COMPUTATIONAL AIRFLOW ANALYSIS PRE- & POST-MAXILLOMANDIBULAR ADVANCEMENT SURGERY IN OBSTRUCTIVE SLEEP APNEA PATIENTS

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An Abstract Presented to the Graduate Faculty of Saint Louis University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Dentistry 2013
Abstract

Purpose: To analyze pharyngeal airflow using computational fluid dynamics (CFD) in obstructive sleep apnea (OSA) patients pre- and post-maxillomandibular advancement (MMA).

Materials and Methods: Digitized pharyngeal airway models of 19 obstructive sleep apnea patients were generated from cone beam computed tomography scans pre- and an average of 18.3 ± 17.3 days post-surgery. CFD was used to simulate and characterize pharyngeal airflow, which was assumed to be turbulent at an inspiration rate of 340 ml/sec. Standard steady-state numerical formulation were used for airflow simulations. Results: Mean pressure drop during inspiration was significantly reduced from 34.82 ± 65.65 Pa pre-surgery to 3.06 ± 3.96 Pa post-surgery. Mean maximum airflow velocity along the airway was also significantly reduced from 11.14 ± 8.49 m/s pre-surgery to 4.09 ± 3.07 m/s post-surgery. There was a significant increase in mean airway volume of 66.8% post-surgery. There was a 75% mean reduction in airway resistance following surgery. There was a decrease in the pressure gradient and total pressure drop following surgery for all 19 patients. There was a statistically significant, moderate, negative correlation between the change in airway resistance and the change in airway volume post-surgery. No correlation was found.
between skeletal advancement and airway volume or airway resistance. **Conclusions:** A decrease in relative pressure implies less effort required for maintaining constant pharyngeal airflow according to CFD analyses on airways of OSA patients following MMA surgery.
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DEDICATION

I dedicate this thesis to my family, friends, colleagues, and teachers who have supported my efforts for the last six and a half years of my dental education.

To my wife Lisa, you have been undoubtedly the most patient and supportive person in both my personal and educational life. Without your love, support, patience, understanding, motivation, and persistence, I would not be the person I am today. Thank you for waiting for your turn.

To my daughter Lucy, you bring me such great joy and happiness with your smile and love. My journey through life is enriched each day with the lessons you teach me as a father.

To my parents, Kathy and Jerry, thank you for supporting my education and for your continued encouragement in the pursuit of my orthodontic career.
ACKNOWLEDGEMENTS

The successful completion of my thesis would not have been possible without help from the following people:

Dr. Ki Beom Kim for serving as chairman of my thesis committee and for his continued input and knowledge that has encouraged me to improve my educational experience.

Dr. Mark McQuilling for spending numerous hours helping me to learn and understand computerized airflow simulation and its implications on the study of obstructive sleep apnea and its role in orthodontics.

Dr. Donald Oliver for his tireless efforts in his guidance to improve the quality of this thesis.

Dr. Michael Schauseil for his help with generating 3D computer models and images and his insightful input into this study.

Dr. G. William Arnett and Dr. Michael Gunson for providing the surgery sample for this study.

Dr. Heidi Israel for her statistical guidance and efforts.

Mr. Dan Kilfoy for his unending patience with installing and providing computer software that has made this thesis possible.
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CHAPTER 1: INTRODUCTION

The clinical recognition of obstructive sleep apnea (OSA) is commonly found by first line providers of dental care, including orthodontists. Common signs and symptoms of obstructive sleep apnea include daytime sleepiness, snoring, hypertension, and type-2 diabetes. Clinical findings include obesity, a thick neck, excessive fat deposition in the palate, enlarged tongue and pharynx, a long soft palate, a retrognathic mandible, and calcified carotid artery atheromas on panoramic and lateral cephalometric radiographs. Many of these findings may be recognizable by dental practitioners. Untreated OSA can have life threatening consequences in severe cases. Generally, patients that undergo treatment for obstructive sleep apnea begin with first phase non-surgical treatment, such as behavioral modification involving weight loss, smoking cessation, or continuous positive airway pressure (CPAP). Additionally, oral appliance therapy can be rendered by a dentist or orthodontist with the hopes of relieving airway obstruction.

In severe cases of OSA, surgical intervention may be necessary and prudent. Orthodontists are presented with dental and skeletal abnormalities that may require orthodontics and surgical intervention to treat the
skeletal and dental imbalances to an ideal result. While numerous surgical treatments are available for OSA, the definitive surgical treatment of choice for severe OSA is maxillomandibular advancement (MMA). The advancement of the maxilla and mandible provides anterior repositioning of the surrounding soft-tissues and pharyngeal airway, thus alleviating pharyngeal airway stenosis and airflow resistance. By increasing the size and volume of the pharyngeal airway, many of the symptoms of obstructive sleep apnea are improved or eliminated.

The study of pharyngeal airway size after MMA has primarily been completed using 2-dimensional radiographs, such as the lateral cephalogram. The drawback with this type of study is the use of 2-dimensional assessment of a 3-dimensional object. Modern advancements in 3-dimensional imaging techniques, such as cone beam computed tomography (CBCT) and magnetic resonance imaging (MRI), have improved the accuracy in the evaluation of 3-dimensional structures. Newer imaging studies using CBCT and MRI have shown an increase in airway volume following MMA surgery.

Study of the pharyngeal airway itself without using invasive techniques has been somewhat limited in the past. With newer imaging techniques available and computer software to simulate airflow, less invasive evaluations can
now be undertaken. 3-dimensional images are now being used along with airflow evaluation techniques such as anemometry, particle imaging velocimetry, and computational fluid dynamics to study pharyngeal airflow.

Limited information exists regarding the quality of airflow improvement following MMA. Many studies demonstrate the improvement in airway volume in the treatment of OSA; however, few studies describe the improvement in airflow characteristics of the pharyngeal airway.

Evaluation of the effectiveness of MMA in the treatment of obstructive sleep apnea will be made possible by studying the differences in pharyngeal airflow in a non-invasive manner through computational fluid dynamics. Also, predicting the surgical skeletal change needed to open the airway during sleep in patients with obstructive sleep apnea could be made possible with further study.
CHAPTER 2: REVIEW OF THE LITERATURE

Pharyngeal Airway Anatomy

The upper airway is a complex structure composed of soft tissue and more than 24 muscles that work in a dynamic biomechanical relationship to perform many different physiologic functions including respiration, deglutition, and vocalization. The upper airway is divided into three sub-regions based on sagittal imaging nomenclature (Figure 2.1): (1) the nasopharynx – a region between the hard palate and nasal turbinates; (2) the oropharynx – a region that is subdivided: retropalatal – the level of the hard palate to the caudal margin of the soft palate; retroglossal – the caudal margin of the soft palate to the epiglottis base; and (3) the hypopharynx – a region from the base of the tongue to the cervical esophagus.

The pharyngeal airway lies posterior to the nasal cavity, oral cavity, and larynx and begins its inferior descent posterior to the nasal turbinates towards the esophagus. The upper airway is bounded superiorly by the basilar portion of the occipital bone and body of the sphenoid; anteriorly by the nasal turbinates, soft palate, tongue, and epiglottis; posteriorly by the superior, middle and inferior pharyngeal constrictor muscles; and laterally
by soft tissue and several muscles, the palatine tonsils, and the pharyngeal fat pads.¹

![Figure 2.1 - Pharyngeal Airway Anatomy - adapted from Burgess²](image)

**Tidal Volume During Sleep**

The tidal volume is the amount of air moved into or out of a resting patient’s lungs with each normal breath. The tidal volume is calculated by dividing the minute volume by the respiratory rate. Normal tidal volume can be
estimated by multiplying the normal body weight by 5-7 ml/kg. The average range of tidal volume in adults is 400-600 ml per inspiration.\(^3\) During non-rapid eye movement sleep, human minute ventilation decreases by about 6% to 15\(^4\)-\(^6\).

**Obstructive Sleep Apnea**

Obstructive sleep apnea (OSA) is characterized by the periodic partial or complete collapse of the upper airway during rapid eye movement (REM) and non-REM sleep that results in episodes of hypopnea (diminished airflow of at least 30% lasting at least 10 seconds) or apnea (absent airflow).\(^7,8,9\) The collapse of soft tissues in the upper airway, and in particular, in the retropalatal and retroglossal regions of the oropharynx, plays a key role in the etiology of OSA.\(^1\) While sites of airway obstruction vary from patient to patient, obstructions typically occur at multiple levels in the airway.\(^10\)

Epidemiologic estimates of OSA prevalence is about 4% for men and 2% for women in the age group 30-60 years for those living in the United States when considering subjective day-time sleepiness.\(^11\) According to the Wisconsin Sleep Cohort Study, OSA prevalence is 24% for men and 9% for women when using only AHI>5 as an objective measure.\(^12\)
OSA prevalence also increases with age and obesity.\textsuperscript{11} Risk factors for OSA include smoking,\textsuperscript{11} obesity and or those with a high body mass index (BMI>25),\textsuperscript{13} snoring, increased neck circumference (collar size greater than 16 inches for women and 17 inches for men),\textsuperscript{14} a modified Mallampati grade III or IV (used to predict ease on intubation)\textsuperscript{15} and factors that decrease respiratory muscle tone, such as excessive alcohol intake,\textsuperscript{13} respiratory depressing drugs,\textsuperscript{15} or neurological disorders.\textsuperscript{15}

Increased airway resistance can be caused by either anatomic and or physiologic factors. While obesity is the main predisposing factor for OSA,\textsuperscript{16} non-obese patients with craniofacial dysplasias, such as micrognathia and retrognathia, are also at a greater risk for OSA.\textsuperscript{17,18}

Additional predisposing orofacial characteristics include hypertrophic palatine tonsils, enlarged uvula, high-arched palate, nasal septal deviation, long anterior facial height, steeper and shorter anterior cranial base, inferiorly displaced hyoid bone, large and or retropositioned tongue, a long soft palate, large parapharyngeal fat pads, and decreased posterior airway space.\textsuperscript{8,15} Physiologic factors are those that functionally reduce dilation of airway muscles, such as the decreased response by the tongue or soft palate in response to
negative airway pressure and increased pharyngeal collapsing forces and pharyngeal compliance.\textsuperscript{15,19} The balance of constricting forces from the negative inspiratory intraluminal suction generated by the diaphragm and dilating forces of the pharyngeal musculature is dysfunctional in obstructive sleep apnea\textsuperscript{20}

Patient sleep positioning also plays a role in the collapsing of the airway.\textsuperscript{15} The supine position is the most susceptible position to airway collapse due to the posterior positioning of the tongue and or soft palate against the posterior pharyngeal wall or the medial collapse of the lateral soft tissue walls of the pharynx.\textsuperscript{19,21} With air flow consequently reduced, the patient must increase the speed of the airflow to maintain the required oxygen supply to the lungs. This increase in airflow velocity causes vibration of soft tissues, which produces snoring.\textsuperscript{8} Mouth opening may also exacerbate upper airway resistance due to the increased collapsibility and or decreased efficacy of dilator muscles.\textsuperscript{8}

The gold standard in the diagnosis of OSA is nocturnal attended polysomnography, which aims to measure the number of apneas and hypopneas during sleep along with monitoring brain activity, eye movement, muscle activity, cardiac rhythm, and pulse oximetry.\textsuperscript{22} The apnea-hypopnea index (AHI)
is the average number of apneas and hypopneas per hour of sleep. The AHI index is used to classify the severity of OSA on the basis of 3 categories: (1) – Mild OSA (5–15 events/hour of sleep; (2) – Moderate OSA (15–30 events/hour of sleep; and (3) – Severe OSA (more than 30 events/hour of sleep). Another index used is the respiratory disturbance index (RDI), which in addition to hypopneas and apneas, includes respiratory effort-related arousals (RERAs). A RERA event is described as an increase in respiratory effort for 10 or more seconds leading to an arousal from sleep, but not meeting the criteria for a hypopneic or apneic event.

Recurrent airway obstruction can have life-threatening consequences due to the reduced amount of air, and therefore oxygen, reaching the lungs. This leads to a reduction in blood oxygen saturation and an increase in carbon dioxide accumulation. The potential negative effects of OSA when left untreated, include disturbances in normal sleep patterns, dry mouth, excessive daytime sleepiness, cognitive impairment, morning headaches, absence of dreams, fatigue, decreased libido, depression, pulmonary and systemic hypertension, polycythemia, stroke, cardiac arrhythmias, and myocardial infarction. Thus, the study of OSA and the characteristics of pharyngeal airflow
are both important for proper diagnosis and appropriate treatment that could potentially be life-saving.

**Treatment for OSA**

Non-surgical and surgical therapies can be used in the treatment of OSA. Non-surgical therapies include diet and lifestyle modification, pharmacologic agents, nasal positive airway devices, and oral appliances. Surgical options for the treatment of OSA include nasal reconstruction, uvulopalatopharyngoplasty (UPPP), uvulopalatopharyngoglossoplasty, uvulopalatal flap, radiofrequency ablation to the base of the tongue, mandibular osteotomy with genioglossus advancement, hyoid myotomy and suspension, tracheotomy, tonsillectomy and adenoidectomy, distraction osteogenesis, and maxillomandibular advancement osteotomy.

**Non-surgical Treatment**

**Diet and Lifestyle modification**

Obese patients should be encouraged to lose weight, however the amount of weight loss needed to improve sleep-disordered breathing and daytime sleepiness is unclear. It is clear however, that weight-loss should be mandatory in OSA treatment as an increase in BMI by one standard
deviation is associated with a 4x increased risk of having an AHI greater than 5 per hour.\textsuperscript{23} Weight reduction after bariatric surgery (non-airway target) in patients with moderate to severe OSA had reduced AHI scores, but moderate sleep apnea persisted.\textsuperscript{25}

Lifestyle factors, such as smoking and alcohol consumption, have been shown to increase airway resistance. Smoking has been shown to produce upper airway edema that results in upper airway resistance. Thus, OSA patients should avoid smoking tobacco.\textsuperscript{23} Alcohol is a respiratory depressant that may exacerbate pre-existing OSA, and thus should be avoided at least four hours prior to sleep.\textsuperscript{23}

Stabilizing the upper airway through body positioning during sleep may help to reduce the AHI by up to eight events per hour.\textsuperscript{26} The preferred sleep position is a lateral recumbent posture or a 30° or 60° head-elevated position with avoidance of the supine position.\textsuperscript{23}

**Pharmacologic Agents**

Some pharmacologic treatment has been aimed at improving the quality of sleep by targeting underlying medical conditions that may contribute to OSA. Currently, there are no widely effective pharmacotherapies for individuals with OSA, except in cases of individuals with
hypothyroidism or with acromegaly. Typically, treating the underlying medical condition can have pronounced effects on the AHI. It has been demonstrated that stimulant therapy with caffeine leads to a small improvements in objective daytime sleepiness, but overall improvement is limited.\textsuperscript{26}

**Positive Airway Pressure Devices**

Positive airway pressure devices, such as continuous positive airway pressure (CPAP), automatic positive airway pressure (APAP), and bi-level positive airway pressure (BPAP) devices, can be all be used in the treatment of OSA. CPAP was first introduced in 1981 as a treatment modality for OSA and is the most commonly used non-surgical therapy.\textsuperscript{27} CPAP is considered to be the most effective method in managing OSA and is considered the gold standard of treatment.\textsuperscript{15} CPAP acts in a non-invasive manner by continuously pumping room air under pressure through a sealed nose or face mask into the upper airway and lungs.\textsuperscript{8} CPAP works to act as a pneumatic splint that elevates and maintains a constant pressure along the upper airway during inspiration and expiration.\textsuperscript{15} Kuna et al. and Schwab et al. found that upper pharyngeal airway dimensions improved more in the lateral aspect than in the anterior-posterior dimension.\textsuperscript{28, 29}
Along with increases in airway area and volume, improvements in subjective and objective measures of sleepiness have been documented as a result of CPAP therapy. Other significant improvements include: snoring, dry mouth, morning headaches, daytime function, perceived health status, and quality of life.\textsuperscript{15} A lack of CPAP therapy compliance, however, can diminish the improvements shown with long-term treatment. Reasons for poor compliance are categorized based on tolerance problems, psychological problems, and lack of instruction.\textsuperscript{30} Patient reports of tolerance problems include mask discomfort, congestion, nasal dryness, chest pain, dry mouth, conjunctivitis, rhinorrhea, pressure sores, epistaxis, skin rash, mask leaks, difficulty exhaling, aerophagia, and bed partner intolerance.\textsuperscript{15} Psychological problems include claustrophobia, lack of motivation, and anxiety.\textsuperscript{15}

Compliance with CPAP therapy is highly dependent on the definition of compliance and the variability that exists within study design. Some research suggests compliance ranges from 50 to 89\% for nasal CPAP.\textsuperscript{31,32,33} When patient compliance is defined as greater than 4 hours of nightly use, 46 to 83\% of patients with OSA have been reported to be non-adherent to treatment.\textsuperscript{34} Mounting evidence indicates that CPAP use for greater than 6 hours
reduces sleepiness, improves daily functioning, and re-establishes memory to normal levels. The effectiveness of CPAP therapy is well-established when compliance is good. Unfortunately, many patients are unable to tolerate CPAP for an indefinite amount of time, which typically leads them to try other modalities of non-surgical OSA treatment.

**Oral Appliances**

Oral appliances are most commonly used for patients with mild to moderate OSA. They can also be used for patients who are intolerant of CPAP therapy or those who refuse surgery. The goal of oral appliance therapy is to increase the posterior oropharyngeal airway space with the intent to reduce collapsibility of the upper airway during sleep.

Two classifications exist for oral appliances: tongue-retaining or mandibular-repositioning. Tongue-retaining oral appliances help to posture the tongue in an anterior direction through negative pressure. Patients who have few or no teeth, macroglossia, or cannot adequately posture their mandible forward are most indicated for tongue-retaining devices. Mandibular-repositioning devices help to posture the mandible and associated structures, such as the tongue and hyoid bone, in an anterior direction, thus
increasing both the anterior-posterior and lateral dimensions of the upper airway.\textsuperscript{15, 36, 37} While these devices are effective with success rates at 54\% defined as reducing AHI to less than 10 and a resolution of symptoms, they are not without negative side-effects.\textsuperscript{38}

Reports of excess salivation, temporomandibular joint pain, dental pain, facial muscle pain, dry mouth, and occlusal change were of a minor and temporary nature.\textsuperscript{7} The most common dental side effects from oral devices includes proclination of the mandibular incisors, retroclination of the maxillary incisors, mesial movement of the mandibular molars, and a decrease in the SNB angle after long term usage.\textsuperscript{39}

\textbf{Surgical Treatment}

The goal of surgical treatment for OSA is to target site specific areas that are the cause for upper airway obstruction. Appropriate surgery should increase the upper airway size resulting in a decrease in airway resistance, thereby reducing the pressure effort to breath.\textsuperscript{15} In general, surgery is most indicated when more conservative therapeutic approaches are unsuccessful or not tolerated well. Patients that have well-identified underlying skeletal abnormalities in cases of moderate to severe OSA
are also indicated for surgery.\textsuperscript{40} Surgical prerequisites include an apnea-hypopnea index greater than 15 (AHI), or apnea index greater than 5 (AI),\textsuperscript{40} a respiratory disturbance index (RDI) greater than 15-20,\textsuperscript{15} lowest oxyhemoglobin desaturation less than 90\%, and excessive daytime sleepiness. Patients must be psychologically and medically stable and readily willing to accept surgery.\textsuperscript{40}

Upper airway surgical procedures for the treatment of OSA fall into three categories: (1) classic procedures that directly enlarge the upper airway; (2) specialized procedures that increase the upper airway by changing the soft tissues elements and or skeletal anatomy and a last resort option, (3) a tracheotomy that bypasses that pharyngeal portion of the upper airway.\textsuperscript{8}

Two staging categories exist for the surgical treatment of OSA. Stage I surgery is considered to be more conservative and site-specific with each surgery targeting a specific area and sometimes occurring as a multi-level approach such as: the nose, the oropharynx (the retropalatal and retroglossal airway) and the hypopharynx.

Stage I surgery includes nasal surgery, uvulopalatopharyngoplasty (UPPP), and base of tongue surgery (which includes genioglossal advancement, modified genioplasty, radiofrequency ablation, and hyoid myotomy).\textsuperscript{15}
Stage I therapy is usually conducted in a stepwise manner according to a methodical protocol where less invasive surgical procedures are first attempted and progressively treat with more surgery based on clinical symptoms.\textsuperscript{40} This may result in unnecessary and additional surgery, which may be painful, dysfunctional, expensive, and ultimately a deterrent for patients to look for definitive surgical treatment.\textsuperscript{40}

Stage II surgery includes maxillomandibular advancement (MMA). MMA is an invasive procedure that surgically moves the maxilla and mandible anteriorly, along with their muscular attachments, to increase the airway space of the nasopharynx, oropharynx, and hypopharynx.\textsuperscript{15}

**Nasal Surgery**

Surgical therapy for the treatment of OSA sometimes begins with nasal airway surgery, such as septoplasty or turbinectomy. While nasal surgery alone typically does not improve or correct OSA, it should be included in the treatment plan because it has been shown to reduce mouth breathing which leads to subjective improvement of sleep quality and increase patient compliance with CPAP.\textsuperscript{15}
Adenotonsillectomy/Tonsillotomy

Hypertrophic adenotonsilar tissue in the presence of a narrow airway and a decreased muscular tone of the oropharyngeal complex is the most common reason for OSA in children. Adenotonsillectomy is considered first-line therapy for OSA in children with the goal in maximizing the upper airway size and preventing soft palate and lateral pharyngeal wall collapse. Adenotonsillectomy, as a treatment for OSA, has been shown to result in curative rates greater than 90% for children. Because excessive bleeding is a common complication associated with adenotonsillectomy, a laser-assisted tonsillotomy can be undertaken that leads to similar curative rates as adenotonsillectomy, but with significantly less pain and bleeding. When adenotonsillectomy is unsuccessful for OSA treatment in children, they remain at risk for worsening OSA into adulthood.

Uvulopalatopharyngoplasty & Laser-assisted

Uvulopalatoplasty

Uvulopalatopharyngoplasty (UPPP) is a procedure undertaken to reduce the degree of pharyngeal obstruction that occurs during an apneic event by surgically removing the uvula and surrounding redundant mucosal tissue.
including the posterior pillar and posterior pharyngeal wall, while preserving the muscular layer.\textsuperscript{43} Based on the criteria for post-operative cure, the success rate for UPPP was 44\% according to Braga et al., which also concurs with the findings of 40-50\%, found by Won et al at 12 months post-surgery.\textsuperscript{41, 44} While UPPP can be curative in some patients, and in particular younger ones, a combination of treatment modalities must be considered.\textsuperscript{44} A similar procedure, the uvulopalatal flap, is preferred over UPPP in most cases because it reduces the risk of nasopharyngeal incompetence due to it being a potentially reversible procedure.\textsuperscript{41} Laser-assisted uvulopalatoplasty (LAUP) is an less-invasive alternative to UPPP that can be performed under local anesthesia in an out-patient setting with similar success rates as UPPP and should be considered during treatment planning.\textsuperscript{45}

**Base of Tongue Surgery**

**Genioglossal Advancement and Genioplasty**

A genioglossal advancement functions to anteriorly reposition the genial tubercle and genioglossus muscle. The procedure places tension on the base of tongue, thereby reducing prolapse into the posterior airway during sleep.\textsuperscript{15} The responder cure rates from a genioglossal advancement
varies from 35-60% depending upon OSA severity.\textsuperscript{41} Potential complications from genioglossal advancement surgery include mandibular fracture, lower incisor root lesions, infection, permanent anesthesia, and seromas.\textsuperscript{41} A modified genioplasty is another technique that advances the genioglossus muscle and chin used for patients with microgenia. While the improvement in facial esthetics is the primary goal of a genioplasty, a secondary benefit of surgery is an increase in airway volume, thus decreasing the likelihood of hypopharyngeal airway collapse.\textsuperscript{15}

\textit{Temperature-controlled Radiofrequency Ablation}

Radiofrequency ablation (RFA) is a procedure that uses radiofrequency energy to reduce tongue volume.\textsuperscript{46} By heating the tongue base and or soft palate to 70-85°C, tissue lesions are created which leads to scarring, tissue volume reduction, and a reduction in upper airway collapsibility.\textsuperscript{15,42} Radiofrequency ablation can be performed in office under local anesthesia and typically requires multiple treatments.\textsuperscript{15} Currently, RFA is not considered a primary procedure in the treatment of OSA, but considered adjunctive therapy.\textsuperscript{41}
**Laser Midline Glossectomy, Lingualplasty, & Epiglottidectomy**

Tongue reduction surgery through laser midline glossectomy or lingualplasty is used to treat OSA for patients with macroglossia and may be combined with epiglottidectomy to increase the hypopharyngeal volume.\(^{15}\) Success rates are highly variable especially for morbidly obese patients. Complications include excessive bleeding, odynophagia, dysphagia, and reduced tongue mobility.\(^{47,48}\) Tongue volume reduction surgery is rarely used due to these morbidities.

**Hyoid Myotomy Suspension**

The advancement of the hyoid bone with the simultaneous advancement of the epiglottis, the tongue base, and the suprahyoid muscles helps to increase the upper airway space, mainly in the retroglossal area.\(^{15}\) This technique involves suturing the hyoid bone to the thyroid cartilage using resorbable sutures after myotomy and dissection of the stylohyoid ligaments.\(^{42}\) Hyoid myotomy suspension is typically performed in conjunction with other upper airway procedures such as UPPP, nasal septoplasty, and/or tonsillectomy.\(^{49}\) Potential complications as a result of hyoid myotomy suspension include seromas, intermittent
aspiration, and the loss of a resorbable suture. A follow-up period of 3-6 months demonstrated an average decrease in the AHI from 46.9 to 21.3.  

Maxillomandibular Advancement Surgery

Maxillomandibular advancement is a Stage II surgical procedure by which the maxilla and mandible are advanced typically 10-15 mm by means of LeFort I and bilateral sagittal-split osteotomies.  

Patients usually undergo Stage II surgical treatment for OSA after they have been incompletely treated with unsuccessful non-surgical or Stage I surgical therapy with persistent obstruction at the base of the tongue. MMA is a definitive therapy that globally targets that multiple sites of obstruction for long-term improvement.  

The primary objective of MMA is to advance the lower facial skeleton and surrounding structures in an effort to pull forward and increase the tension of the attached soft tissues (e.g., tongue base and soft palate), as well as anatomically enlarge the entire velo-oro-hypo-pharyngeal airway. Frequently, craniofacial characteristics, such as maxillary and mandibular deficiencies, influence pharyngeal airway obstruction more than previously suspected. OSA
patients with these craniofacial characteristics are most appropriate for curative surgical correction by MMA. The success of maxillomandibular advancement surgery is dependent on the definition of success. A successful surgical outcome has been defined in some studies as having an AHI or RDI less than 10. For those studies using an AHI or RDI of less than 10, surgical success rates have been found to range from 65% to 97%. Other studies define a successful surgery with an AHI or RDI of less 20 because this correlates with decreased patient mortality. These studies have found surgical success rates from 83% to 100%.

**Tracheotomy**

A tracheotomy is a surgical procedure by which a tracheostomy tube is inserted into an opening in the neck through the trachea bypassing the upper airway allowing respiration. Tracheotomy is usually a last-resort option for the treatment of OSA, but may be considered for the long-term management of patients with life threatening OSA when CPAP is ineffective or for unsuccessful previous surgeries. Despite a tracheotomy being a curative procedure in the treatment of severe OSA, the associated psychosocial problems and morbidity prevent its widespread
acceptance for patients who can undergo alternative surgeries.\textsuperscript{21, 59}

\textbf{Airway Imaging}

Airway imaging techniques used in the diagnosis of OSA have greatly improved with the further understanding of OSA pathophysiology.\textsuperscript{60} Treatment planning and evaluation of surgical and non-surgical therapies which target specific areas of obstruction are now possible with newer imaging modalities. Airway imaging can be done using numerous techniques such as acoustic reflection, fluoroscopy, and nasopharyngoscopy.\textsuperscript{61} However, the most common airway imaging modalities are lateral cephalometric radiography, magnetic resonance imaging (MRI), and computed tomography (CT).

While panoramic radiography offers little diagnostic information specific for the diagnosis of OSA, it can provide pre-operative records useful in surgical treatment planning, postoperative assessment of the anatomic changes and its allows one to monitor the periodontal and dental conditions of OSA patients being treated with oral appliances.\textsuperscript{62}

Lateral cephalometric radiography is the most widely used imaging technique for hard and soft tissue evaluation for patients with OSA.\textsuperscript{63} Orthodontists and oral surgeons
routinely use lateral cephalograms for evaluating the facial skeleton, the dentition, the effects of growth on treatment, and the airway. The relatively low cost, low-dose radiation and wide availability in dental offices allows lateral cephalograms to be easily obtained in an office setting. The limitations of a lateral cephalogram are that it is a static, two-dimensional image that is gathered with the patient in an upright position during a non-apneic event. Consequently, three-dimensional volumetric data cannot be gathered from two-dimensional images. Cephalometric data should be interpreted in light of the diagnostic information from a sleep study, clinical history, and a physical examination.60

Evaluating three-dimensional structures is better suited utilizing newer imaging technologies such as MRI and CT. They provide greater detail in three dimensions of hard and soft tissue structures of the head and neck. Standard CT imaging not only provides three-dimensional images of the airway, but also volumetric data as well.

**Magnetic Resonance Imaging**

Magnetic resonance imaging (MRI) uses electromagnetic energy and radio waves to assess various types of soft tissue without exposing the patient to ionizing radiation.
MRI has equal resolution, but much greater contrast than CT scanning – this is especially useful in studying OSA as it allows more detailed visualization of soft tissues of the pharyngeal airway. Rapid image acquisition MRI, also known as fast MRI, can be used to examine the airway in a dynamic manner. Fast MRI can obtain 0.8 images at 1 image per 1 second, which allows multidimensional views and visualization of the dynamic shape of the pharyngeal airway during inspiration and expiration. Despite the ability of the fast MRI to show anatomic obstruction during apnea, the limitations of using MRI include: the large size of the MRI machine, noisy scans, taking several minutes for a scan, claustrophobic effects of being inside the machine, and its relative expense. These limitations negate its use as a routine imaging assessment for patients with OSA.

**Standard Computed Tomography**

Standard CT images are obtained as 1-2mm slices in axial or coronal planes or both, from the patient in the supine position, which is the typical position of a patient who is having an apneic event. The slices are combined and reconstructed into three-dimensional images. Increased cost and radiation exposure to the patient, static images,
poorer quality imaging of soft tissue, and are the shortcomings of standard CT imaging.\textsuperscript{65}

**Fast Computed Tomography**

Fast CT imaging is more useful in the study of OSA as it allows the active capturing of images of the dynamic movement of the hard and soft tissues of the pharyngeal airway during respiration. Like standard CT, fast CT imaging uses two-dimensional images that are combined to create a three-dimensional image by acquiring eight contiguous scans every 0.7 seconds. Fast CT provides a more physiologically significant assessment of the upper airway compared with standard CT imaging due to its ability to capture the dynamic component of sleep apnea, while carrying the same drawbacks as standard CT.\textsuperscript{60}

**Cone Beam Computed Tomography**

Cone beam computed tomography (CBCT) uses divergent x-rays that form a cone to capture a three-dimensional image. The scanner rotates around a patient’s head capturing up to 600 images that are reconstructed to create a digital volume composed of three-dimensional voxels of anatomical data which can be manipulated with software.\textsuperscript{66} Advantages of CBCT imaging include lower radiation exposure to the
patient, wide availability, relatively low cost compared to standard CT, images can be captured in sitting or supine positions, and its allows for accurate assessments of the upper airway. Disadvantages of CBCT imaging include initial cost, static image, and poor soft tissue resolution.

**Airway Volume Change Following MMA Surgery**

The study of oropharyngeal airway volume change following MMA surgery has generally been undertaken using two-dimensional imaging techniques, such as lateral cephalometric radiography, that provides a limited assessment of the overall volume change following surgery. Three-dimensional imaging using CT or MRI provides the necessary information to accurately assess the volume changes post-MMA surgery. While few studies using three-dimensional imaging to measure post-surgical volume changes exist, the limited data suggests the long term stability in volume change remains.

Raffaini and Pisani found a 56% increase in posterior airway space volume 6-12 months following MMA surgery for Class II correction in patients with OSA using CBCT. Abramson et al. found a 60% increase in pharyngeal airway volume immediately following MMA surgery in conjunction with genial tubercle advancement using CT. Hernandez-
Alafaro et al. found a 68% increase in pharyngeal airway volume 146 days following MMA surgery for treatment of OSA using CBCT. Zinser et al. found a mean airway volume increase of 45% following MMA. Faria et al. found a 26.72% mean increase in the retropalatal region and 27.2% mean increase in the retroglossal region of the oropharyngeal airway six months following MMA. A case report for a patient treated with MMA for OSA found an 81% increase in pharyngeal airway volume following CBCT analysis. Further evidence of stable long-term increases in oropharyngeal airway volume following MMA surgery includes research by Burgess et al. Burgess analyzed 55 pre- and post-operative CBCTs and found a significant long term change in airway volume.

**Study of Airflow**

The human upper airway is the passage that allows the exchange of gases between the lungs and ambient air. Detailed investigations of upper airway airflow patterns are challenging due to the complexities of airway anatomy, limitations of in vivo experiments, and costliness of in vitro studies. The quantitative information about airflow distribution has been limited in the past, however newer imaging techniques along with computer technologies, such
as hot-wire anemometry, particle imaging velocimetry, and computational fluid dynamics (CFD), have become a viable tool for analyzing airflow in the human upper airway.

**Anemometry**

The measurement of wind force and velocity is called anemometry and is accomplished using an anemometer. There are various types of anemometers used to measure air velocity such as cup anemometers, windmill anemometers, laser-doppler anemometers, sonic anemometers, acoustic resonance anemometers, ping-pong ball anemometers and hot-wire anemometers. Hot-wire anemometers are well-suited for the scientific study of turbulent airflow. \(^{73}\) Hot-wire anemometers use very fine tungsten or platinum wires heated-up electrically to or above the ambient room temperature and held constant. As flowing air passes over the wire, the wire is cooled. As the wire tries to maintain either a constant temperature or current, a relationship can be derived from the resistance of the wire and the amount of heat lost can be used to calculate airflow velocity. \(^{73}\) Hot-wire anemometers are useful in the study of turbulent airflow and provide excellent spatial resolution and high-frequency response. Flow-resistance in nasal airway models using hot-wire anemometry found a good
correspondence in pressure losses between the predicted and actual models.\textsuperscript{74} However, hot-wire anemometers tend to be fragile, need to be recalibrated frequently due to dust accumulation, and carry a high cost.\textsuperscript{73}

**Particle Image Velocimetry**

Particle Image Velocimetry (PIV) is an optical method of flow visualization that can provide instantaneous velocity information for a two-dimensional plane for either gaseous or liquid fluids.\textsuperscript{75} When air is used, micron-sized droplets are introduced to the flow that allow for visualization. Using a camera, laser and synchronizer, the particles in a fluid can be detected by the light scattered from the laser pulses and recorded by the camera. The synchronizer acts as an external trigger that coordinates the laser pulse and camera exposure. Over a period of exposures, the particles can be measured between frames and their velocity calculated.\textsuperscript{76} Nasal airflow characteristics have been patterned and analyzed using PIV.\textsuperscript{77-79} Advantages of using PIV are that it is relatively non-intrusive to the flow of the fluid, measurements can be taken on a whole cross section of the flow field, and it is capable of providing spatial and temporal fidelity. The disadvantages of using PIV are its high cost for the equipment, it can
only measure velocities in two dimensions, and in some cases the particles do not perfectly follow the motion of the fluid due to particles having a higher density.\textsuperscript{76}

**Computational Fluid Dynamics**

Computational fluid dynamics (CFD) is a form of fluid mechanics that utilizes numerical calculations and algorithms to simulate and analyze fluid flow with the aid of computers. CFD is comprised of three separate functions: (1) pre-processor, (2) solver, and (3) post-processor.\textsuperscript{80}

The pre-processor is used in preparation for the simulation. First, the physical boundaries of the model, also known as the geometry, are defined. Geometry definition provides information as to where the simulation will occur (i.e., inside or outside the geometry). Next, the volume (or domain) occupied by the fluid is divided into discrete cells known as the mesh. The mesh can be further subdivided into smaller cells known as the subdomain. Mesh generation is critical for the accuracy of the simulation because CFD simulation depends on the number of cells defined in the mesh. A typical computational mesh of the upper airway regions consists of 500,000 - 1,600,000 elements depending on the volume included in the domain.\textsuperscript{81,82,83,84,85} Further, the physical properties and
boundary conditions of the system are defined such as fluid density, viscosity, type of fluid flow, type of turbulence, how fluid interacts with surroundings, compressibility and heat transferability. Once model preparation and boundary conditions are set, the model is sent into the processor for fluid flow simulation.\textsuperscript{86}

CFD fluid flow simulation is started after pre-processing. The governing equations are solved in a manner that generates a sequence of improving approximate solutions until a steady state is achieved. After completion of fluid flow simulation, the post-processor is used for analysis and visualization of the resulting solution.\textsuperscript{80}

The post-processor is the final step in CFD simulation and functions to organize and display data for fluid flow analysis. Animations and graphical illustrations can be generated to allow for visualization and interpretation of the results.\textsuperscript{87}

Advantages of CFD include its relatively low cost, simulations can be executed in a short period of time, the ability to theoretically simulate any physical condition, the ability to simulate ideal conditions, and it provides comprehensive information that allows for the analysis and
visualization of a large number of locations of interest and evaluation of flow parameters.

Limitations of CFD include: the reliance upon physical models of real world processes (e.g. turbulence, compressibility, chemistry, multiphase flow, etc.); solutions can only be as accurate as the physical model on which they are based; and the potential for the introduction of numerical errors such as round off errors, and truncation errors due to approximations in the numerical models (although this can be somewhat mitigated through grid refinement of the mesh).\textsuperscript{80}

**Governing Fluid Flow Equations**

Computational fluid dynamics predicts fluid flow characteristics by solving the flow governing equations. The fundamental basis for almost all CFD problems are the Navier-Stokes equations. The Navier-Stokes equations are based on three fundamental principles: (1) mass can neither be created nor destroyed, (2) force equals the time rate of change of momentum, & (3) energy can neither be created nor destroyed, it can only change form.\textsuperscript{88} A commonly used turbulence model in CFD is the Reynolds-Averaged Navier-Stokes (RANS) Re-Normalization Group (RNG) $k-\varepsilon$ turbulence model.\textsuperscript{89} The RNG $k-\varepsilon$ turbulence model is a two equation
model that accounts for history effects like convection and diffusion of turbulent energy and is specifically used to account for the effects of smaller scales of motion.\textsuperscript{90} The $k-\varepsilon$ turbulence model has been used in other upper human airway studies because of its lower-computing power requirements and less expensive to run.\textsuperscript{84, 85, 91} Other resolving equations include the $k-w$ turbulence model and the Large Eddy Simulation (LES) model which is more time-accurate and can directly solve the large range of turbulent scales, but is more expensive and time consuming to use.\textsuperscript{92, 93}

**Types of Fluid Flow**

The characteristics of fluid flow include two forms: laminar and turbulent flow. Laminar flow is characterized by the motion of particles of a fluid moving in a parallel fashion with little disruption within the flow layers and is considered to be low velocity. Conversely, turbulent flow is characterized by high velocity particles mixing with disruptions resulting in eddies (the swirling of fluid and the reverse current created when a fluid flows past an object). Laminar flow is considered to be of high momentum diffusion (the spread of momentum between particles of matter) and low momentum convection, while the opposite is
true with turbulent flow. Transitional fluid flow is the process of laminar flow becoming turbulent flow or vice versa. \(^{80}\)

**Factor Effecting Oropharyngeal Airflow and Volume**

The characteristics of airflow in the oropharyngeal airway are impacted by various factors such as the volumetric flow rate, the velocity and acceleration of the air, the type of fluid flow entering the airway coming from the nasal passage and oral cavity (laminar, transitional, or turbulent), the surrounding anatomy (areas of constriction can cause turbulent airflow and increased pressure), patient positioning, and the stage of respiration (inspiration vs. expiration). \(^{93,94}\)

Using a modified Muller technique, inspirational pressures of -20, -40, and -60 mmHg, during CBCT scans, demonstrated a progressively decreasing posterior airway space, thus increasing the likelihood of airway collapse. \(^{95}\) Fluctuations in airway area during tidal breathing can also be significant in subjects with OSA compared to control subjects. Research from Arens et al. found a smaller upper airway cross-sectional area and airway narrowing during inspiration and airway dilatation occurred during expiration. \(^{96}\)
Patient positioning during airway scans can have a significant effect on posterior airway space. The response of oropharyngeal structures to gravity showed the soft palate, epiglottis and entrance of the esophagus moved caudally with a change from supine to sitting upright, and posteriorly when the position changed from upright to supine. The cross-sectional area of the airway in the upright position was larger than in the supine position.\textsuperscript{97}

Tissue compliance and decreased intra-luminal pressure can also have significant effects on the behavior of airflow. Three-dimensional flow features such as separation and transition from laminar to turbulent flow can also affect the flow pressure to a significant degree. Various attributes of airflow such as static pressure, wall shear stress, turbulence, magnitude of velocity, relative pressure, and airway resistance can be measured using airway models and CFD.\textsuperscript{93}

**Effects of Obstructive Sleep Apnea on Airflow**

Obstructive sleep apnea can have considerable effects on airflow behavior including static and relative pressure, velocity and turbulence. OSA is typically associated with snoring, which is caused by vibration of the margin of the soft palate and or walls of the pharynx, and is linked to
the flaccidity of the palatal muscles during sleep. Patients sleeping in a supine position are more prone to snoring due to the soft palate and tongue falling into the air stream. However, even heavy snoring is not always indicative of the existence of OSA.

The narrowing of the pharyngeal airway space and its eventual collapse and obstruction is a function of its wall structures (compliance) and the intraluminal air pressures. OSA patients tend to have pharyngeal tissue that is highly compliant due to fat deposition within the walls of the pharyngeal musculature. During sleep, the pharyngeal muscle tone decreases, resulting in a greater likelihood for airway collapse. Where the walls are highly compliant, a small drop in intraluminal pressure can cause a large change in the cross-sectional area which also causes an increase in airflow velocity that is necessary to maintain a constant flow rate. During large positive transmural pressures, the pharynx becomes distended and stiff and at large negative values, the cross-sectional area decreases greatly and collapse can occur. The necessary driving force in airflow is a result of a decrease in pressure on the downstream side of the constriction and a corresponding increase in pressure on the upstream side of the stenotic area.
Additionally, turbulent airflow increases as a result of airway constriction and recirculation of air there.\textsuperscript{93, 94} Turbulence results from changes in airway shape and abrupt changes in airflow velocity.\textsuperscript{100} Increased turbulence on the downstream side of the constriction can also contribute to a decrease in pressure and further airway collapse.\textsuperscript{94}

**Airflow Studies using Computational Fluid Dynamics**

Hahn et al. found that air flow inside the nasal cavity is laminar for low flow rates and turbulent for medium or high flow rates.\textsuperscript{101} This implies that air flow that is laminar in nature could transition to turbulent flow during periods of heavy breathing or due to partial obstructions within the pharynx.\textsuperscript{94} The likelihood in airway collapse is increased by a cause in pressure drop due to the transitional nature of the airflow. Shome et al. found, in modeling airflow in the pharynx, that the pressure drop lies in the 200-500 Pa range and that the onset of turbulence was found to precipitate an increase in pressure drop by 40\%.\textsuperscript{94} The results by Shome et al. confirmed that the airflow in the pharynx lies in the laminar to turbulent transitional flow profile, and consequently a small or subtle change in airway geometry can significantly affect the characteristics of airflow.\textsuperscript{94} CFD simulations of the
upper airway by Sung et al. found maximum air velocity and lowest pressure in the narrowest part of the velopharynx, suggesting it to be the most likely area for airway collapse. Similar results by Mihaescu et al. found that the highest axial velocity was located at the site of minimum cross-sectional area (retropalatal pharynx) resulting in the lowest level of static wall pressure and thus increasing airway collapsibility.

Predicting the therapeutic outcome of upper airway oral devices has been attempted using CFD. Research by De Backer and colleagues found that a decrease in upper airway resistance and an increase in upper airway volume correlate with both a clinical (reduction in AHI > 50% of baseline) and an objective improvement, suggesting that the outcome of mandibular advancement device treatment can be predicted using CFD. Zhao et al. found the restricted area at the velopharynx directly induced a jet flow with significant velocity increase and pressure drop. Additional work by Zhao and colleagues found the lowest pressure often occurs close to the soft palate and base of the tongue, however changes in airway geometry alone did not significantly correlate with treatment response with mandibular advancement splint therapy.
The validation of CFD in the study of upper airway fluid flow was conducted using physical models built through stereolithography and compared to digitized models. Mylavarapu et al. found an average error of 20% over all ports of the physical model versus the digitized model.\textsuperscript{105} Their study also found the highest positive pressures in the retroglossal region below the epiglottis, the lowest negative pressures in the retropalatal region while the largest pressure drop was observed at the tip of the soft palate. This was due to airflow acceleration in the narrow retropalatal region.\textsuperscript{105}

The study of the effects of MMA on OSA patients using CFD has shown that the cross-sectional area of the narrowest part of the upper airway was increased in all dimensions. The simulated results showed a less constricted upper airway, with less velocity change and decreased pressure gradient across the entire domain during passage of air. Yu et al. concluded that less breathing effort was required in the post-operative airway.\textsuperscript{106}

Powell and colleagues studied four patients with sleep-disordered breathing who underwent surgery or used positive airway pressure devices and compared them to healthy controls. Pre-treatment airways below the obstruction site showed flow separation, generated re-
circulation and thus turbulence. Significant decreases in maximum airflow velocities were found post-treatment along with significant improvements in airway resistance (decrease in static pressure).\textsuperscript{93}

Perak et al. studied airway resistance and compliance in children with OSA using CFD and discovered the evolution of airway collapse and flow resistance. The upper airway of children with OSA was found to be more compliant during tidal breathing. In one patient, the distal oropharynx was more compliant than the nasopharynx and was found to be the flow-limiting segment of the airway. Another subject had a more compliant nasopharynx during inspiration and apparent stiffening of the distal oropharynx, indicating the nasopharynx as the rate limiting segment. This method may help to differentiate anatomical and functional factors in airway collapse.\textsuperscript{107}

Patterns in pharyngeal airflow associated with sleep-disordered breathing demonstrated airflow separation and generated re-circulation airflow regions and turbulence below the minimum cross-sectional area of obstruction in pre-treatment pharyngeal airways studied using CFD. At the same volumetric flow rate, airflow field instabilities disappeared and airflow characteristics improved in post-treatment modeling. Velocities decreased from 18.3 m/s to
6.3 m/s, while airway resistance improved from 4.3 Pa/L/min to 0.7 Pa/L/min.\textsuperscript{93} Another study demonstrating greater negative pressure within the pharyngeal cavity was found in 60 patients with OSA with CFD modeling leading to greater likelihood of airway collapse.\textsuperscript{108}

The soft tissue changes and pressure effort to breath after MMA in the treatment for OSA were significantly affected as studied through CFD. Sittitavornwong et al. found a significant increase in airway dimension as measured from the occipital base to pogonion and was significantly correlated with an improvement in AHI and a decreased pressure effort of the upper airway.\textsuperscript{109}

CFD has been used to demonstrate a direct positive correlation between the apnea-hypopnea index and pressure drops during inspiration across the most constricted areas of the pharynx.\textsuperscript{110}

Airflow characteristics were measured on a cadaveric model using genioglossal advancement (serial advancement from 1mm to 3mm, 7mm, and 9mm) and CFD on high resolution CT scans. Velocity increased and pressure decreased after 9mm advancement secondary to increased airway diameter and less abrupt changes in airway geometry.\textsuperscript{111}

A complex model was used to simulate airflow and structural interaction by using a fluid-structure
interaction (FSI) model and compared to CFD simulations in the study of OSA. Both models found the base of the tongue and the posterior soft palate to be areas that were most prone to collapse. In these areas, faster flow velocity caused large negative pressure to occur. Both CFD and FSI simulations provided information on areas of collapse, while FSI supplied a more realistic result than CFD.\textsuperscript{112}

Several investigations of MMA effects on OSA found that a decrease in pressure effort was needed to maintain a constant airflow rate. A decrease in negative pressure was found, meaning less effort was required to breathe.\textsuperscript{93, 113-115}

In a limited sample study, pharyngeal airflow analysis in OSA patients post-MMA surgery found a decrease in turbulence, pressure gradients and a reduced pressure drop was required to move a constant volumetric flow indicating a decrease in resistance of over 90\% for three out of four patients. Huyhn et al. found that areas of stenosis can cause a decreased local relative pressure and lower levels of pressure distal to the constricted area can result in further airway collapse, especially in areas that are highly compliant.\textsuperscript{115}
Purpose of the Study

The purpose of this study is to analyze and compare pharyngeal airflow characteristics in patients with obstructive sleep apnea pre- and post-maxillomandibular advancement surgery using computational fluid dynamics. The change in pressure, change in airway resistance, and change in maximum magnitude velocity will be measured and compared. Correlations among airway resistance, airway volume, and skeletal advancement will also be analyzed.
Literature Cited


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CHAPTER 3: JOURNAL ARTICLE

Abstract

Purpose: To analyze pharyngeal airflow using computational fluid dynamics (CFD) in obstructive sleep apnea (OSA) patients pre- and post-maxillomandibular advancement (MMA).

Materials and Methods: Digitized pharyngeal airway models of 19 obstructive sleep apnea patients were generated from cone beam computed tomography scans pre- and an average of 18.3 ± 17.3 days post-surgery. CFD was used to simulate and characterize pharyngeal airflow, which was assumed to be turbulent at an inspiration rate of 340 ml/sec. Standard steady-state numerical formulation were used for airflow simulations.

Results: Mean pressure drop during inspiration was significantly reduced from 34.82 ± 65.65 Pa pre-surgery to 3.06 ± 3.96 Pa post-surgery. Mean maximum airflow velocity along the airway was also significantly reduced from 11.14 ± 8.49 m/s pre-surgery to 4.09 ± 3.07 m/s post-surgery. There was a significant increase in mean airway volume of 66.8% post-surgery. There was a 75% mean reduction in airway resistance following surgery. There was a decrease in the pressure gradient and total pressure drop following surgery for all 19 patients. There was a statistically significant moderate, negative correlation between the change in airway resistance and the change in
airway volume post-surgery. No correlation was found between skeletal advancement and airway volume or airway resistance. **Conclusions:** A decrease in relative pressure implies less effort required for maintaining constant pharyngeal airflow according to CFD analyses on airways of OSA patients following MMA surgery.

**Introduction**

Obstructive sleep apnea (OSA) is a sleep-related breathing disorder characterized by the partial or complete collapse of the upper airway during both rapid eye motion (REM) and non-REM sleep.\(^1\), \(^2\) Epidemiologic estimates of OSA prevalence are approximately 9-24% for middle-aged adults with up to 80% of patients remaining undiagnosed.\(^3\), \(^4\) Sleep-related breathing disorders can lead to debilitating cardiovascular diseases, hypertension, stroke, angina, headaches, disruption of normal sleep routine, excessive day-time sleepiness, poor-work performance, occupational accidents, xerostomia, cognitive dysfunction, depression and exacerbation of Type II diabetes, epilepsy and asthma.\(^5\)-\(^12\)

Various therapies exist in the treatment of OSA. Continuous positive airway pressure (CPAP) is a highly effective therapeutic modality for the treatment of OSA and
remains the gold-standard.\textsuperscript{6} Other non-surgical treatments for OSA include oral appliances, such as mandibular advancement and tongue-retaining devices and have shown some limited success in OSA treatment.\textsuperscript{13} Multi-level surgical interventions play an important role as second-line treatment for anatomical obstruction.\textsuperscript{14} The purpose of surgical interventions for OSA are to create lasting effects on the anatomy of the upper airway, thus permanently relieving airway obstructions and improving airflow. A highly effective Stage 2 surgical option for the treatment of severe OSA is maxillomandibular advancement (MMA) surgery with success rates of 65\% to 100\%.\textsuperscript{15-18} Additionally, patients with craniofacial abnormalities or multiple obstructions along the airway can be treated with MMA as first line surgical therapy.\textsuperscript{19}

The study of pharyngeal airflow following MMA surgery has been targeted as an area of interest using computational fluid dynamics (CFD). Computational fluid dynamics provides a method for the indirect study of pharyngeal airflow. Shome et al. studied the cross-sectional area change in response to different treatments (CPAP, mandibular repositioning devices, and surgery) and found there was a decrease in relative pressure in relation to cross-sectional area of the airway.\textsuperscript{20} Sung et al. found
maximum airflow velocity and lowest pressure at the narrowest part of the velopharynx.\textsuperscript{21} Using CFD, Yu et al. found less velocity change and a decreased pressure gradient across the model during air passage post-MMA surgery.\textsuperscript{22} Ito et al. constructed hybrid models composed of post-treatment nasal cavities superimposed on pre-treatment nasal cavities and post-treatment nasal and pharyngeal airway models to simulate airflow and found a decrease in pressure effort to breathe evidenced by a decrease in the negative pressure post MMA surgery.\textsuperscript{23} Laminar and turbulent air flows have been shown to be significantly less at all levels of the airway after MMA surgery.\textsuperscript{24} Lastly, numerous investigations found a decrease in airway resistance following MMA surgery.\textsuperscript{23, 25-27}

The purpose of this study is to analyze and compare pharyngeal airflow characteristics in patients with obstructive sleep apnea pre- and post- maxillomandibular advancement surgery using computational fluid dynamics.

**Materials and Methods**

**Patient Selection**

Pre- and post-treatment CBCTs of 19 patients (9 male and 10 female) who had undergone both orthodontic treatment and maxillomandibular advancement surgery were used in this
retrospective study. The mean age was 38.6 ± 14.3 years (mean age for males was 40.8 ± 12.9 years; mean age for females was 36.6 ± 15.9 years). The sample was retrieved from the private office of two oral and maxillofacial surgeons in Santa Barbara, CA. Post-surgical CBCT scans were taken at an average of 18.3 ± 17.3 days.

**Inclusion criteria:**

1. Having a history of obstructive sleep apnea
2. Being treated with both orthodontics and maxillomandibular advancement surgery.

**Exclusion criteria:**

1. Having craniofacial syndromes
2. Having surgical maxillary expansion

The surgical procedures completed were carried out by two oral surgeons using the same surgical techniques. A non-segmental Le Fort I osteotomy was used to advance the maxilla, while bilateral sagittal split ramus osteotomies were used to advance the mandible. In areas of significant surgical movement, bone grafts were used and both jaws were rigidly fixated. Centric relation was verified prior to fixation to ensure the seating of the mandibular condyles.
**CBCTs**

CBCT scans were taken pre- and post-MMA surgery using the same i-CAT machine (Imaging Sciences International, Hatfield, PA). Imaging field of view was 23 cm by 19 cm with a voxel size of 0.4 mm. Pre-surgical scans were taken with an inter-occlusal wax bite in centric relation. Post-surgical scans were taken with the condyles in centric relation and no wax bite. Mimics 3D software (version 15.0, Materialise, Leuven, Belgium), Geomagic (version 2012, 3D Systems, Rock Hill, SC), and Dolphin 3D (version 11.0, Chatsworth, CA) were used to view, analyze, and manipulate the CBCT scans.

**Calculation of Surgical Movement**

The calculation of the anterior-posterior surgical movement was measured for the maxilla and mandible by converting the CBCT scan from a three-dimensional volume to a two-dimensional lateral cephalogram image utilizing the “build x-rays” feature in Dolphin Imaging. The skeletal landmarks used to measure surgical movement were Sella, Nasion, A-point, and B-point. A reference plane was drawn through Sella and Nasion and then 7° (SN-7°) was subtracted. A perpendicular line was drawn through the corrected horizontal plane from Nasion and then the
distance to A-point and B-point was measured and compared pre- and post-surgery (Figure 3.1).

Figure 3.1: Lateral cephalograms demonstrating measurement of surgical movement

Isolating the Pharyngeal Airway

The CBCT scans were imported into Mimics software as DICOM (Digital Imaging and Communications in Medicine) files to generate a volumetric image of the scanned region. Once the volume was generated, the pharyngeal airway of interest was isolated. The superior border was defined by creating a plane through left and right porus acusticus externus and nasion; the anterior border was defined by
creating a perpendicular plane to the superior border going through the most anterior and middle point of the Sella-wall; the inferior border was defined by creating a horizontal plane parallel to the superior plane through the most inferior and anterior point of C3. The anterior and posterior wall of the volume was defined by the natural border of the pharynx. The uvula was removed in all cases to avoid artifacts (Figure 3.2).

Figure 3.2: Airway volume model segmentation boundaries
Computer Modeling and Mesh Generation

Pharyngeal airway models were imported into Geomagic to check for model integrity. Models were transferred into SC/Tetra Pre-processing software (version 9.0, Software Cradle Corporation, Osaka, Japan) for model and mesh generation. Inlet, outlet and wall boundaries were defined manually (Figure 3.3).

Appropriate grid size, number of tetrahedral elements and octree size of 0.5 mm was chosen for the mesh model using the same protocol used by Huyhn et al. (Figure 3.3).26 The final mesh models of the airways had an average of 314,193 tetrahedral elements.

Figure 3.3: (A) 3-D Airway Model and (B) Mesh model file demonstrating tetrahedral elements
Solving Methods

Mesh models were imported into SC/Tetra Solver (version 9.0, Software Cradle Corporation, Osaka, Japan) for airflow simulation. A turbulent model flow, the RNG k-ε model, was used to simulate turbulent airflow within the pharyngeal airway, similar to the turbulent model equations used in the Huynh et al.\textsuperscript{26} and Sung et al. studies.\textsuperscript{21} The RNG k-ε model was chosen because of its minimal computing power required for flow simulation. Detailed governing equations for turbulent flow can be found in the Appendix. Using a volumetric flow rate of 340 ml/sec, corresponding inlet boundary velocities were calculated for each model using the formula \(Q=AV\). Inlet area, \(A\), was determined from the pre-processor function in SC/Tetra for each model. The outlet boundary condition was set at a static pressure of 0 Pa. The walls of the model, which were assumed to be rigid and non-compliant, were set to no-slip conditions. Air flow simulations were completed using the SC/Tetra Solver function on a PC with an Intel® Core™ i7 CPU Q740 (1.73GHz) with 8GB of RAM. After solver functions were completed, SC/Tetra Post-processor software (version 9.0, Software Cradle Corporation, Osaka, Japan) was used to analyze and visualize the fluid flow data.
Magnitude of Airflow Velocity Measurements

The maximum magnitude of airflow velocity was measured for all 19 patients pre- and post-surgery. All measurements were recorded in the mid-sagittal plane of the airway. Velocity measurements were made using the SC/Tetra post-processor.

Pressure Calculations and Airway Resistance

The post-processor function of SC/Tetra was used to calculate the change in pressure, \( \Delta p \), from the inlet to outlet boundary over the digitized model for all 19 patients pre- and post-surgery. All measurements were recorded in the mid-sagittal plane of the airway. Airway resistance, \( R \), was measured for all 19 patients pre- and post-surgery. Resistance was calculated with \( \Delta p \) by using the equation \( R = \Delta p/F_{ua} \), where \( F_{ua} \) is the mass flow rate. The mass flow rate can be derived from the equation \( F_{ua} = Q\rho \), where \( Q \) is the volumetric flow rate and \( \rho \) is the density of air.\(^{28}\)

Statistical Analysis

Analysis of the data was completed using IBM SPSS Statistics 19.0 (Armonk, NY). Descriptive statistics calculated the mean and standard deviation for maxillary
and mandibular advancement, airway volume change, change in pressure, airway resistance and maximum magnitude of velocity. Paired t-tests were used to test for significant differences for change in pressure, maximum velocities and airway volume observed pre- and post-surgery. Pearson correlations among airway resistance, airway volume change, and skeletal advancement were analyzed. A significance level of $p < 0.05$ was used.

**Results**

**Cephalometric Data**

The mean maxillary advancement was $4.5 \pm 2.2\text{mm}$, while the mean mandibular advancement was $9.1 \pm 3.8\text{mm}$. Maxillary advancement refers to the change in point A between pre- and post-surgery, while mandibular advancement refers to the change in point B between pre- and post-surgery as measured from a perpendicular line from a corrected horizontal plane (SN-7°) from Nasion. All measurements were taken in the horizontal plane.
Volumetric Data

Means and standard deviations for airway volume pre- and post-MMA surgery and percentage change in airway volume are presented in Table 3.1. There was a statistically significant increase in post-surgery airway volume.

Table 3.1 Volumetric measures (mm$^3$): means, standard deviations

<table>
<thead>
<tr>
<th>Measure</th>
<th>$T_0$</th>
<th>$T_1$</th>
<th>% Change</th>
<th>Paired t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>S.D.</td>
<td>Mean</td>
<td>S.D.</td>
<td>Mean</td>
</tr>
<tr>
<td>Airway Volume</td>
<td>1.35x$^{-5}$</td>
<td>5.00x$^{-6}$</td>
<td>2.26x$^{-5}$</td>
<td>7.05x$^{-6}$</td>
<td>66.80%</td>
</tr>
</tbody>
</table>

*P<0.05

Airflow Data

Means and standard deviations for change in pressure and % change in airway resistance and maximum airflow velocity in the mid-sagittal plane pre- and post-surgery are presented in Table 3.2 and Table 3.3 respectively.

Table 3.2 Pressure measurements in the mid-sagittal plane (Pa): means, standard deviations, %Δ airway resistance, and paired t-test

<table>
<thead>
<tr>
<th>Measure</th>
<th>$T_0$</th>
<th>$T_1$</th>
<th>%Δ Resistance</th>
<th>Paired t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>S.D.</td>
<td>Mean</td>
<td>S.D.</td>
<td>Mean</td>
</tr>
<tr>
<td>Change in pressure</td>
<td>34.82</td>
<td>65.65</td>
<td>3.06</td>
<td>3.96</td>
<td>-75.35</td>
</tr>
</tbody>
</table>

*P<0.05
Table 3.3 Maximum velocity in the mid-sagittal plane (m/s): means, standard deviations, and paired t-test

<table>
<thead>
<tr>
<th>Measure</th>
<th>$T_0$ Mean</th>
<th>$T_0$ S.D.</th>
<th>$T_1$ Mean</th>
<th>$T_1$ S.D.</th>
<th>Paired t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>11.14</td>
<td>8.49</td>
<td>4.09</td>
<td>3.07</td>
<td>3.503</td>
<td>.003</td>
</tr>
</tbody>
</table>

*P<0.05

There was a statistically significant decrease in pressure drop along the airway after surgery. The mean decrease in airway resistance was $75.35\% \pm 23.04\%$. Post-surgery patients exhibited a significantly greater reduction in pressure drop along the airway ($\text{Mean} = 3.06 \pm 3.96 \text{ Pa}$) versus pre-surgery patients ($\text{Mean} = 34.82 \pm 65.65 \text{ Pa}$).

There was a statistically significant decrease in maximum airflow velocity along the airway after surgery. Post-surgery patients exhibited a significant decrease in maximum airflow velocity along the airway ($\text{Mean} = 4.09 \pm 3.07 \text{ m/s}$) versus pre-surgery patients ($\text{Mean} = 11.14 \pm 8.49 \text{ m/s}$).

**Correlation Analysis**

Correlations among airway resistance change and skeletal advancement and airway volume change and skeletal advancement are displayed in Tables 3.4 and 3.5 respectively.
Table 3.4 Correlations among airway resistance and skeletal advancement

<table>
<thead>
<tr>
<th>Measure</th>
<th>ΔR</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔA-point</td>
<td>-.107</td>
<td>.332</td>
</tr>
<tr>
<td>ΔB-point</td>
<td>-.340</td>
<td>.077</td>
</tr>
<tr>
<td>ΔVol</td>
<td>-.682</td>
<td>.001</td>
</tr>
</tbody>
</table>

*P<0.05; ΔA-point is the amount of maxillary advancement, ΔB-point is the amount of mandibular advancement, ΔR is the change in airway resistance, ΔVol is the change in airway volume.

Table 3.5 Correlations among airway volume and skeletal advancement

<table>
<thead>
<tr>
<th>Measure</th>
<th>ΔVol</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔA-point</td>
<td>.327</td>
<td>.086</td>
</tr>
<tr>
<td>ΔB-point</td>
<td>.217</td>
<td>.187</td>
</tr>
<tr>
<td>ΔR</td>
<td>-.682</td>
<td>.001</td>
</tr>
</tbody>
</table>

*P<0.05; ΔA-point is the amount of maxillary advancement, ΔB-point is the amount of mandibular advancement, ΔR is the change in airway resistance, ΔVol is the change in airway volume.

There was a statistically significant moderate, negative correlation between the change in airway resistance and the change in airway volume post-surgery. Very weak to weak, negative correlations were found between skeletal advancement and change in airway resistance; weak, positive correlations were found between skeletal advancement and change in airway volume, however, those correlations were not statistically significant.
DISCUSSION

In this study, we compared pharyngeal airflow characteristics using CBCT and CFD before and after maxillomandibular advancement surgery in patients with obstructive sleep apnea. We found MMA led to an increase in airway volume and an alteration in airway geometry, thus leading to improvement in stenotic areas in the airway post-surgery. This increase in pharyngeal airway cross-sectional area led to a decrease in airway resistance, which led to a decrease in pressure effort. Using anatomically correct airway models and a RNG $k$-$\varepsilon$ turbulence flow model, we found a significant reduction in pressure drop and maximum airflow velocity after MMA. In general, as airway constriction was relieved post-MMA, the pressure effort required to maintain the same constant airflow as the pre-surgery models decreased as well.

Maxillomandibular advancement surgery has been shown to be a highly effective therapy in the treatment of severe obstructive sleep apnea.\textsuperscript{15, 17, 18, 29-33} While the current number of studies quantifying MMA treatment results using computational fluid dynamics are limited, completed research in this area of interest has shown results similar to the present study. Although limited in sample size, Huynh et al. found similar results for pressure drop
changes and reduction in airway resistance (90%) post-MMA surgery using CFD.\textsuperscript{26} Powell et al. found a 65% reduction in mean maximum airflow velocity and an 83% reduction in mean airway resistance for patients with sleep-disordered breathing.\textsuperscript{27} Fan et al. found airway resistance decreased by 40% following surgical procedures to improve airway size.\textsuperscript{34} Our study found a 48% reduction in mean maximum airflow velocity and a 75% reduction in mean airway resistance following MMA surgery. The airflow characteristics analyzed in this study demonstrated a clear improvement post-surgery.

The Reynolds numbers were measured for three patients to further investigate pharyngeal airflow type: a patient representing the maximum pressure drop reduction measured between pre- and post-MMA (patient 1); a patient closest to the mean pressure drop reduction of all 19 patients (patient 17); and a patient representing the least measured pressure drop reduction (patient 18). Measuring the Reynolds number allowed us to characterize the fluid flow as laminar, transitional, or turbulent. Generally, laminar flows are represented by a Reynolds number less than 2000 and turbulent flows greater than 4000. Fluid flow between 2000 and 4000 is considered to be transitional.\textsuperscript{35}
As expected, the Reynolds numbers for patient 1 show a transitional to turbulent airflow approximately 30mm from the inlet pre-surgery, while post-surgery results show a laminar airflow for the entire airway with significant improvement in the airway size and relief of the constriction (Figure 3.4). Correspondingly, there was a significant reduction in airway resistance (98%), a significant increase in airway volume (144%), and 5.7mm and 12.5mm of maxillary and mandibular advancement respectively for patient 1. Figure 3.5 shows the pressure contour in the mid-sagittal plane for patient 1 that demonstrates the improvement in airway stenosis in the anterior-posterior direction and reduction in pressure drop.

![Figure 3.4 Reynolds numbers along the pharyngeal airway for maximum pressure drop reduction (patient 1)](image-url)
Figure 3.5 Contour of relative pressure (Pa) for maximum pressure drop reduction (patient 1) along the mid-sagittal plane at (A)T₀ & (B)T₁

For the average patient, the Reynolds numbers for patient 17 demonstrate a laminar to transitional airflow approximately 35mm from the inlet pre-surgery, while post-surgical results demonstrate only laminar airflow for the entire airway with some improvement in airway stenosis (Figure 3.6). There was a moderate decrease in airway resistance (75%), a minimal increase in airway volume (24%), and 5.0mm and 12.6mm of maxillary and mandibular advancement respectively. Figure 3.7 shows the pressure contour in the mid-sagittal plane for patient 17 that shows moderate increases in areas of stenosis in the anterior-posterior direction and obvious areas of pressure reduction and reduced pressure drop post-surgery.
Figure 3.6 Reynolds numbers along the pharyngeal airway for mean pressure drop reduction (patient 17)

Figure 3.7 Contour of relative pressure (Pa) for mean pressure drop reduction (patient 17) along the mid-sagittal plane at (A) T₀ & (B) T₁

Patient 18 demonstrated little change in Reynolds numbers for the airway between pre- and post-surgery results and largely remained in the laminar airflow range
Interestingly, there was only a small decrease in airway resistance (10%) along with an unexpected decrease in airway volume (-4%) post-MMA. The quantity of maxillary advancement was average (5.0mm), while only a small amount of mandibular advancement (3.0mm) was seen. The pressure contour in the mid-sagittal plane for patient 18 shows almost no difference in the pressure gradient between pre- and post-surgery (Figure 3.9). While the pre- and post-MMA surgery AHI number was unknown, it is possible the OSA was not as severe for patient 18, as it was for patient 1 given the findings in this study.

Figure 3.8 Reynolds numbers along the pharyngeal airway for minimum pressure drop reduction (patient 18)
Detailed airway analysis of patient 1 pre- and post-surgery show an area of obvious constriction and the resultant effects of the stenosis at the minimum cross-sectional area, Figure 3.10. As the pressure begins to drop near the constriction, the axial velocity increases, which causes vortices to be formed at the anterior and posterior pharyngeal wall by the jet instabilities. This reduction in static pressure may lead to increased susceptibility to collapse. Figure 3.11 demonstrates the improvement in airway stenosis and the resultant effects of airway widening on airflow for patient 1 following surgery.
Figure 3.10 Pre-surgery (A) pressure, (B) velocity and (C) eddy viscosity coefficient contours for maximum pressure drop reduction (patient 1)

Figure 3.11 Post-surgery (A) pressure, (B) velocity, and (C) eddy viscosity contours for maximum pressure drop reduction (patient 1)
The static pressures above the airway constrictions were significantly higher in the pre-surgery models with the pressure dropping post-constriction versus the same areas in the post-surgery models, where the pressure drop was minimal. The average airflow velocities distal to the constriction were significantly higher in the pre-surgery models relative to the post-surgery models. The inverse relationship between pressure and velocity post airway constriction is best demonstrated within each pre-surgery model from patient to patient. According to the Bernoulli principle, pressure and velocity are inversely related within a given tube for a given streamline. The results of the present study demonstrate the adherence to the Bernoulli principle.\textsuperscript{36}

The authors of this study acknowledge the following limitations: truncation of the airway domain, measurements for airflow characteristics were taken in the mid-sagittal plane only, patients were awake during scans, the stage of respiration was unknown, patients were scanned in an upright position, wax bites were used during pre- but not post-surgery scans, and the AHI was unknown. This study does not take into account the effects of inspiration and expiration on airway rigidity, therefore the value of movement and compliance of the soft tissue of the airway
was not considered. It has been documented that the pharyngeal airway resistance for a given person changes over the respiratory cycle, showing the influence of dynamic airway geometry. Towards the end of the inspiratory cycle, increased resistance causes increased breathing effort due to the increased negative intraluminal pressure buildup. In light of these limitations, the pressure distribution and resistance in the upper airway of patients with obstructive sleep apnea were found to be significantly less following surgery and validate the results of other studies with similar methodology.

More realistic simulations could be made possible by using a model approach that accounts for the deformability of the soft tissue of the pharyngeal airway, while including calculations for the interaction between the fluid flow and the compliant airway wall. This methodology is known as Fluid-Structure Interaction (FSI) and includes movement of the airway wall due to pressure and shear forces that act on the wall. Only a few studies using FSI have been completed and most have used simplified or 2-D airway models that require a large amount of computational power. Combining FSI with dynamic imaging, such as Sleep MRI, which has shown to be useful in identifying areas of airway obstruction during both the inspiratory and
expiratory phases of respiration\textsuperscript{43}, may lead to more anatomically and functionally accurate airway models that allow for the improved study of pharyngeal airflow in patients with OSA.

**CONCLUSIONS**

In summary, CFD simulations are a useful tool for the study of the effects of maxillomandibular advancement surgery on pharyngeal airflow in patients with obstructive sleep apnea. Through CFD modeling, the current study demonstrated that there was a statistically significant reduction in the pressure drop following maxillomandibular advancement surgery. The mean airway resistance was reduced by 75\%, indicating an improvement in airflow following MMA surgery, thus requiring less pressure effort to breathe.
Literature Cited


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44. Wilcox DC. Turbulence Modeling for CFD. DCW Industries Inc. 1993; La Canada.
APPENDIX

Governing Equations:

The governing equations for an incompressible steady flow with constant velocity are the Navier-Stokes equations, which include the conservation of mass and the conservation of momentum equations. The conservation of mass equation is shown below in differential form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

Where $\rho$ is the air mass density, $t$ is time and $u$ is the air velocity. The conservation of momentum equations are shown below in tensor form:

$$\rho \frac{\partial}{\partial x_j} (u_j u_i) = \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) + S_\phi$$

where:

$$S_\phi = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right)$$

In these equations $\rho$ is the air mass density, $x_j$ represents the coordinate direction, $u_{ij}$ are the mean velocity components in Cartesian coordinates, $\mu$ is the fluid viscosity and $S_\phi$ is the strain.
In order to account for turbulence, the Navier-Stokes equations are Reynolds-averaged, where the flow variables are split into mean and fluctuating components, then substituted back in to the original Navier-Stokes set. After an order of magnitude analysis reduces terms, the Reynolds-Averaged Navier-Stokes equations can account for turbulent effects by replacing the laminar viscosity, $\mu_0$, with the effective (time-averaged) viscosity:

$$\mu = \mu_0 + \mu_t$$

where:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$$

is the turbulent, or eddy viscosity. $C_\mu$ is a constant $= 0.085$ and to calculate the variables $k$ and $\epsilon$, representing the turbulent kinetic energy and dissipation, respectively, the RNG $k$-$\epsilon$ turbulence model was used. The equations for this model are shown below.

$$\rho \frac{\partial(u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \alpha_t \rho \mu \frac{\partial k}{\partial x_j} \right) + \rho \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \rho \epsilon$$

$$\rho \frac{\partial(u_j e)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \alpha_t \rho \mu \frac{\partial e}{\partial x_j} \right) + C_{\epsilon 1} \frac{\epsilon}{k} \rho \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_{\epsilon 2} \frac{\epsilon^2}{k} - R$$

where:
In the equations above, \( \nu_{mol} \) is the molecular dynamic viscosity and \( \nu_{eff} \) is the effective dynamic viscosity. \( R \) is the characteristic length \((=\sqrt{A_{in}/\pi} \) with \( A_{in} \) as the area at the inlet section), \( \rho \) is the fluid viscosity, \( u_{ij} \) are the velocity components in Cartesian coordinates, \( x,y,z \) are the coordinate axes, \( x_{ij} \) are the coordinate directions, \( \eta \) is the expansion parameter, \( C_\mu, C_{\varepsilon 1} \) and \( C_{\varepsilon 2} \) are constants equal to 0.085, 1.42 and 1.68 respectively.\textsuperscript{44}
VITA AUCTORIS

Patrick Gerald McShane was born on March 3, 1980. He was born and raised in Peoria, Illinois. He is the youngest of three children.

Dr. McShane graduated high school in 1998 from Peoria Notre Dame High School. In 2002, he obtained his Bachelor of Science degree from the University of Wisconsin-Madison, majoring in Psychology. He obtained his Doctor of Dental Medicine degree from Southern Illinois University School of Dental Medicine in 2011 and was also elected into the Omicron Kappa Upsilon dental honor society. In the same year, Dr. McShane was accepted into the orthodontic residency program at Saint Louis University, where he is currently obtaining a certificate in orthodontics and a Master of Science in Dentistry.

Dr. McShane is planning on staying in the St. Louis area where he will pursue private practice.