beginning during the first week of life and continuing for 6-weeks prior to CL repair. They noted that the remodelling of the alveolar segments was very effective with lip taping. In addition, lip taping was inexpensive and easily applicable with minimal associated risks.(48) The use of lip taping accomplished the goals of surgical lip adhesion without any surgical intervention.(48)

The proposed goals for NAM include improving alignment and approximation of alveolar segments, correcting malposition of nasal cartilages, and elongating the columella.(6) Sabarinath et al. demonstrated the effectiveness of NAM in patients with unilateral CLP in reducing the severity of the initial cleft deformity mainly at the anterior portion of the maxillary arch.(45) NAM enables the surgeon to achieve a better and more predictable outcome with less scar formation.(49)

A better lip and nasal form reduce the number of surgical revisions required for formation of excessive scar tissue, oronasal fistulas, and nasal and labial deformities.(49, 50) In order to properly achieve the desired outcomes using NAM, a family commitment is required.(1) Levy-Bercowski et al. reported that although soft tissue irritation was the most common complication observed, compliance issues were of greater concern.(51)

As techniques for intrauterine repair improved, there was new hope as to the utility and possibility of foetal surgery for craniofacial disorders.(52) This was followed by animals studies focusing on foetal correction of certain craniofacial disorders like CL/P.(53-57) The potential advantages of foetal surgery included scarless wound healing which would prevent harmful consequences of the malformation and extra-uterine repair such as maxillary growth restriction.(58) This in turn would decrease the need for future additional treatments.(52) Despite these advances, there are still too many unsolved problems associated with intrauterine surgery.(52) Amongst others, major risks of preterm labour make it so that it is not currently a standard of care.(6)

The goal of CL repair is to approximate the medial and lateral lip elements at all levels. These include the nostril sill, cutaneous roll, vermillion-cutaneous junction, and vermillion-mucosal junction. This must be completed without interruption or loss of landmarks and by excising tissue when there is excessive height and providing length where tissue is short.(59) Lip repair is commonly performed at 3 months. While the timing is not absolute, the simple rule of 10s can be applied. The infant must be at least 10 pounds and at least 10 weeks of age.(60) There is no one uniform technique that is applied to all CL repairs. The choice of the procedure is up to the plastic surgeon and can vary depending on the patient's clinical presentation.(60)

In the 18th century, Le Monnier was the first surgeon to describe, and receive credit for, a CP repair.(61, 62) In CP repair, the aim is to re-create an anatomically intact and functional palate in order to improve feeding and achieve normal speech all while minimizing maxillary growth restriction.(59) The closure of the oral and nasal mucosae divides the oral and nasal cavities and provides potential space for alveolar bone graft placement. By repositioning the levator veli palatini muscles from a posteroanterior to a lateromesial course, this creates an intact velopharyngeal sphincter.(6) In order to minimize growth disruption, surgical dissection should be limited to only as much as required in order to achieve normal palatal anatomy.(6) The timing of palatoplasty is typically between 9 and 12 months of age. Early repair (< 12 months) has been shown to significantly improve speech outcomes.(63) Improved middle ear function has also been noted in some studies.(64) Delaying repair allows for greater uninterrupted maxillary growth. The majority of surgeons favor early repair because the resulting facial growth imbalance is corrected in most at skeletal maturity with orthodontic treatments and orthognathic surgery. The compensatory articulations that are caused by persistent velopharyngeal insufficiency (VPI), are much more difficult to correct.(6)

1.2 Velopharyngeal Insufficiency

1.2.1 Definition

The production of normal speech depends upon the functional and structural integrity of the velopharynx.(7) The velopharynx is a complex and dynamic structure that separates the nasal and oral cavities during sound production.(7) Adequate velopharyngeal function (VPF) refers to complete closure of the velopharynx during speech such that no air escape occurs through the nose during oral consonant production.(59) Complete closure of the velopharyngeal sphincter is required for the normal production of all but the nasal consonants (In English, /m/, /n/, /ng/).(1) The term velopharyngeal dysfunction (VPD) includes any abnormal velopharyngeal function regardless of the cause.(65) VPD can be categorized into 3 subtypes. Velopharyngeal insufficiency (VPI) is a term used to denote an anatomic or structural defect that is responsible for inadequate closure of the velopharyngeal valve.(7) Velopharyngeal incompetence refers to VPD caused by impaired neuromotor control of the velum or pharyngeal wall. Velopharyngeal mislearning refers to VPD not caused by structural or neuromotor abnormalities.(6)

The normal functioning of the velopharyngeal sphincter involves composite movements of the velum and the pharyngeal walls. The velum moves posterosuperiorly, the posterior pharyngeal wall ventrally and the lateral pharyngeal walls mesially.(6) Skolnick et al.(66) and Croft et al.(67) described closure patterns of the velopharyngeal port which indicated the predominant moving component of the velopharyngeal sphincter. The coronal closure pattern is effected primarily by velar elevation.(7) In sagittal closure, movement is ensured primarily by the lateral pharyngeal walls. The velum contacts the lateral pharyngeal walls as opposed to the posterior pharyngeal wall as is seen with the other closure patterns.(7) Circular closure involves movement of both the velum and the lateral pharyngeal walls in equal proportions.(7) Finally, in circular closure with Passavant's ridge, in similar fashion to circular closure, there is movement of both the velum and lateral pharyngeal walls with an additional ventral movement of the posterior pharyngeal wall. This results in a truly sphincteric closure pattern (figure 4).(67)

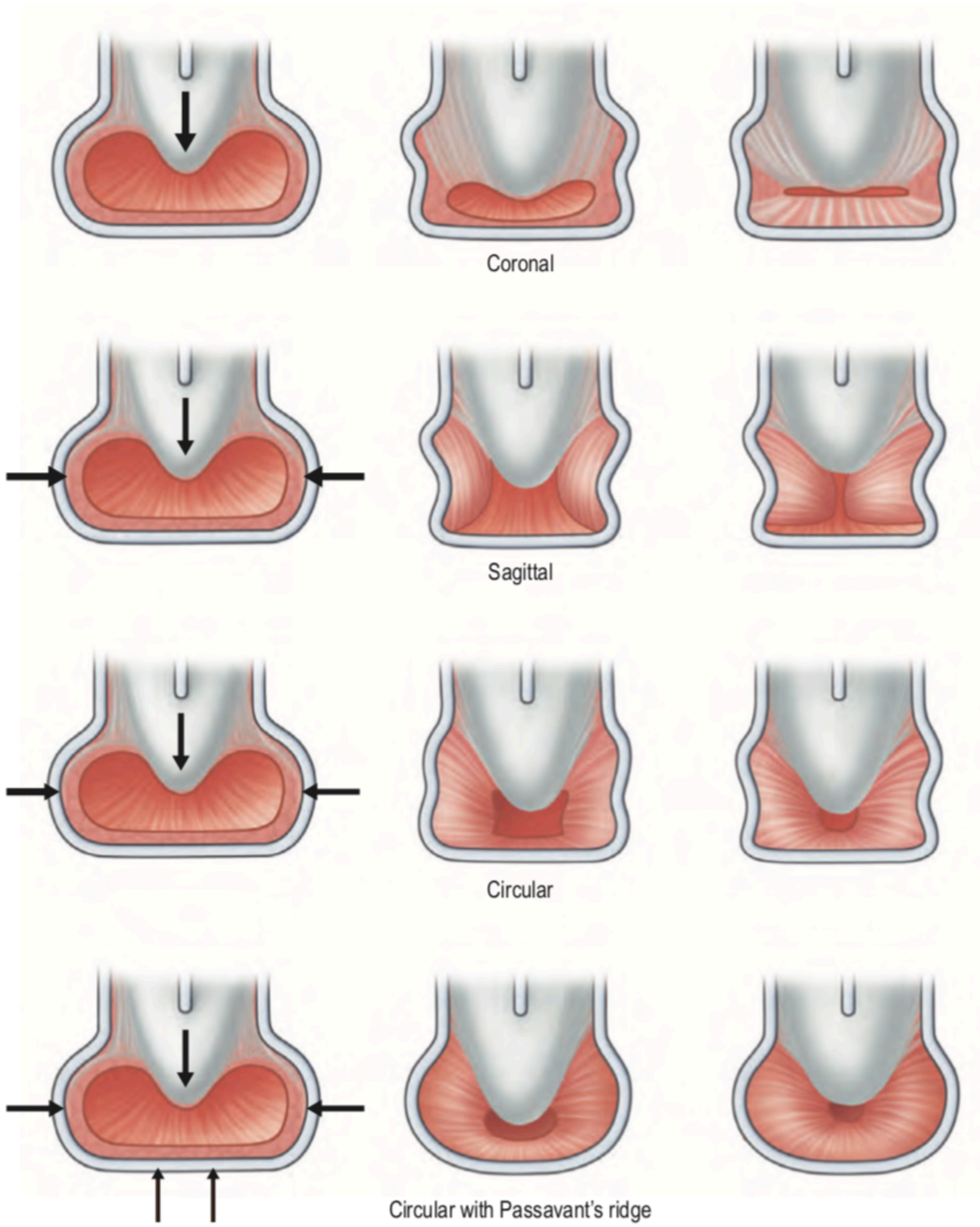

Figure 4. Adapted from Neligan. Plastic Surgery (7) Velopharyngeal closure patterns as described by Skolnick et al. and Croft et al.

1.2.2 Etiology, Diagnosis and Management

Risk factors for VPI include history of CP, delayed CP repair, submucosal CP, and surgical procedures that alter the velopharyngeal anatomy.(1) These surgeries can include but are not limited to, palatoplasty, tumor resection or adenoidectomy. After palatoplasty, in the absence of an oronasal fistula, VPI is most commonly the result of impaired velar mobility due to extensive scarring.(7) VPI is seen in an estimated 20% of patients who underwent prior repair of CP.(68) A systematic review of the literature comparing different surgical techniques for palatal closure found an increased incidence of VPI in straight-line intervelar veloplasty repair when compared with Furlow double-opposing Z-plasty.(69) Finally, VPD can be seen in association with certain syndromes such as trisomy 21, 22q11.2 deletion syndrome and Kabuki syndrome.(1) History of stroke, head injury, head and neck cancer with an anatomic defect or radiation exposure can also lead to acquired pharyngeal dysfunction or hypotonia.(1)

For patients born with CL/P, evaluation of their VPF begins as soon as they are capable of articulating some intact oral consonants.(6) This usually occurs between 2 to 3 years of age and continues at regular intervals into early adulthood.(1) These evaluations must be performed by trained speech pathologist with extensive experience in treating patients with oral clefts.(6) In patients with VPI, there is usually nasal air escape and resulting hypernasality. Articulatory errors such as distortions, substitutions and omissions come as a secondary effect of VPI. These patients, as a result, have decreased intelligibility of their speech.(59)

The diagnosis of VPI can be made with use of both subjective and objective measures. The use of perceptual speech assessments (PSA) by experienced speech language pathologists remains the gold standard for the diagnosis.(70) During PSA, an assessment of intelligibility, resonance, voice and articulation are performed. Presence of nasal emission, hypernasality, nasal rustle/turbulence, facial grimacing and compensatory articulations are noted.(6) Spontaneous speech and provocative samples are assessed using standard lists.(71) When possible, audio or video recording should be archived for pre-and post-treatment comparisons. Based on the evaluation, the speech language pathologist can make preliminary decisions regarding treatments.(7)

Instrumental objective measures of VPF can serve as useful adjuncts to PSA.(7) In addition to the diagnosis of VPD, they can provide insight into the severity of the disease.(6) Instrumental assessments can be divided into acoustic and aerodynamic. Nasometry is an acoustic measure that quantifies oral and nasal air pressure, nasal airflow, and in turn, calculation of an estimated velopharyngeal port size.(6) It is performed with use of air pressure transducers that are inserted into one nostril and into the mouth. A flowmeter is inserted into the other nostril.(6) An estimated velopharyngeal port size of less than 10 mm^2 equates to normal airflow. A port size of larger than 20 mm^2 equates to severe hypernasality, and an estimated port size between 10 and 20 mm^2 is considered mild to moderate.(65) Nasalance scores have been shown to correlate with perceptual assessments of resonance.(72)

The use of aerodynamic instruments such as multiview videofluroscopy and nasoendoscopy permits continuous observation of the dynamic activity of the velopharyngeal valve over time during connected speech.(73) Proper imaging of the velopharynx is crucial for making treatment decisions.(7) During nasoendoscopy, a flexible fibreoptic endoscope is inserted into the nasal cavity to observe velopharyngeal closure during speech. The procedure is generally performed by an otorhinolaryngologist in the presence of a trained speech language pathologist.(7) Cooperation from the patient is required and therefore nasoendoscopic assessments cannot be performed until 4 to 5 years of age. Multiview videofluoroscopy can be performed as early as 2 to 3 years of age. This technique requires less cooperation from the patient.(7) It consists of static and dynamic frontal and lateral radiographic views of the velopharynx.(6) It provides information regarding palatal length, pharyngeal depth and velopharyngeal gap size.(7)

The foundation of management for cleft speech disorders is speech therapy.(59) It may be used as a primary treatment or as an adjunct to surgery.(1) Nahai et al. describe that 70% of their patients with VPI are managed with speech therapy alone.(60) Even when surgery is required to correct an anatomic or structural defect, speech therapy is needed to correct compensatory articulation errors.(1) During speech therapy, the techniques implored include sucking and blowing exercises, electrical and tactile stimulation, biofeedback and articulation therapy.(6)

All surgical procedures for VPD aim to reduce the velopharyngeal cross-sectional area.(7) Prosthetic management is indicated when conservative management fails and surgery is contraindicated.(74) In patients with velopharyngeal incompetence a palatal lift prosthesis is used, while in patients with VPI, this is carried out with use of a pharyngeal obturator.(75-78) The pharyngeal obturator is a maxillary prosthesis with a posterior extension that separates the nasopharynx and oropharynx restoring the soft palate defect and allowing for adequate velopharyngeal closure.(76, 79)

Surgical modalities for treatment of VPI include pharyngeal flap, sphincter pharyngoplasty and Furlow double-opposing Z-plasty. The choice of surgery can be based on the location of the velopharyngeal closure deficiency.(6) In patients with minimal circular gaps, a Furlow double-opposing Z-plasty can be used.(6) Ideal candidates for sphincter pharyngoplasty are those with limited lateral pharyngeal wall motion and coronal closure patterns.(1) In patients with good lateral pharyngeal wall motion with circular or sagittal closure patterns, a pharyngeal flap can be considered.(80) A recent meta-analysis of two randomized controlled trials comparing pharyngeal flap to sphincter pharyngoplasty in the treatment of VPI, suggested the superiority of the pharyngeal flap when assessing VPI resolution following surgery.(81)

1.3 Orthognathic Surgery & Imaging

Patients with CP are at risk of abnormal facial growth in the form of maxillary hypoplasia.(60) Maxillary advancement (MA) is a common orthognathic procedure with various indications, including mandibular prognathism, maxillary deficiency or hypoplasia, obstructive sleep apnea, hemifacial macrosomia and others. Advancement of the maxilla induces significant structural changes to the velum and the pharyngeal soft tissues that make up the velopharyngeal valve. MA therefore has the potential of altering sound production and increasing the risk of developing post-operative VPI. While some studies have shown that maxillary osteotomies result in VPI,(82) other studies have not.(83) The evidence supporting the claim that VPI develops after MA is not clearly established.(73)

Pre-surgical planning should consider the anatomy of velopharyngeal structures in children, which is markedly different than that of adults. In relation with other oral structures, the tongue and epiglottis are larger, the larynx is higher, the arytenoid cartilage is bulging, and the trachea is softer. These small differences can cause dramatic changes in velopharyngeal function. Furthermore, surgeons need to plan for growth.(84) Growth of the upper airways shows two peaks. The first is between 0 and 5 years of age, while the second happens between the ages of 12 and 16.(85) Selection of patients who have completed their maxillofacial growth may be preferable to avoid growth bias and to obtain reliable results. MA is generally performed at a mean age of 22.7 years.(84) Apart from aesthetic facial improvement, this surgery has also been shown to improve mood, affect, social interactions, as well as speech.(86)

Le Fort 1 MA is often part of the management plan for patients presenting with malocclusion (from clefts, amongst others) to correct prognathism or to relieve the obstruction in patients with obstructive sleep apnea.(87, 88) Pre-operative imaging of the upper airway allows for adequate surgical planning, while post-operative imaging allows the surgeon to measure the effects of orthognathic surgery.

Lateral cephalometric radiographs are a routine part of the diagnosis and treatment planning process for orthognathic surgery.(89) They also allow clinicians to evaluate structural changes following surgery.(89) There is extensive normative data in the literature describing the use of cephalograms in assessing the impact of orthognathic surgery on the pharynx.(84) Cephalograms are widely available, simple and inexpensive. However, soft tissue visualization is limited, and only static 2D views of the pharyngeal anatomic changes are provided as this imaging modality cannot document the dynamic function of the velum.(90-92) Additionally, post-operative cephalograms commonly demonstrate increased nasopharyngeal depth,(93-96) increased velar angle(95) and either increased(93, 96, 97) or constant velar length,(94, 95, 98) but fail to document certain aspects of the velopharyngeal space, such as the lateral wall movement.(92) With recent advances in orthognathic surgery, there is an increased need for more detailed and precise imaging. Computerized Tomographic (CT) scans can facilitate surgical planning and assess treatment outcomes. CT offers better demonstration of soft tissue positioning. It also has the ability to evaluate anteroposterior and lateral distances, and cross-sectional areas at different levels of the pharynx.(99)

1.4 Hypothesis and Objectives

With the anterior displacement of the maxilla, a compensatory increase in the lateral wall contribution is critical to adequate velopharyngeal closure. Given that the muscles (pharyngeal constrictor and palatopharyngeus muscles) forming the lateral walls remain attached to the maxilla, the anterior displacement of the latter is expected to increase the tension which the lateral walls are subjected to, forcing them to adopt a straighter shape (as opposed to their usual concave shape), resulting in a decreased lateral distance. Therefore, with an increased anteroposterior distance and a decreased lateral distance, it was hypothesized that the overall velopharyngeal area and volume would not change significantly.

The purpose of this study was to document changes in airway anatomy, as measured on 3D CT scans after Le Fort 1 MA. Additionally, the aim was to compare differences in airway anatomy in patients with and without CP. As mentioned, we hypothesized that in patients undergoing MA, there are modifications in the structural anatomy of the naso- and- oropharynx. But more specifically, we hypothesized that although the dimensions of the velopharyngeal space are modified, its surface area and volume do not change significantly.

2 – METHODOLOGY AND RESULTS

A detailed description of the methods used for this study, as well as the results and analysis are presented in the following article.

2.1 ARTICLE

Volumetric Velopharyngeal Space Modifications in Patients with and without Cleft Palate Undergoing Le Fort 1 Maxillary Advancement

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DISCLOSURES

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ABSTRACT

Background & Purpose: The effects of maxillary advancement (MA) on velopharyngeal anatomy have primarily been studied using lateral cephalometric radiographs. However, with recent advances in orthognathic surgery, there is an increased need for more detailed and precise imaging such as computerized tomographic (CT) scan reconstructions, to help in surgical planning and to measure outcomes. The purpose of this study is to compare the pre-and post-operative velopharyngeal space configuration modifications as measured on CT scans. The aim is also to assess differences in these airway measures between patients with and without history of prior repaired cleft palate (CP).

Methods: This is a retrospective cohort study of 44 patients with and without CP who were treated with MA for midface hypoplasia and secondary malocclusion at skeletal maturity. The pre-and post-operative CT scans were compared with respect to pre-established landmarks. Linear distances, cross-sectional areas, and volumes were measured using 3-dimensional (3D) CT scan reconstructions.

Results: For the linear distances measured, a statistically significant difference was found when comparing the pre-and post-operative measures of the narrowest part of the nasopharynx and the narrowest part of the retropalatal airway space (25.1 vs 28.5 mm $p=0.001$ and 6.5 vs 7.6 mm $p=0.026$, respectively). Retropalatal cross-sectional areas, nasopharyngeal cross-sectional areas and the volumetric assessment of the nasopharyngeal space showed no statistically significant differences when comparing pre-and post-operative scans ($p>0.05$). The main effect of palatal repair (CP vs. Non-CP) showed that there was only a statistically significant difference for the measures of the narrowest part of the nasopharynx and the nasopharyngeal cross-sectional area ($p=0.045$ and $p=0.04$, respectively). Mean changes in the measures did not differ over time (pre- and post-op) depending on whether there was prior history of CP repair.

Conclusion: Our results support the hypothesis that although structural modifications of the pharyngeal space are inherent to MA in patients with CP, its surface area and volume do not change significantly. These changes are also independent of history of previous CP repair.

Keywords: Cleft lip, Cleft palate, Velopharyngeal insufficiency, Orthognathic surgery, Maxillary advancement, Le Fort, Computed tomography, Cephalometric, Anatomy

INTRODUCTION

Cleft lip and palate (CLP) are common congenital anomalies with a prevalence of 1 to 2 births per 1000.(1) When a cleft palate (CP) is present, the muscular insertions on the soft palate are abnormally configured. Surgery is not only aimed at closing the palatal defect but also at correcting this abnormal configuration by establishing continuity and proper muscular orientation.(2)

Abnormal facial growth is commonly seen in patients with CP.(3) Repair of CP induces palatal scarring which restricts growth of the maxilla in all directions, resulting in iatrogenic maxillary insufficiency. Correction of this maxillary retrusion is carried out 60% of the time in these patients(4) with the Le Fort 1 osteotomy being undertaken in almost 84% of them.(5)

During maxillary advancement (MA), there is concomitant advancement of the soft palate. This can lead to an increase in the space between the velum and the posterior pharyngeal wall. In patients without prior CP repair, this gap is usually compensated for by the lateral pharyngeal walls and the palatal musculature. Patients with CP are at higher risk of velopharyngeal insufficiency (VPI) because their scarred palatal musculature restricts this innate compensatory mechanism.(6, 7) So while orthognathic surgery has a potentially beneficial effect on speech due to the reestablishment of the maxillomandibular equilibrium, it may contribute to the worsening of pre-existing hypernasality in patients with CP.(8)

The use of cephalograms in evaluating airway size and shape changes after MA has been extensively described.(9) However, with recent advances in orthognathic surgery, there is an increased need for more detailed and precise imaging to help in surgical planning and to measure outcomes. Computerized tomographic (CT) scans have the advantage of imaging structures in 3 dimensions, evaluating sagittal depth, transverse diameter and pharyngeal airway volume. CT reconstructions have become crucial in surgical planning and yield superior surgical outcomes.(10-12)

The purpose of this study was to document changes in airway anatomy, as measured on 3-Dimensional (3D) CT scans after Le Fort 1 MA. Additionally, differences in airway anatomy in patients with and without CP were compared. It was hypothesized that in patients undergoing MA, there are modifications in the structural anatomy of the naso- and- oropharynx. But more specifically, it was hypothesized that although the dimensions of the pharyngeal space are modified, its surface area and volume do not change significantly.

MATERIALS AND METHODS

This was a retrospective single center cohort study of patients with and without CP who were treated with Le Fort 1 MA at our institution. This study was approved by the ethics committee at Sainte-Justine University Affiliated Hospital in Montreal.

Subjects

The inclusion criteria stipulated that subjects must have undergone: 1) Le Fort 1 MA at Sainte-Justine Hospital between 2012 and 2018, and 2) pre-and post-operative 3D CT scans from the top of the cranium to the base of the epiglottis. Both patients with and without history of repaired CP were included. Patients who 1) had inadequate documentation, 2) underwent craniofacial procedures that did not include Le Fort 1 MA, or 3) were lacking pre-operative or post-operative CT scans, were excluded. Any syndromic patient was excluded.

Surgical Procedure

The surgical procedures for all subjects included in this study were done by the same Plastic and Reconstructive Surgeon (D.B). All patients underwent a Le Fort 1 MA. Of the 44 patients included, 35 underwent concomitant bilateral sagittal split osteotomies (BSSO). Rigid fixation with titanium miniplates was used in all patients.

Image acquisition

As per protocol implemented by the principal investigator, all patients undergoing any form of orthognathic surgery undergo pre-operative CT scans for virtual surgical planning. The scans were done at various time points but all within a year of the surgery. The most commonly noted time points were between 1 and 3 months pre-operatively.

The post-operative CT scans are done as part of the principal investigators normal practice for post-operative complication assessment. The most common time point for these was 3 days post-operatively.

All subjects in the study underwent CT scans in the supine position with the head and neck in a neutral position and with the Frankfurt horizontal plane perpendicular to the ground. Images were acquired at 1 mm intervals along the axial plane from the top of the cranium to the base of the epiglottis. The software used to reconstruct the images was Voxar®. It allowed the following images to be computerized 1) the original axial view 2) coronal view 3) sagittal view and 4) 3D reconstruction.

Image analysis

One author evaluated all CT images by identifying landmarks and by measuring linear distances, cross-sectional areas, and the nasopharyngeal volume. A second independent evaluator, who is a radiologist specialized in head and neck imaging, evaluated a subset of the CT images. Inter-rater reliability was calculated. The landmarks and measurements were those used by Gokce et al.(13), Jakobsone et al.(14) and Mason et al.(15)

The landmarks identified were as follows: Posterior Nasal Spine (PNS), Retro Velum (RV), and pharyngeal wall borders (Upper Pharyngeal Wall – UPW, Nasopharyngeal Wall – NPW) (Table 1).

The linear distances were studied on the midsagittal plane (MSP) through the nasal septum and included 1) the narrowest part of the nasopharynx (PNS-UPW) and 2) the retropalatal airway space (RV-NPW). The velar length (VL) and velar thickness (VT) were also measured (Figure 1) (Table 2).

The pre-and post-operative upper airway cross-sectional areas (CSAs) of each patient were studied at two levels. The levels for the area measurements were settled on the MSP. CSAs were measured on the axial slices by following the perimeter of the airway with the cursor. The following cross-sectional areas were measured (Figures 2 & 3) (Table 3).

1. Nasopharyngeal cross-sectional area (NPa): Along a horizontal plane at the narrowest distance between the posterior nasal spine and the upper posterior pharyngeal wall (PNS-UPW plane).
2. Retropalatal cross-sectional area (RPa): along a horizontal plane at the narrowest distance between the soft palate and the nasopharyngeal wall (RV-NPW plane).

Using the same axial slice along the RPa, the largest anteroposterior (AP) and latero-lateral (LL) distances (RPa AP & LL) were measured. The AP measure evaluates the distance between the velum and posterior pharyngeal wall, while the LL measure assessed for lateral wall position following MA. These measures were included as part of the linear distances assessed (Figure 4).

The technique used for evaluation of the magnitude of maxillary advancement (MMA) was based on those used by Abramson et al.(16) Lye et al.(17) and Turvey et al.(18) For MA and position, the true horizontal axis was defined as the sella-nasion line rotated 6° clockwise from the Sella turcica (S). The posterior vertical reference line (PVRL) was a line passing through S and perpendicular to the true horizontal. The anterior vertical reference line (AVRL) was a line passing through point A (most concave point of anterior maxilla) and perpendicular to the true horizontal. The distance between AVRL and PVRL were measured before and after MA and is referred to as the MMA (in millimeters).

Three-dimensional analysis of the airway was performed by the 3D volume rendering package of the software Voxar®. In order to calculate the nasopharyngeal volume (NPV), the boundaries of the nasopharyngeal airway space were set as follows: (1) anterior, a vertical plane running through the PNS, the soft palate, the base of the tongue, and the anterior wall of the pharynx; (2) posterior, the posterior pharyngeal wall; (3) lateral, the lateral walls of the pharynx, including the full extensions of the lateral projections; (4) upper, the roof of the nasopharynx (PNS-UPW plane); and (5) lower, a plane passing through the lower border of the velum perpendicular to the sagittal plane (RV-NPW plane) (Figures 5 & 6).(13, 14) Once the boundaries were set in the sagittal view, the corresponding axial view was obtained. By following the perimeter of the airway with the cursor at 5 levels between the upper and lower boundaries, the NPV was automatically calculated (Table 4).

Data analysis

Data analysis was done using SPSS® Statistics version 25. An independent samples t-test was used to assess the differences in age between the two groups. A chi-squared test was used to determine whether a significant difference existed in the gender distribution between the two groups. Finally, a Mann-Whitney U test was used to assess the differences in timings of pre-and post-operative scans between the two groups.

Two-way mixed ANOVA was used in order to compare the mean differences between the groups (CP vs Non-CP) and the mean differences in the pre-and post-operative measurements (within-groups). The additional purpose of the two-way mixed ANOVA was to understand if there was an interaction between the group variables and the surgery variable. That is, whether the differences seen over time (pre-and post-op) varied depending on whether there was history of prior CP repair.

Finally, a sub-group analysis was performed comparing those who underwent bimaxillary surgery (MA + BSSO) with those who underwent MA surgery alone. A Mann-Whitney U test was used to assess differences in RPa, RPa AP and RPa LL between these two groups. Interrater reliability was assessed using an interclass correlation coefficient. P-value of < 0.05 was considered statistically significant for all analyses.

RESULTS

A total of 44 patients (24 males, 20 females) underwent MA at an average age of 20.3 years (range, 15-29 years). 23 subjects had a prior CP repair. Of the 23 subjects, 6 had bilateral CLP, 8 and 5 had left and right unilateral CLP respectively, 1 had an isolated CP and 3 had submucosal CP.

When comparing the average age at the time of surgery, there was no statistically significant difference between the two groups (p=0.392). Looking at gender distribution, there was a clear discrepancy between the CP and Non-CP groups. There was a higher proportion of males in the CP group (73.9 %) whereas that of females in the non-CP group was higher (66.6%), a difference that was statistically significant (p=0.007) (Table 5).

The mean maxillary advancement for the CP group was 6.2 mm while for the non-CP group it was 4.2 mm. This difference was not statistically significant (p=0.571) (Table 5).

The average delay between the pre-operative scans and surgery was 74.4 days (range 28-208) for the CP group and 99.5 days (range 20-390) for the non-CP group. For timing of the post-operative scans, the mean number of days for the CP group was 21.7 (range 1-365) and for the non-CP group it was 12.5 (range 1-128). There were no statistically significant differences between the two groups (Table 6).

For the linear distances computed, PNS-UPW distance went from 25.1 mm in the pre-operative period to 28.5 mm post-operatively(p=0.001). Of the remaining linear distances measured, a statistically significant difference was found when comparing the pre-and post-operative measures of the RV-NPW (6.5 mm vs. 7.6 mm, p=0.026), VT (8.2 mm vs. 9.6 mm, p=0.031) and RPa AP (7.5 mm vs. 8.6 mm, p=0.013) distances (Table 7).

After surgery, no statistically significant changes in the CSAs were recorded. No change was observed for the NPa (pre: 375.2 mm^2 vs post: 370.4 mm^2, p=0.435) and RPa (pre: 129.8 mm^2 vs post: 145.7 mm^2, p=0.525). There was also no statistically significant difference in the pre-and post-operative measurements of the NPV (4.1 cm^3 vs. 4.3 cm^3, p= 0.401) (Table 8).

The main effect of palatal repair (CP vs. Non-CP) showed that there was only a statistically significant difference for the PNS-UPW and NPa measures (p=0.045 and p=0.04, respectively). There were no statistically significant interactions between time and group. That is, mean changes in the measures did not differ over time (pre-and post-op) depending on whether there was prior history of CP repair.

Differences in pre-to post-operative change for the RPa, RPa AP and RPa LL measures between those who underwent MA with or without concomitant mandibular repositioning were computed. For the RPa LL distance change, a statistically significant difference was found between the mean increase of 2.98 mm in the MA group alone and the mean decrease of 1.77 mm in the maxillomandibular surgery group (p-value = 0.027). No change was noted between the two groups for the RPa and RPa AP measures (p=0.104 and p=0.647, respectively).

On all 88 scans (44 patients), measures were assessed by a single evaluator (E.S.). A second independent evaluator (R.J.) used the same technique to measure 20 randomly selected scans (10 patients). The interclass correlation coefficient was 0.989.

DISCUSSION

The purpose of this study was to evaluate the changes to the velopharyngeal anatomy after MA using 3D CT scans. In addition, the differences in these measures between patients with and without prior CP repair were compared. Several studies have measured surface areas and volumes of the nasopharynx, oropharynx and hypopharynx following MA using CT scans.(19-23) However, there is no clear consensus as to the morphological changes seen following MA.

MA is performed when patients have completed their maxillofacial growth in order to obtain reliable and predictable results.(9) Average age of the combined groups at the time of surgery was 20.3 years. Schendel et al. (23) demonstrated progressive enlargement of the posterior airway in childhood until age 15. Given that all included patients were older than 16 years old, this possible source of bias was eliminated. There was no difference in age at the time of surgery between the CP and non-CP groups.

Epidemiologically, CL/P has a male to female ratio of 2:1.(24) Our patient population consisted primarily of patients with CL/P. This could potentially explain the significant difference in gender distribution between the CP and non-CP groups that was found. Aras et al. did report a difference in gender distribution between their study groups, but they did not provide an explanation for such a finding. Most related studies, however, have not identified an uneven gender distribution.(25-27)

Maegwa et al. separated patients into one of two categories based on the amount of MA performed. Advancements up to 10 mm were associated with maintaining baseline or improving speech intelligibility, whereas advancements above 10 mm were associated with decreased intelligibility and hypernasality.(28-30) Despite these described complications, there are many benefits to MA. Apart from the aesthetic facial improvement, this surgery has also been proven to improve mood, affect, social interactions, as well as speech ability (figures 7 & 8).(31) The mean maxillary advancement for the CP group was 6.18 mm and 4.24 mm for the non-CP group. With a relatively limited amount of advancement in the present study compared with up to 12.4 mm in some,(32) significant changes in surface areas and volumes were not expected.

The literature assessing structural airway changes in patients undergoing MA is limited. The majority of published studies focus primarily on the structural changes to the airway and their impact on patients with obstructive sleep apnea.(11, 13, 16, 33, 34) To the best of our knowledge, the anatomical changes of the velum studied on CT scans have yet to be reported. Patients with no history of CP have the ability to compensate for the structural changes following MA which prevents any adverse effects on VPF and speech.(35) Cephalometric analyses of these changes have been reported but published results are inconsistent. Ko et al. described these changes as increases in nasopharyngeal depth, VL and velar angle and a decrease in VT.(36) Wu et al. reported an increase in VL with no change in VT.(37) In this study, the anatomical changes to the velum, VL and VT, were assessed using CT scans. While VL did show a trend towards an increase from the pre-operative period to the post-operative period, this change was not significant. This is consistent with reports by Ko et al.(36) and Heliovaara et al.(38) Furthermore, the difference in VL from the pre-to the post-operative period was independent of whether or not patients had a prior CP repair. A significant increase was noted when comparing the pre-and post-operative measures of VT. While a decrease in VT due to velar stretch may have been expected, the increase noted may be attributed to post-operative edema as most scans were completed in the acute post-operative period.

We found a statistically significant increase in the linear distance RV-NPW(p=0.026) following MA. Similarly, the RPa AP distance significantly increased following MA (p=0.013). Chang et al.(20) and Gokce et al.(13) both described similar findings reporting an increase in the AP distance between the soft palate and posterior pharyngeal wall. Gokce et al.(13) also reported a statistically significant increase in the PNS-UPW distance which was consistent with our findings. These changes are attributed to the anterior displacement of the maxilla and the subsequent pull on the velum and velopharyngeal muscles following the Le Fort 1 osteotomy.(13)

It was thought that with advancement of the maxilla and the velum, the lateral pharyngeal walls would compensate to maintain an unchanged overall area and volume. For instance, Kumer et al. used videofluoroscopy and reported increased motion of the lateral pharyngeal walls following MA.(39) The LL distance at the level of RV-NPW was used to assess this change. Although not statistically significant, a trend towards a decrease was noted. This is however not consistent with other studies reporting an increase in the LL distance.(13, 33, 34) We then compared those who underwent exclusive MA to those who underwent maxillomandibular surgery and noticed a significant difference in the RPa LL distance. While those who underwent exclusive MA saw an average increase of 2.98 mm, those who underwent a maxillomandibular surgery actually saw an average decrease of 1.77 mm. Degerliyurt et al.(22) led a study comparing the structural airway changes between patients who underwent exclusive mandibular setback and patients who underwent maxillomandibular surgery. They found that lateral pharyngeal narrowing was only statistically significant in the mandibular setback group. They attributed this difference to the displacement of the medial pterygoid muscles caused by the mandibular setback.(40) Our findings are thus similar and show that maxillary surgery might counteract the reduction in lateral width, which is an effect of mandibular setback.(41)

Although changes in AP and LL distances were seen, the overall surface area measures did not change significantly in our sample. Similarly, Jakobsone el al. found no statistically significant change in velopharyngeal CSA after MA.(13) Abramson et al. did report an increase in the minimum velopharyngeal CSA after MA.(16) However, their mean maxillary advancement was of 9.2 mm which is significantly higher than that of the present study. When analyzing the difference in NPa between the two study groups, it was significantly smaller in the non-CP group both pre-and post-operatively. This change was likely a reflection of the significant difference in the PNS-UPW distance between the two study groups.

With respect to NPV, no statistically significant difference was observed. Chang et al.(11) and Gokce et al.(13) both reported statistically significant increases in NPV following MA. Jakobsone et al.(14) found no significant change in NPV following MA but rather reported a trend towards a decrease. Aras et al. led a similar study using CT scans to measure and compare total airway volume in patients with and without CP. Although there was a decrease in the volume of cleft patients' due to the scar tissue contracture, it was not statistically significant.(21)

Several limitations are worth noting in this study. First, due to its retrospective nature, there were no instructions given to the patients during the CT scans. Therefore, there was no standardisation of verbal guidance in terms of holding their breath, swallowing or proceeding normally. Similarly, CT scans only offer a static evaluation of a dynamically functional structure. So, while airway size, shape and dimensions may be an indicator for residual VPI,(42-44) they do not substitute for a dynamic assessment of velopharyngeal closure.

Another limitation is the fact that not all scans were performed at the same time pre-and post-operatively. Due to the acute post-operative timing of the scans, the presence of edema may have introduced bias to the results. Having the scans done at standardized time frames minimizes bias and makes the obtained results more comparable.

CONCLUSION

The goal of the present study was to identify useful anatomic and morphologic changes to the velopharyngeal space following MA in patients with and without history of prior surgery for CP. Our results support the belief that although some structural modifications of the pharyngeal space are inherent to MA in patients with and without CP, the surface area and volume do not change significantly. These changes are also independent of history of previous CP repair.

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Table 1. Landmarks used for CT scan assessment

Landmarks	Description	Definition
PNS	Posterior nasal spine	The point on the retropalatal anterior pharyngeal wall, just behind the posterior nasal spine (PNS) point
UPW	Upper pharyngeal wall	The intersection point of posterior pharyngeal wall and the line from basion (B) to PNS
NPW	Narrowest pharyngeal wall	The intersection of the posterior pharyngeal wall to the narrowest space of the retropalatal region
RV	Retro Velar	The intersection of the posterior surface of the soft palate to the narrowest space of the retropalatal region

Table 2. Linear distances assessed on CT scan

Distances	Description	Definition
PNS-UPW	Narrowest part of the nasopharynx	The distance from the posterior nasal spine to the horizontal counterpoint on the posterior pharyngeal wall
RV-NPW	Narrowest part of the retropalatal airway space	The narrowest distance between the soft palate (SP) to its horizontal counterpoint on the posterior pharyngeal wall, representing the minimal airway dimension at the retropalatal region
VL	Velar length	Distance between the posterior border of the hard palate (PNS) and center of the uvula
VT	Velar thickness	Distance from the velar knee to the velar dimple
RPa AP	Anteroposterior distance at the RPa	Anteroposterior distance along the retropalatal cross-sectional area
RPa LL	Latero-lateral distance at the RPa	Latero-lateral distance along the retropalatal cross-sectional area

Table 3. Cross-sectional areas assessed on CT scan

Areas	Description	Definition
NPa	Nasopharyngeal cross-sectional area	Along the horizontal plane of PNS-UPW
RPa	Retropalatal cross-sectional area	Along the horizontal plane of RV-NPW

Table 4. Volumetric space assessed on CT scan

Volume	Description	Definition
NPV	Nasopharyngeal volume	Airway formed between the PNS-UPW and the RV-NPW planes

Table 5. Characteristics of Patients Included

	Total (n=44)	CP (n=23)	Non-CP(n=21)	p-value
Age, years$^{\psi}$	20.3	20.6	19.9	0.392
Gender$^{\phi}$				
Male, %	54.5	73.9	33.3	**0.007**
Female, %	45.5	26.1	66.6	
MMA (mm)$^{\psi}$	5.21	6.18	4.24	0.571

$^{\psi}$Independent Samples Student's T-test was performed to compare means for normally distributed variables.
$^{\phi}$Chi-squared test was used to measure associations between frequencies.
p-value < 0.05 was considered statistically significant.

Table 6. Comparison of Pre-and Post-operative scan timing

	CP n=23	Non-CP n=21	p-value
Average # of days from pre-op scan to surgery	74.4	99.5	0.533
Average # of days from surgery to post-op scan	21.7	12.5	0.808

Mann-Whitney U test was performed to compare means for not normally distributed variables.
p-value < 0.05 was considered statistically significant.

Table 7. Linear distance analysis

	Pre-op	Post-op	p-value (within group)	p-value (between group)	p-value (Interaction)
PNS-UPW (mean), mm	25.1 +/- 5.6	28.5 +/- 5.4	**0.001**	**0.045**	0.943
CP	26.6 +/- 5.3	30.0 +/- 5.6			
Non-CP	23.5 +/- 5.5	27.0 +/- 4.9			
RV-NPW (mean), mm	6.5 +/- 4.3	7.6 +/- 5.1	**0.026**	0.621	0.608
CP	6.1 +/- 5.0	7.4 +/- 6.1			
Non-CP	7.0 +/- 3.4	7.9 +/- 3.8			
Velar Length (mean), mm	32.3 +/- 7.6	33.5 +/- 9.4	0.284	0.096	0.417
CP	31.1 +/- 7.6	31.3 +/- 10.4			
Non-CP	33.8 +/- 4.1	35.8 +/- 7.6			
Velar Thickness (mean), mm	8.2 +/- 2.0	9.6 +/- 4.4	**0.031**	0.980	0.797
CP	8.1 +/- 2.0	9.7 +/- 4.3			
Non-CP	8.3 +/- 1.9	9.5 +/- 4.6			
RPa LL (mean), mm	17.2 +/- 9.5	16.4 +/- 9.3	0.320	0.058	0.817
CP	14.7 +/- 10.8	14.0 +/- 10.8			
Non-CP	20.0 +/- 6.7	19.0 +/- 6.8			
RPa AP (mean), mm	7.5 +/- 5.0	8.6 +/- 5.0	**0.013**	0.805	0.921
CP	7.4 +/- 6.6	8.4 +/- 6.5			
Non-CP	7.7 +/- 2.4	8.8 +/- 2.7			

Two-way mixed ANOVA was used in order to compare the mean differences between the groups (CP vs Non-CP) and the mean differences in the pre-and post-operative measurements (within-groups). The interaction p-value reflects whether the differences seen over time (pre-and post-op) varied depending on the groups.
p-value < 0.05 was considered statistically significant.

Table 8. Area and Volumetric Analysis

	Pre-op	Post-op	p-value (within group)	p-value (between group)	p-value (Interaction)
NPa (mean), mm²	375.2 +/- 120.6	370.4 +/- 142.6			
CP	416.9 +/- 111.4	424.8 +/- 137.4	0.751	**0.04**	0.435
Non-CP	329.5 +/- 115.8	310.8 +/- 125.9			
RPa (mean), mm²	129.8 +/- 102.1	145.7 +/- 99.9			
CP	138.0 +/- 127.0	147.3 +/- 119.5	0.410	0.723	0.525
Non-CP	120.8 +/- 67.3	143.9 +/- 75.5			
NPV (mean), cm³	4.1 +/- 2.3	4.3 +/- 2.4			
CP	3.9 +/- 2.5	4.4 +/- 2.5	0.291	0.857	0.401
Non-CP	4.2 +/- 2.0	4.3 +/- 2.3			

Two-way mixed ANOVA was used in order to compare the mean differences between the groups (CP vs Non-CP) and the mean differences in the pre-and post-operative measurements (within-groups). The interaction p-value reflects whether the differences seen over time (pre-and post-op) varied depending on the groups.
p-value < 0.05 was considered statistically significant.

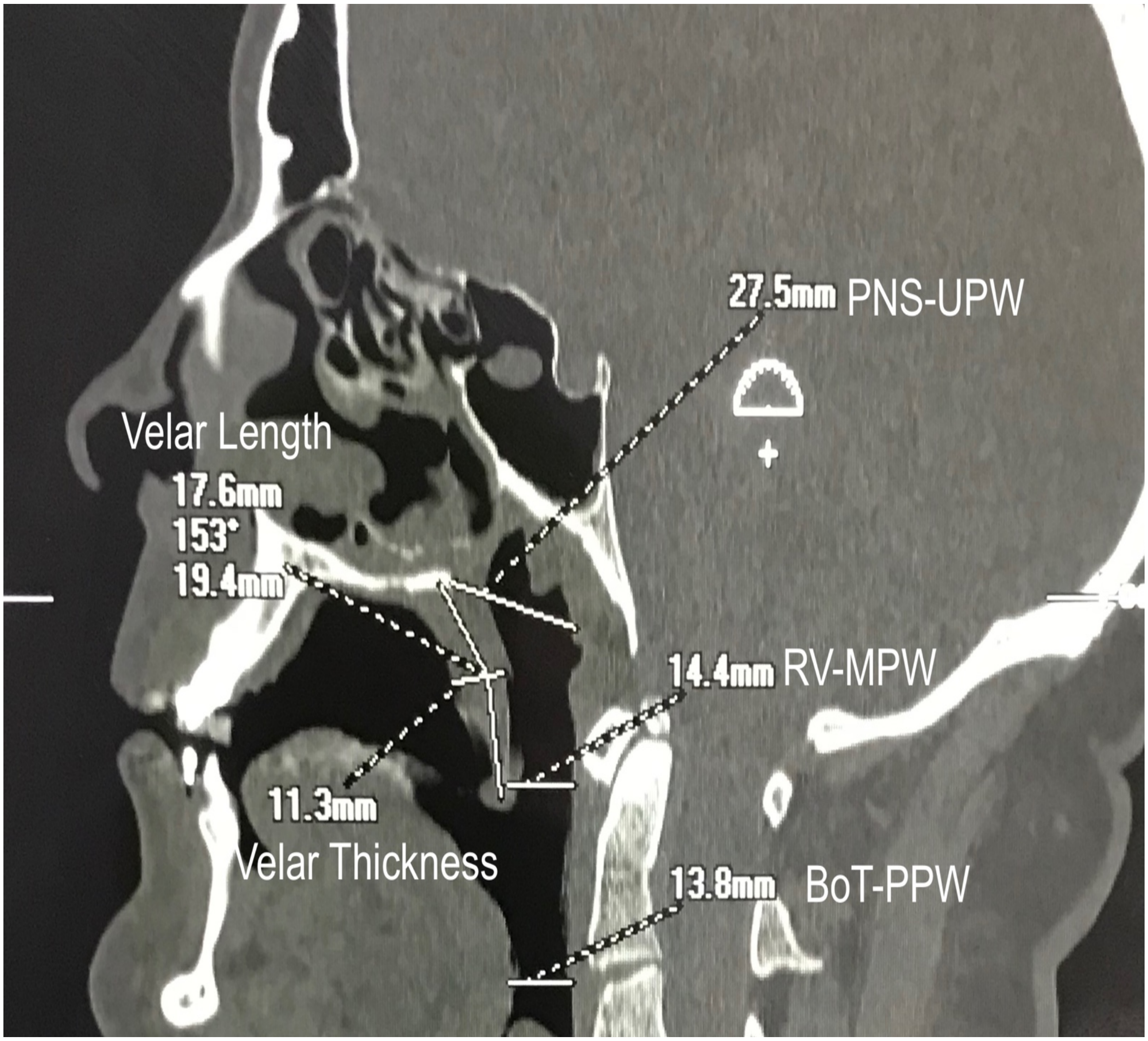

Figure 1. Linear distances assessed on sagittal reconstruction of CT scan

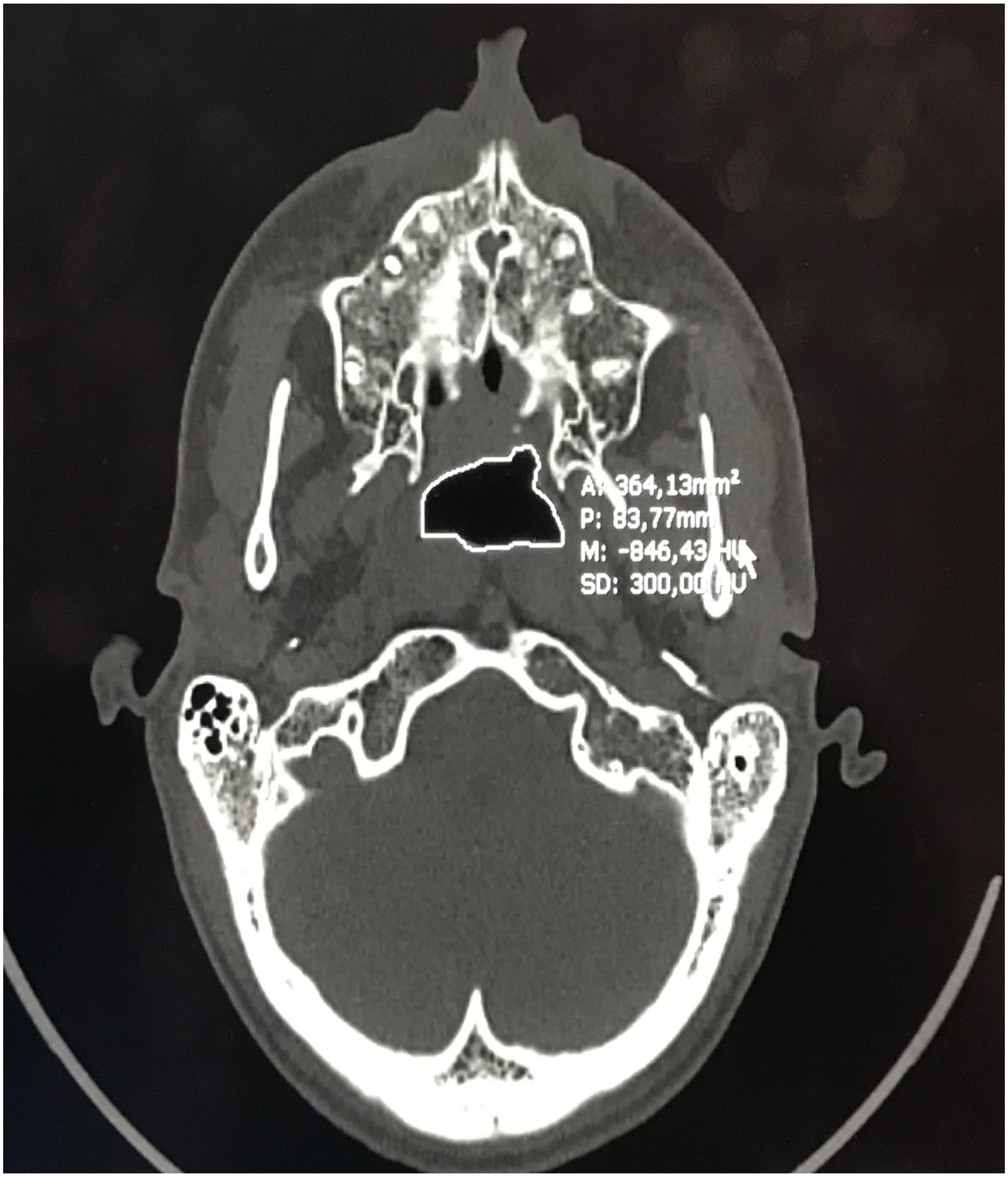

Figure 2a. Example of pre-operative nasopharyngeal CSA assessment

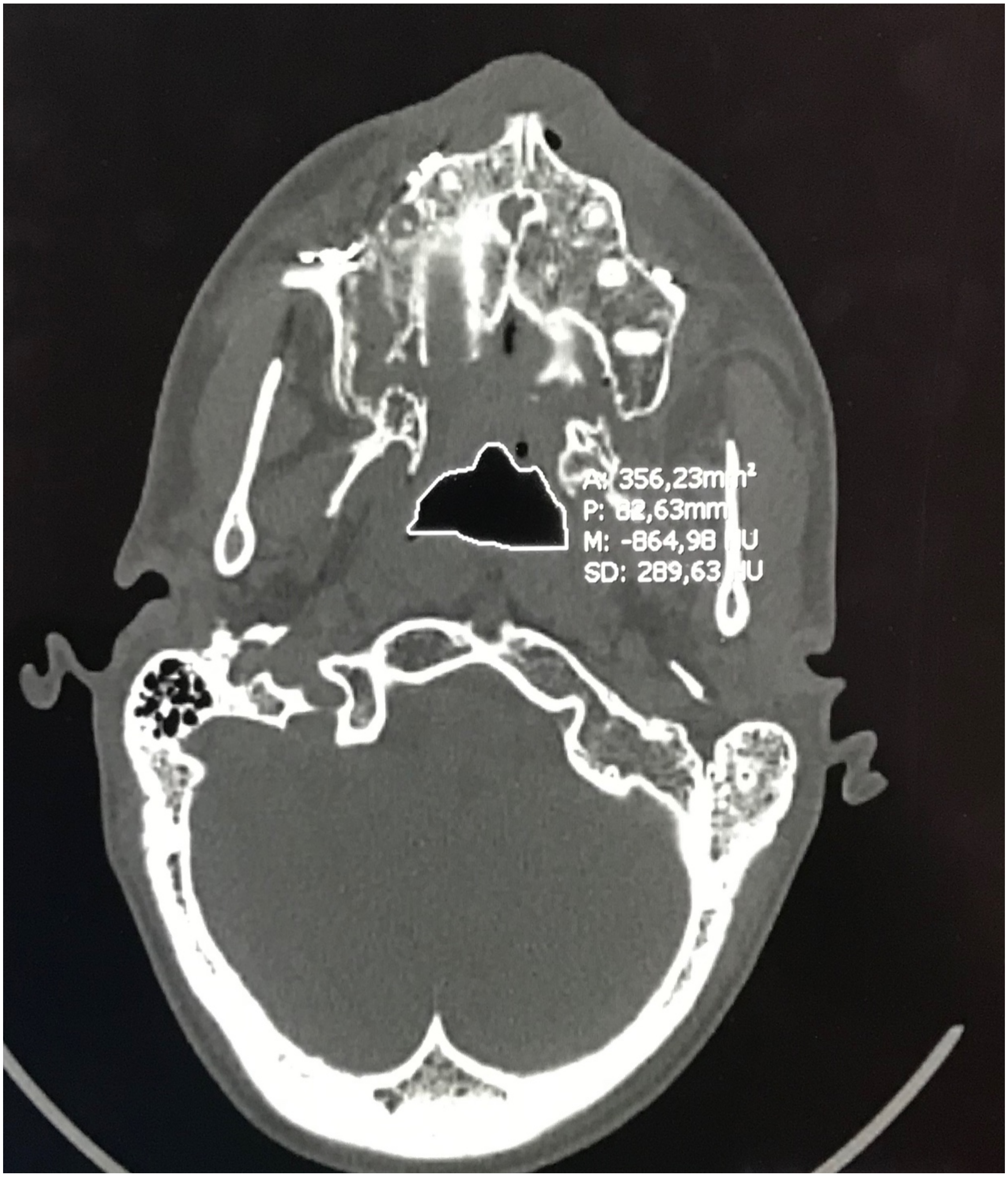

Figure 2b. Example of post-operative nasopharyngeal CSA assessment

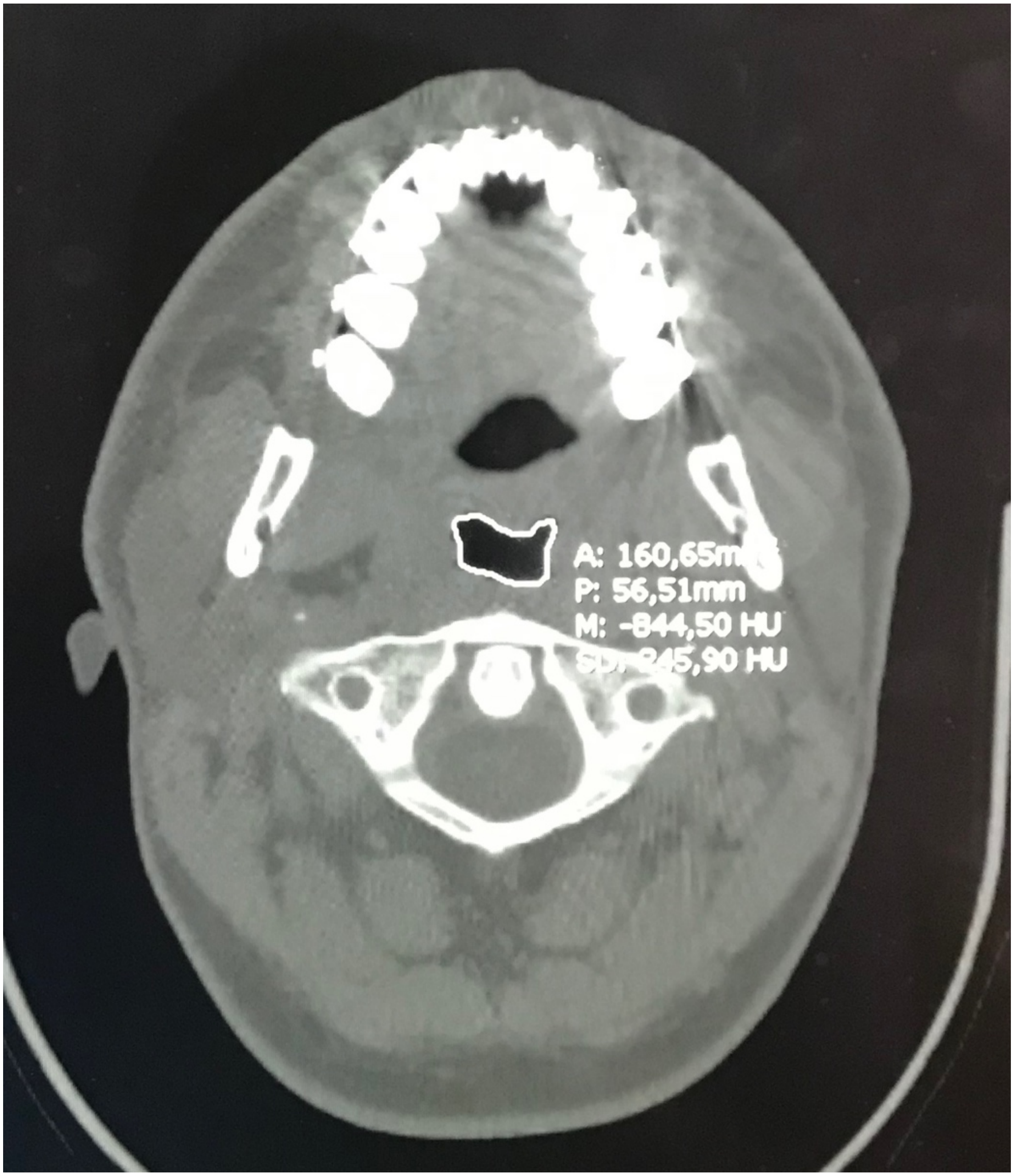

Figure 3a. Example of pre-operative retropalatal CSA assessment

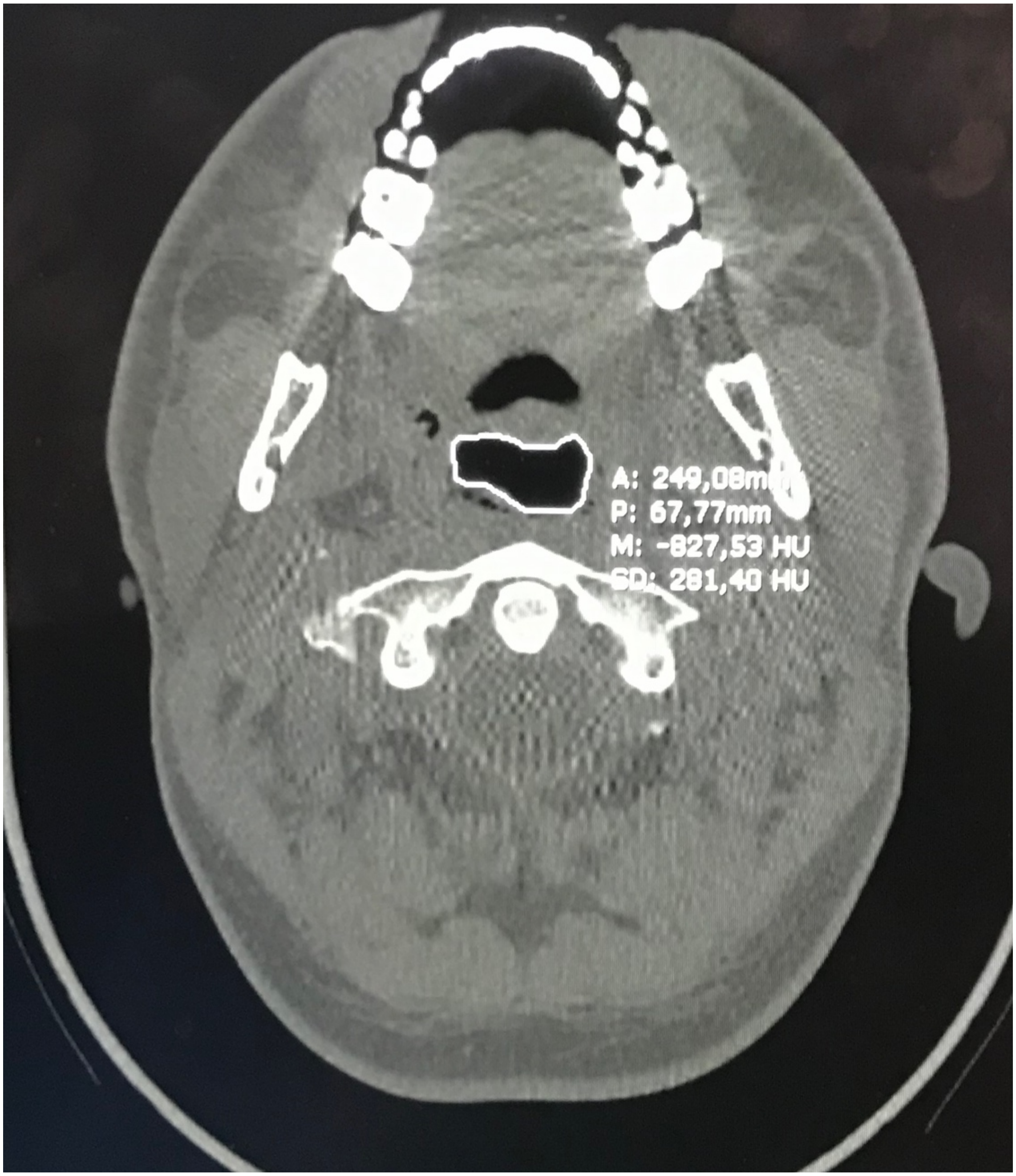

Figure 3b. Example of post-operative retropalatal CSA assessment.

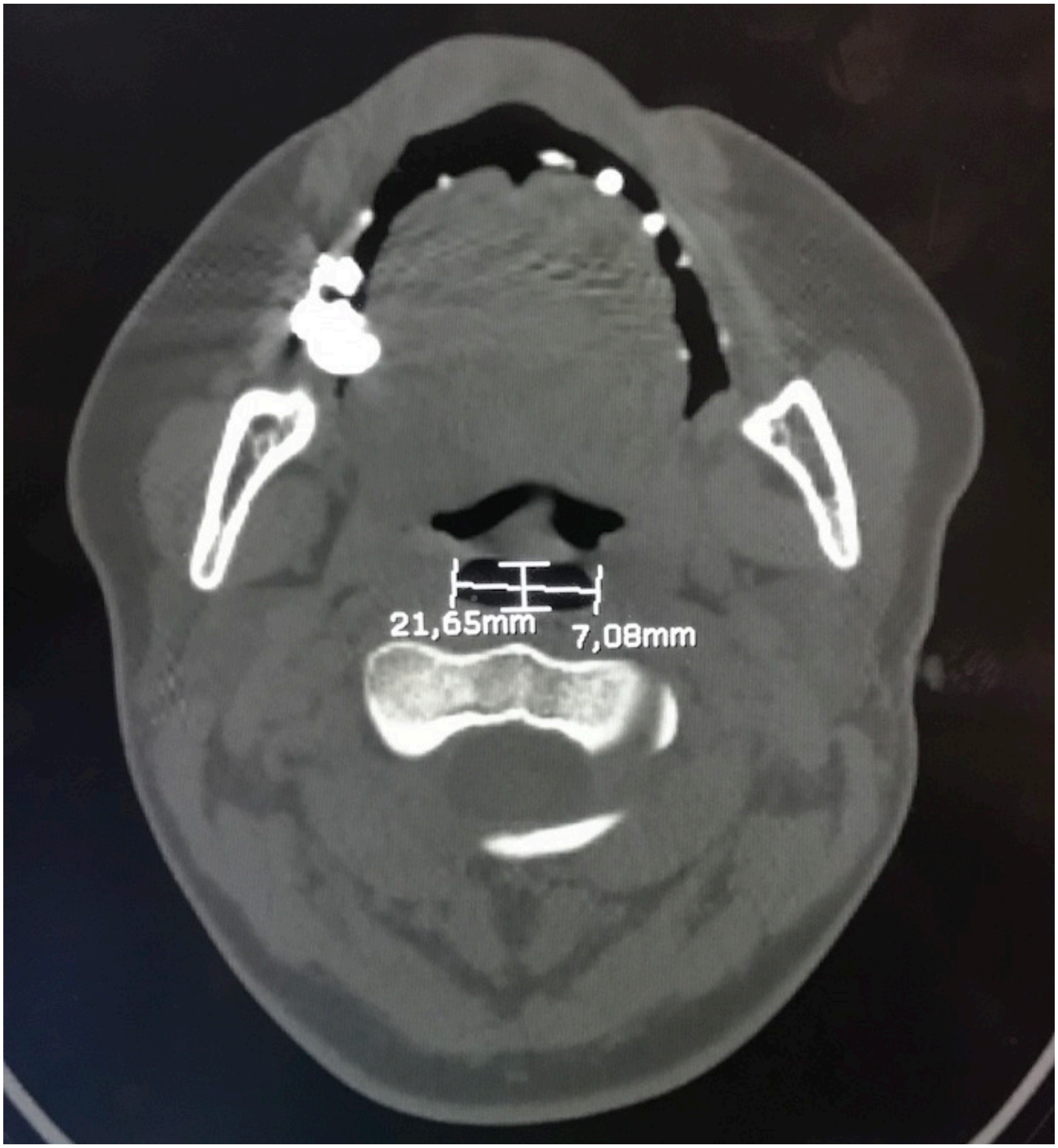

Figure 4a. Example of pre-operative AP and LL distances along the RPa.

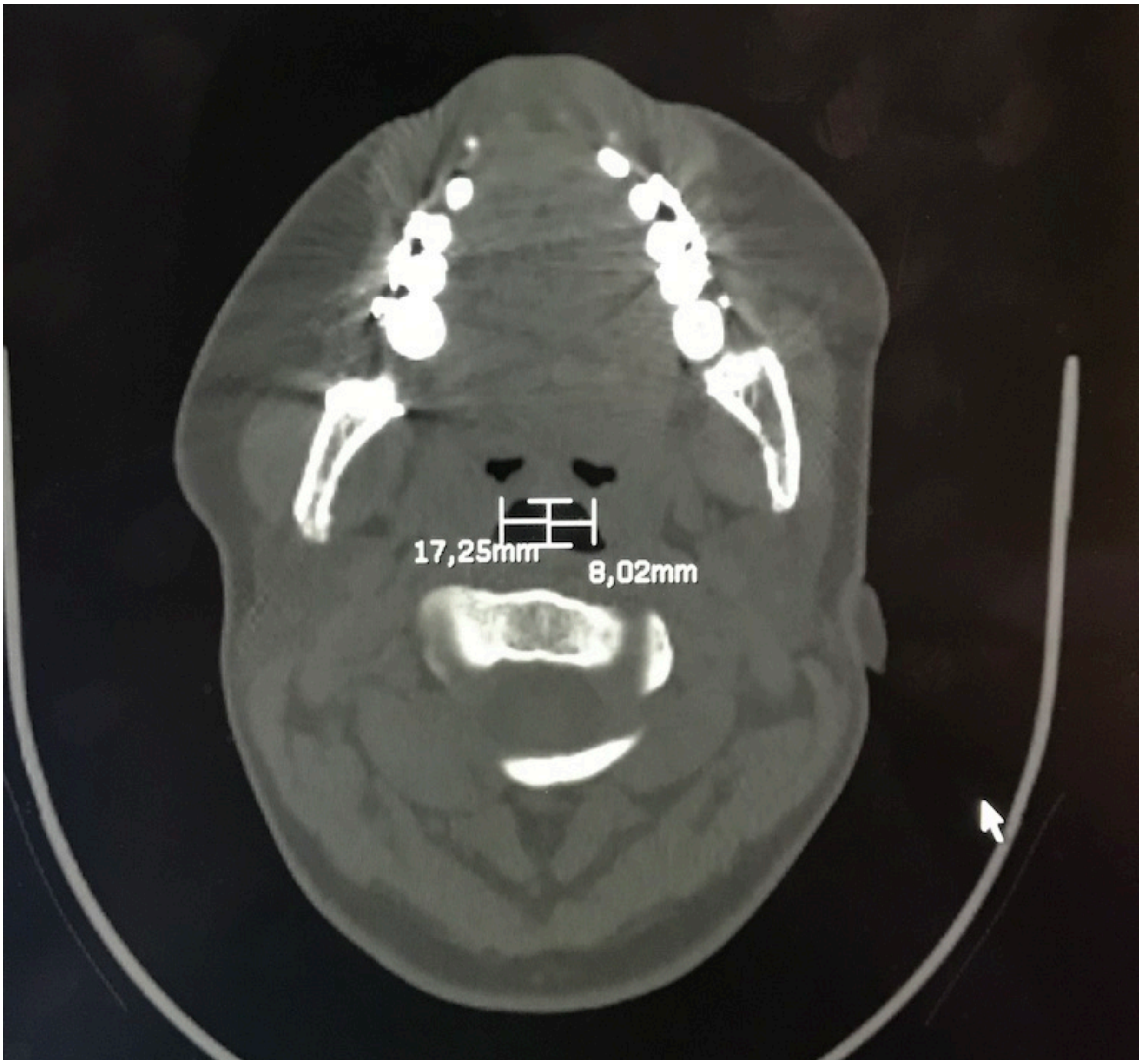

Figure 4b. Example of post-operative AP and LL distances along the RPa.

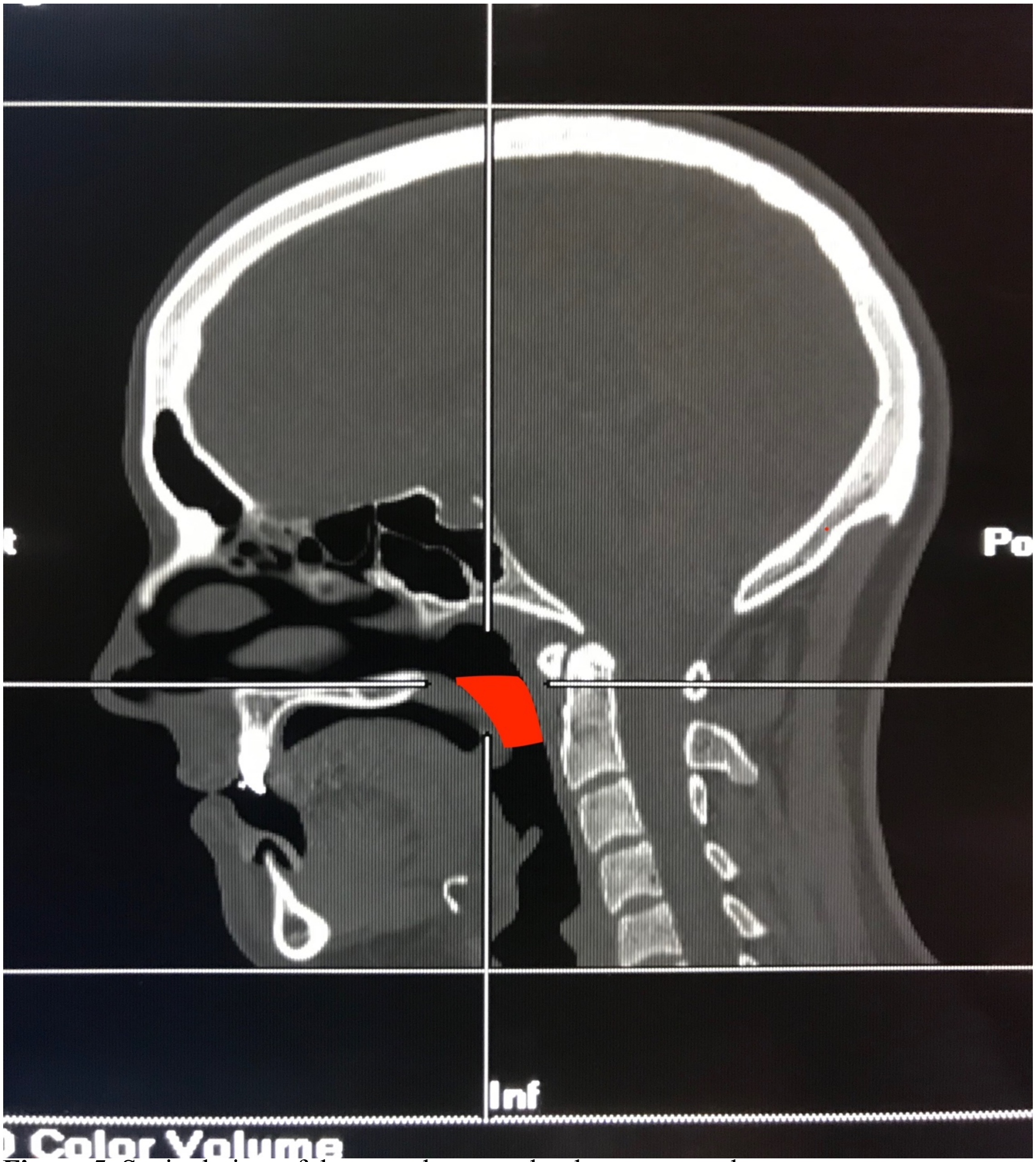

Figure 5. Sagittal view of the nasopharyngeal volume assessed.

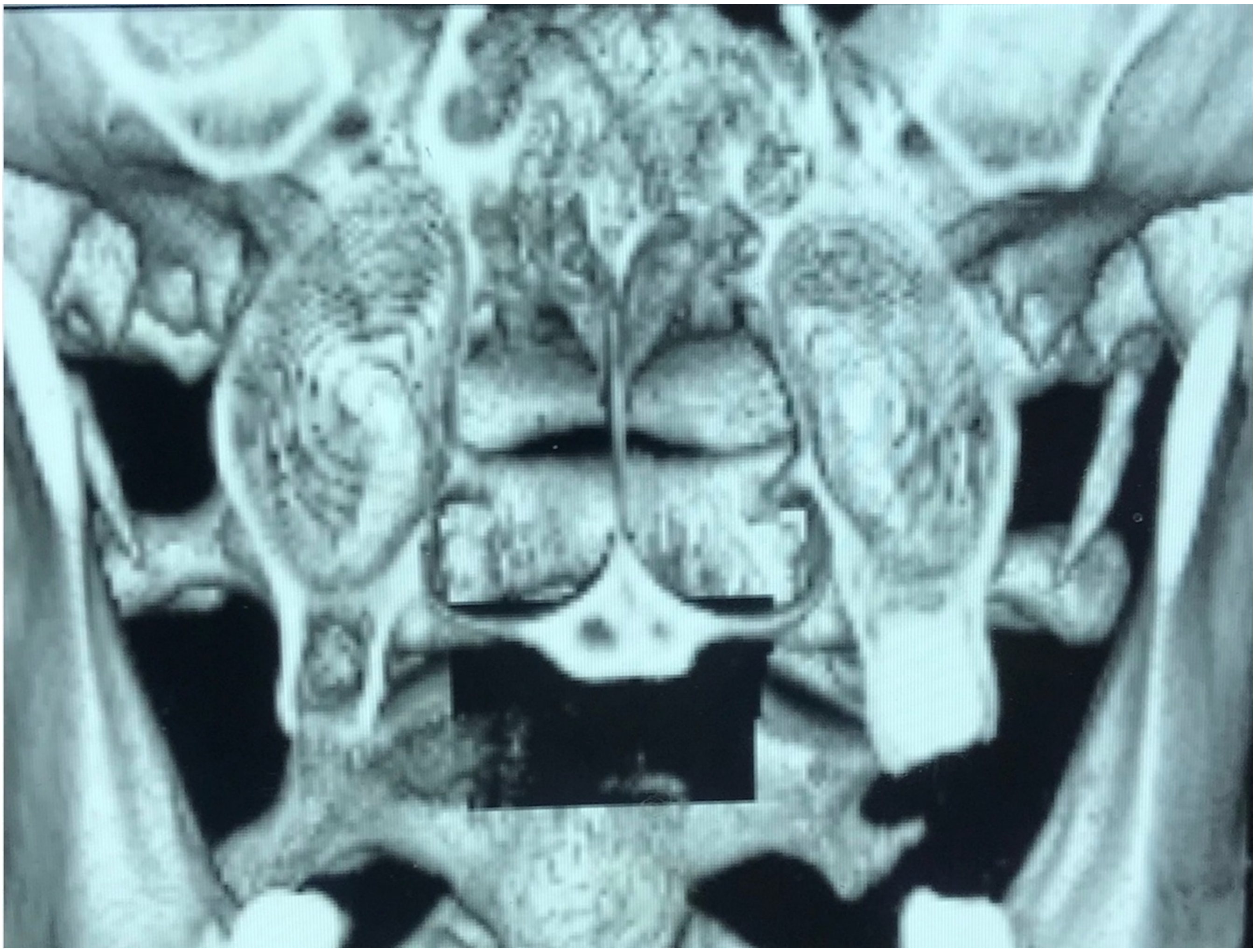

Figure 6. Coronal view of the nasopharyngeal volume assessed.

Figure 7a & 7b. Top: Pre-operative occlusion of a patient with prior history of repaired CP, Bottom: Post-operative occlusion of a patient with prior history of repaired CP

Figure 8a & 8b. Left: Pre-operative photo of a patient with prior history of repaired CP, Right: Post-operative photo of a patient with prior history of repaired CP.

3 – DISCUSSION

We sought to examine the changes in velopharyngeal anatomy after MA using 3D CT scans in patients with and without history of prior repaired CP. The primary purpose of our study was to determine whether or not significant changes to the velopharyngeal space are to be expected following MA. As a secondary outcome, we sought to determine if significant differences in airway anatomy existed between patients with and without CP. Since airway dimensions can serve as indicators for VPI, our goal was to demonstrate that development of VPI after MA should not be of particular concern in both patients with and without CP.

CLP repair are generally performed at a very young age. The standard of cleft care includes CL repair at 3 months and CP repair at 12 months. This timing is determined by weighing the benefits and consequences of early surgical interventions. With respect to patients with CP, there is an inverse relationship between the amount of maxillary restriction and the patients age at the time of surgery. The older the patient, the less maxillary restriction there will be. However, this must be balanced with the possibility of developing poor articulation habits when the surgery is performed too late.(61)

It has long been reported that patients with a repaired CP undergoing MA are more likely to develop VPI.(100) This is likely due to the combination of developmental malformations, as well as scar tissue formation following surgical interventions.(86) However, it is thought that patients without CP are not necessarily at a greater risk for VPI due to the ability of the pharyngeal walls and soft palate to compensate for the anatomical changes following MA.(101)

Several studies have attempted to understand the relationship between MA and VPI in patients with CLP. Janulewicz et al. reported that a decrease in competent VPF was observed amongst patients (42% to 18%), that the proportion of patients with borderline VPF increased (9% to 22%) and that of those with complete VPI increased (13% to 20%).(100) Speech scores also significantly dropped as hypernasality increased following a deterioration of VPF.(100) Improvement in articulation related to the anterior dentition was however observed, reflecting the positive impact of surgery on occlusion.(100) Trindade et al. using nasometry and pressure flow measures found a significant increase following surgery in nasalance scores and velopharyngeal orifice area, respectively.(82)

While some studies have demonstrated a decrease in VPF following MA in patients with CLP, others have not. Evaluating speech and using nasoendoscopic studies, Sell et al. found no statistically significant differences in the pre-and post-operative data points.(102) Similarly, Lin et al. found no statistically significant differences when comparing pre-and post-operative speech assessment data.(103) Phillips et al. looked at hypernasality and nasoendoscopy to predict VPF post-operatively. VPI was seen in only two of the 16 patients who were judged pre-operatively as having normal resonance. They concluded that patients with normal resonance as determined by perceptual assessments are at a much lower risk of post-operative hypernasality.(104) Finally, Kim et al. stated that patients with previously repaired CP and no pre-operative VPI are not at a greater risk of developing VPI after MA as compared to patients without CP.(105)

Lateral cephalometric radiographs have been the most commonly employed imaging modality in the anatomic evaluation following MA. Its simple comparison method amongst groups, its low cost, along with its simplicity and availability has favored its use.(106, 107) However, there are several limitations associated to note. These include, using a 2D representation of 3D structures, as well as the limited visualization of air and soft tissue.(90, 106, 108) In addition, cephalometric analysis cannot document lateral wall contribution to closure of the velopharyngeal space.(108) Finally, x-ray spread may cause distortion and uneven magnification of structures. Therefore, morphology analysis of patients with severe facial asymmetry is not always accurate.(91, 109)

CT offers a compelling alternative in the evaluation of anatomic changes following orthognathic surgery. It allows for the visualization of 3D distances and depths, and analysis of airway cross-sectional areas and volumes. As mentioned above, CT also provides advantages with respect to soft tissue and air visualization. Good correlation of linear airway measurements have been reported between lateral cephalograms and CT reconstructions.(110) However, the negative consequences of CT use include higher degree of radiation exposure and while it may provide soft tissue visualization, it remains a static evaluation of velar function.(106, 107, 110-112)

Surgeons at our institution routinely prescribe both pre-and post-operative CT scans for patients undergoing MA. Using these CT scans, we were able to identify classic cephalometric landmarks and evaluate linear distances, cross-sectional areas and the nasopharyngeal volume. We hypothesized that the AP distance at the level of the soft palate would increase while the LL distance would decrease. We believed these changes would not affect surface areas and volume, nor would there be a significant difference when comparing a population of patients with and without CP.

Our results supported our belief that with an advancement of the maxilla and the velum, the lateral pharyngeal walls would compensate to maintain an unchanged overall area and volume. A significant increase was found for the AP distance at the level of the soft palate when comparing the pre-and post-operative measures. Although not statistically significant, a trend towards a decrease for the LL distance was noted. While these changes in AP and LL distances were seen, the overall surface area and volumetric measures did not change significantly supporting our initial hypothesis.

Several limitations are worth noting in our study. First, due to its retrospective nature, there were no instructions given to the patients during the CT scans. Therefore, there was no standardisation of verbal guidance in terms of holding their breath, swallowing or proceeding normally. Pae et al.(113) demonstrated with cephalograms that body position affects the size of airways (increased soft palate thickness and increased AP distance of velopharyngeal space when supine). Airway size has also been shown to change depending on the breathing phase, with an enlargement of the upper airway CSA observed at the end of inspiration.(114) Therefore, body positions and breathing phase are both important elements to consider when assessing patients' airways. So, while the positioning of our included patients was controlled for, the simultaneous control of breathing was not.

The velum and pharyngeal walls are dynamic structures that create a seal between the nasal and oral cavities during oral speech production. As mentioned earlier, assessment of the dynamic VPF can be performed with use of multiple modalities. These include but are not limited to PSA, nasoendoscopy, nasometry and videofluoroscopy. In our study, CT scans were used to assess the structural changes to the velopharyngeal space following MA. While CT scans offer certain advantages, they only allow for a static evaluation of a dynamically functional structure. So, while airway size, shape and dimensions may be an indicator for residual VPI,(115-117) they do not substitute for a dynamic assessment of velopharyngeal closure.

The retrospective nature of our study did not allow us to control for several confounding variables. The timing of the pre-and post-operative scans were not uniform. While the timing of the pre-operative scans was less likely to introduce bias due to the nature of the study, the same cannot be said for the post-operative scans. Due to their acute timing in the post-operative period (generally at day 3), the presence of edema may have introduced bias to the results. In addition, having the scans performed at a later time would have allowed us to better assess for the physiologic compensation of the airway following MA. So, having the scans done at standardized time frames would have minimized bias and made the obtained results more reliable.

4 – CONCLUSION

The goal of the present study was to identify useful anatomic and morphologic changes to the velopharyngeal space following MA in patients with and without history of prior surgery for CP. Our results support the belief that although some structural modifications of the pharyngeal space are inherent to MA in patients with and without CP, the surface area and volume do not change significantly. These changes are also independent of history of previous CP repair. We believe the use of 3D reconstruction using CT scans should be the first choice for evaluation of the upper airway. Not only does it provide the surgeon with an understanding of the underlying anatomical structures during pre-operative planning, it also allows for assessment of structural changes following surgery. These changes serve as key indicators for functional outcomes. Future studies should correlate these anatomic results to dynamic velopharyngeal function assessments and development of VPI.

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