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Application Of Computational Fluid Dynamics To Assess The Aerodynamics Of Upper Airway In The Field Of Orthodontics – A Review

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Abstract: Diagnostic tools for upper airway includes acoustic rhinomanometry, nasal endoscopy, cephalometry, magnetic resonance imaging (MRI), cone-beam computed tomography (CBCT) and computed tomography (CT). It is pivotal to consider various craniofacial risk factors for sleep disordered breathing and upper airway obstructions in the decision-making and treatment planning in contemporary orthodontic treatment. The clinical interpretation should homogenise airway-grading and study of airflow characteristics. Computational Fluid Dynamics (CFD), is a numerical simulation method, which is commonly used by researchers to enumerate the various mechanical properties in the upper respiratory tract and thus, any obstruction in the upper airway can be interpreted and diagnosed. CFD has been recognised as a unique technique in the field of cardiovascular and respiratory medicine, in demonstrating and assessing complex physiological flow patterns using structured mathematical equations. This article discusses the various studies in orthodontics that has used CFD to analyse and annotate the upper airway characteristics and flow analysis. The aim and objective of this article is to review the various applications of CFD and how it can be used as an efficient tool to assess the aerodynamics of the upper airway in the field of airway- focussed orthodontics.

Keywords: Computational Fluid Dynamics (CFD), Airway analysis, Three dimensional analysis, SDB (Sleep Disordered Breathing), Obstructive Sleep Apnoea (OSA).

1. INTRODUCTION

Recent advancements in interpretation of variations in the growth and function of the nasal cavities, nasopharynx and oropharynx are trending at a faster pace, making the diagnosis and planning more accurate. The pedagogical approach to subsume the plethora of scientific-technological advancements calls for us to shift our paradigm from emphasis on skill acquisition to knowledge application. This change in line of thought enlightened many orthodontists to look beyond and deeper. The orthodontic profession has polarized around many issues for years: genetic vs epigenetic cause of malocclusion, extraction versus expansion, conventional versus self-ligating bracket, and hard tissue versus soft tissue versus functional paradigm. A growing mountain of scientific evidence suggests that respiratory and aberrant breathing disorders, such as chronic obstructive sleep apnoea have customarily been cognate with dentofacial aberrations.(1) Malocclusion, skeletal and soft tissue discrepancies are signs of significant issues that the brain and body are attempting to cope with. If we evaluate and address the negative changes of the jaw discrepancies, we can restore balance and eliminate deficiencies in the way our facial skeleton grow, the way our airways expand and accommodate, and allow dentition to settle in the most ideal manner.

'Airway-focused orthodontics' is a credo which focuses on the orthodontic clinical practice which aims to accomplish ideal bi-jaw relationship, oral function, proximal and occlusal teeth contact. Airway and circulation are the elixir for function of growth and development and is hierarchically considered as the most important function for humans. It is therefore fundamental to have a patent airway with coherent nasal breathing for the growth and development of craniofacial structures. Previous studies have indicated that maxillary morphologic differences exist between individuals with normal airway systems and those with airway problems.(1-3) Mouth-breathing profoundly affects the facial form and is regarded as a pre-disposing factor to the development of the long-face syndrome or adenoid facies. A correct tongue posture and nasal breathing contributes significantly to the establishing an ideal form and function of the oral cavity.(1) The initial four years of life marks the momentous stages of craniofacial development and by 12years, nearly ninety percent of craniofacial development is already attained. (4) Therefore, it can be surmised that a person is prone to OSA or SDB as early as 12 years of age in adjunct with the morphometric features that put adults at risk for this developing condition. It is hence, pivotal to address and diagnose these features at an early age to markedly reduce the developing symptoms or avert the condition in future. Research studies have failed to meet a final conclusion in an attempt to establish cause and effect relationship in-terms of airway studies related to orthodontics.(5-7)

Therefore, studying airway characteristics with appropriate diagnostic tools can aid in establishing an accurate diagnosis which, also contributes to developing contemporary treatment protocols be it preventive, interceptive, or corrective orthodontics designed to improve the upper airway.

Paradigm shift from two-dimensional (2D) to three dimensional (3D) analysis

Majority of the airway studies conducted to examine the upper respiratory tract anatomy comprised of 2D studies. Soon, the 2D analysis of a 3D structure lacked validity and the introduction of CBCT embarked with a revolution in the domain of radiographic diagnosis. The pronouncement should leverage records such as acoustic rhinomanometry, nasal endoscopy, cephalometry, magnetic resonance imaging (MRI), cone-beam computed tomography (CBCT) and computed tomography (CT). Cephalograms, also known as the true lateral radiographs of skull are recorded using cephalostats at end expiration. Several cephalometric composite analysis is used to rule out any risk factors associated with collapsibility of the upper airway dimensions.(8,9) In spite of being cost-effective, obtainable, customarily in orthodontic practice, the major drawback of cephalograms is the two dimensional portray of a three dimensional structure which is recorded in erect position. MRI is useful in volumetric analysis of airway and aids in assessing the dimensions of airway in multiple planes.

It is important to factor the craniofacial risks and the aetiology involved in upper airway collapsibility and SDB, for structuring a sequential treatment plan in contemporary orthodontic treatment. Along with the routine clinical evaluation, an orthodontist must probe into the factors responsible for affecting the airway collapsibility and consider conflating airway grading and airflow characteristics. Computational fluid dynamics (CFD), is a distinctive numerical simulation method, which is used to describe the mechanical properties of the upper airway, and is extensively used to elucidate the obstacles in the upper airway by researchers. (10)

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is a sector in aerodynamic engineering for overall analysis of fluid flow, energy transfer, and its correlated phenomena by the means of computer-based simulation.(10) CFD is a comprehensively adopted strategy for solving complex problems, engineering areas and its use is now being recognised in various branches of medical sciences involving circulation and airway analysis. CFD can be applied in various aspects of engineering and biomedical fields such as aerodynamics and hydrodynamics of vehicles, power plants including turbines, electronic and chemical engineering, external and internal environmental architectural design, marine and environmental engineering, hydrology, meteorology, and biomedical engineering.(11)

The motion of fluids, and how the fluid flow behaviour influences processes can be assessed using CFD software. Fundamental mathematical equations are used to describe the physical properties of fluid motion. These equations are usually in partial differential form and they govern the process of interest. Hence, the equations are often called the governing equations. Navier Stroke’s equation is applicable and are deciphered by using super-computer programming languages. The study of the fluid flow is reflected through numerical simulations which are derived from programs performed on high speed super computers to attain numerical solutions. (12,13)

The fundamental principle of circulation, breathing, flow characteristics of body fluids and how the system components are expected to perform can be assessed and standardised for research studies by the medical researchers. Any design alteration in the models can be executed and hence, this may provide a better conclusive oversight to develop bio-medical interventions. (12)

CFD Model Construction

Initial step of CFD simulation requires analysing the upper airway with the furtherance of a geometrical model. The geometric model will aid in analysing and describing the airway dimensions. It is generated from the scanned images based on MRI or CBCT of the upper airway. (Figure 1)

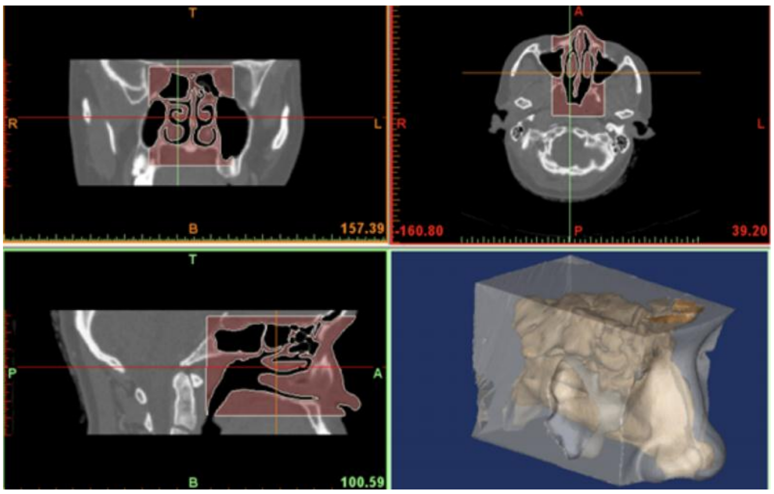

Figure 1 - CT scan images and 3D model of human nasal cavity (13)

Initially the fluid domain of interest is identified followed by segmentation process. During segmentation, the domain is further divided into smaller segments with the grids and elements; which is known as mesh generation in the fluid domain of interest. Mesh generation can be carried out via commercial software's such as ANSYS Workbench, ANSYS ICEM CFD, CFD-GEOM, Tgrid and Gridgen.(5,8,14)

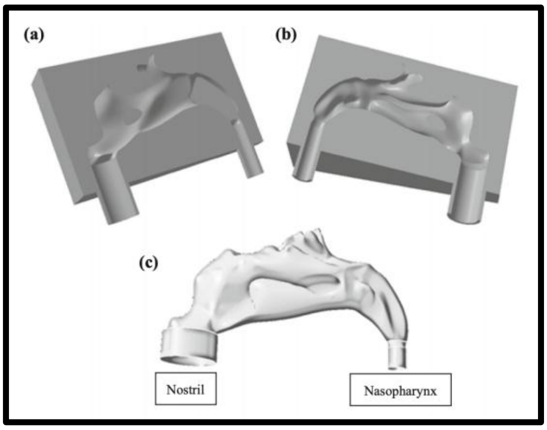

Figure 2 - Left and (b) right halves of the left nasal cavity model and (c) full nose model with its salient features (13)

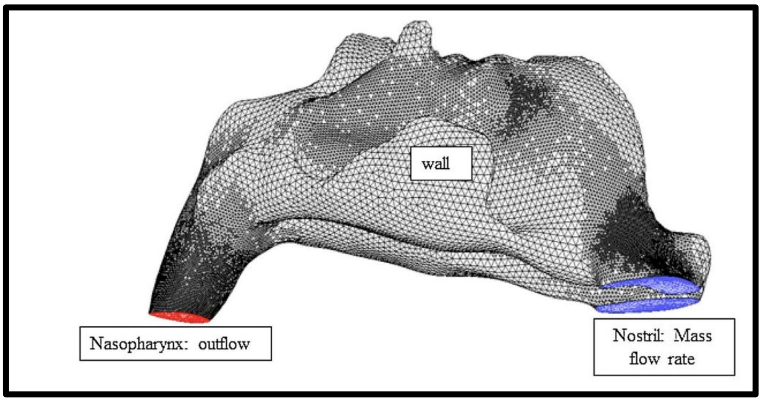

Figure 3- Volume mesh of 3D computational model of human nasal cavity (13)

According to Lee, all the details of flow-related information and overall performance assessments of CFD are classified into three main facets, namely pre-processor, solver (processor) and post-processor. The procedure of constructing CFD modelling is described as in Figure.

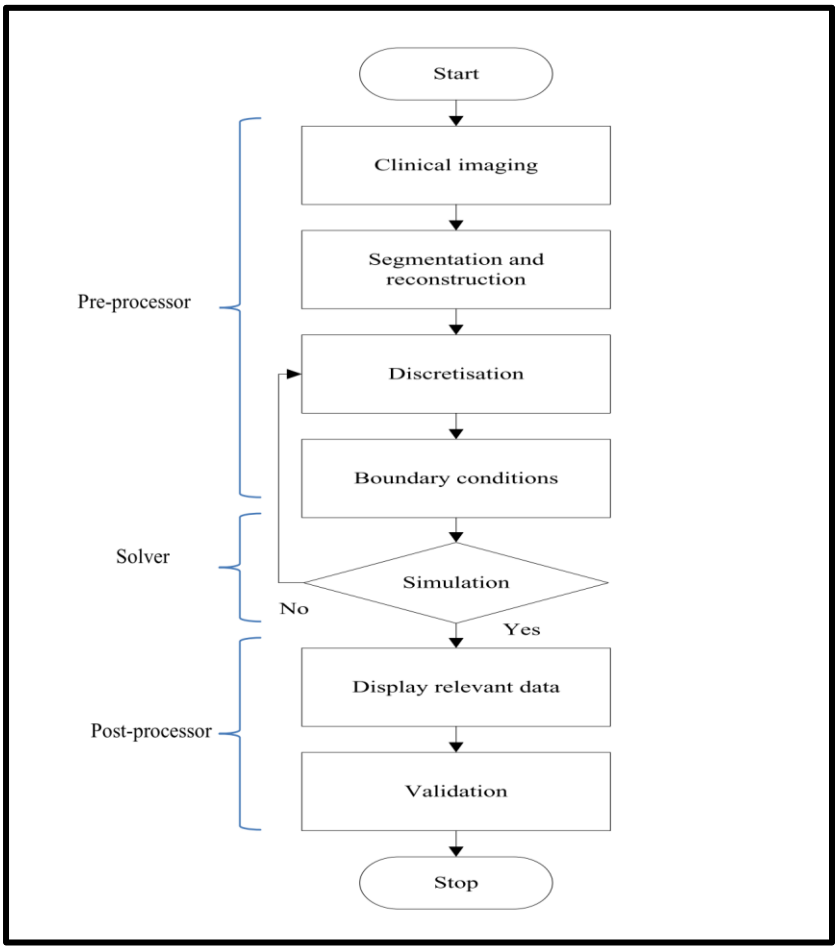

Figure 4- CFD workflow (13)

Referring to Figure 4, the pre-processor is the input of modelling element that includes problem thinking, discretisation (meshing) and generation of a computational model. The solver is the processing element, where it involves numerical solution methods by virtue of governing equations and algebraic solution. The post-processor is the output element where the computational results are visualized by achieving an acceptable convergence of the equations of state that had been solved for each cell.(11)

A Literature Review of CFD in Dentofacial Orthopaedics

Understanding pharyngeal aerodynamics for the detection of pathophysiology in obstructive sleep apnoea patients is vital for the prediction of outcome of airway changes acquired via surgical technique. CFD analysis using CT data of respiratory tract gives a deeper understanding of the airflow characteristics. One of the treatment recommendation for OSA is maxillomandibular advancement. However, only the morphological analysis was performed to evaluate the direction and distance of maxillomandibular surgical prediction. To improve preoperative prediction, the effects of airway changes with respect to the maxillomandibular movement was investigated with a one-dimensional model using fluid simulation. An analysis which was closer to the clinical condition was simulated with actual flow measurements, which served as an added advantage of CFD. A scientific basis for using accumulated preoperative measurement data was established for a determinate prediction of postoperative outcomes.(15)

In a study by Sang-Jin Sung et al, computerised simulations were used to describe aerodynamics of the upper airway. The images of OSA patient were exported from CT data in DICOM format and models were constructed. Bionix software was used to transform the image into a 3-D CFD model of the human upper airway. After model construction, it was meshed into 725,671 tetra-elements with turbulent airflow at an inspiration rate of 170, 200, and 230 ml/s per nostril. The velocity magnitude, flow distribution, and relative pressure was calculated. It was found that the medial and ventral nasal airway regions had predominant airflow velocity. The narrowest portions of the velopharynx exhibited maximum air velocity (15.41 m/s) and lowest pressure (negative 110.8 Pa). He concluded that CFD analyses of upper airway using the CT data is an effective tool in predicting the surgical outcomes for modifying the airway in patients with obstructive sleep apnoea.(16)

Yu et al simulated the flow fields of upper airways in 2 patients who were diagnosed with obstructive sleep apnoea and required maxillomandibular advancement as treatment protocol. After the geometrical reconstruction of upper airway (pre and post-surgery), from the CBCT images, consequent three-dimensional surface model was rendered for measurement and computational fluid dynamics simulation. They were able to quantitatively assess the airway which showed less constriction post surgically with less velocity change and decreased pressure gradient. This study validates the possibility of CFD in imparting an insight into the pathogenesis of OSA and its treatment effects.(17) Improvement of airflow characteristics after maxillomandibular advancement was studied by Somsak Sittitavornwong et al, where he concluded that CFD with 3-dimensional geometrical reconstruction is a predictive tool in analysing the anatomical airway changes in patients diagnosed with OSA syndrome and post-surgical results could be compared and studied.(18)

The dimensions of upper airway significantly affects the aerodynamics with both orthodontic and orthopaedic appliances significantly altering the facets of oropharyngeal regions. Xu et al is his study established that the shape of pharyngeal airway significantly affects the internal pressure distribution in children diagnosed with obstructive sleep apnoea.(19) Tomonori et al evaluated the airflow characteristics using CFD to assess the nasal airway in patients treated with rapid maxillary expansion devices for any improvement of nasal airway ventilation after the treatment. 3-dimensional volumes of nasal cavity was reconstructed using CT data and the airway pressure and velocity were simulated by using computational fluid dynamics. It was found that the post treatment, significant improvement in the airway was noted with regard to the airway pressure (80.55 Pa) which has considerably reduced and the airflow velocity which was slower when compared with the pre-treatment result. The author concluded that CFD software was successful in detecting an improvement of nasal airway ventilation by rapid maxillary expansion.(20) Ghoneima et al. performed a comparative study of pre and post treatment finite element models to assess the effect of RME on the airway flow rate and pattern using CFD. A constant volume flow rate was used for both the models to simulate the inhalation process, and the wall was set to be rigid and stationary. Laminar and turbulent analyses were applied. The positive effect of RME was believed to be the key reason for alleviating the symptom of breathing disorders in the subjects. Nasopharyngeal and oropharyngeal areas showed maximum turbulence and hence depicted relatively larger velocity and pressure compared to laminar flow.(21)

The influence of miniscrew-assisted rapid palatal expansion (MARPE) for studying the variation of airflow in the pharyngeal airway (PA) was studied by Hur et al. The upper airway models of an adult patient diagnosed with OSAS was derived from the CBCT data pre- and post-treatment. CFD with fluid-structure interaction analysis was done on these models with seven and nine cross-sectional planes (interplane distance of 10 mm) in the nasal cavity (NC) and pharynx, respectively, set along PA. Based on the finding from CFD analysis, they concluded that there was improvement in the airflow characteristics and decreased airway resistance in the PA with the use of MARPE.(22)

CFD proved to be an efficient tool to analyse airway in post-surgical patients to compare and assess the improvement in airway after maxilla-mandibular advancement (MMA) surgery. Ki Beom Kim studied computational airflow analysis after maxillomandibular advancement (MMA) surgery performed on pharyngeal airway models of OSA patients (19 samples), pre-surgery and an average of 18.3- 17.3 days post-surgery. The pharyngeal airflow characteristics was assumed to be turbulent at an inspiration rate of 340 mL/s. He concluded that a decrease in relative pressure implies less effort required for maintaining constant pharyngeal airflow according to CFD analyses on airways of OSA patients after MMA surgery.(23) Comparison of pre-surgical and post-surgical pharyngeal airflow characteristics was analysed in another study by Darshit H. Shah et al in Skeletal Class III patients who underwent mandibular setback surgery. The CBCT scans of 29 patients who had orthodontic decompensation followed by mandibular setback surgery were obtained at T1 (before surgery), T2 (6months after surgery and T3 (1year after surgery). CFD was done to simulate and characterize pharyngeal airflow from the digitized pharyngeal models. It was concluded that pharyngeal airway volume was decreased and relative mean negative was increased following mandibular setback surgery. This result conveyed that an increased effort was required from a patient for maintaining a constant pharyngeal airflow after the mandibular setback surgery. Thus, it is important to consider the envelope of discrepancy in patients undergoing large amount of mandibular setback surgery. OSA symptoms should be re-evaluated in such patients and the treatment plan should be amended accordingly.(24)

Retrognathic Class II malocclusions in untreated children have reduced upper airway dimensions. A fixed functional appliance was associated with a significant increase in upper airway volume and MCA in children when compared with controls.(25) The effect of fixed functional appliance, such as Herbst also contributed to improved ventilation of oropharyngeal and hypopharyngeal airway. Iwasaki et al studied the pressure and velocity of upper airway using CFD in 21 patients with Class II malocclusion and confirmed that CFD was a useful tool is structuring and planning OSA treatment in growing children. (26)

Iwasaki et al used CFD to analyse the upper respiratory airflow in children with unilateral cleft lip and palate (UCLP). After evaluating the upper airway ventilation condition, they found that the UCLP group had a significantly higher nasal resistance, maximal upper airway pressure and pharyngeal airway pressure in comparison with the conrol group. They concluded that nasal and pharyngeal effects in the airway significantly contributed to upper airway obstruction in children with UCLP.(2)

Merits and Limitations of Biomedical Applications in CFD

There are many merits when considering CFD. Apart from valuating the characteristic of airflow in nasal breathing, it may also be explored in different aspects of biomedical science such as to analyse the post-surgical outcomes, facilitate in carrying out precision surgery, high efficacy and benign medical equipment which can denote better understanding of anatomical and physiological aspect of the human biology. (31)(32) CFD has the capacity to simulate flow conditions that are not reproducible during experimental tests found in geophysical and biological fluid dynamics, such as scenarios that are too huge, too remote, or too small to be simulated experimentally. (26) The main reason why CFD has lagged behind in the medical field is probably due to the sophistication of human anatomy and behaviour of body fluid within the circulatory system. (10)

CFD is limited to describe physical models and quality of input data of real-world processes in order to determine the accurate CFD solutions such as turbulence, multiphase flow, and compressibility. Thus, numerical results must be thoroughly analysed and examined in order to properly make critical judgements about the computed results. The mechanical engineer and the medical professional should work in-joint effort to generate an effective outcome. An interdisciplinary approach should be designated which should generate input on results obtained at every step of the whole process.

2. CONCLUSION

As we piece together airway and health, the orthodontic and dentofacial profession must begin to sanctify itself in identifying and integrating sleep disorders due to airway conditions. The coadunation of advanced image processing and geometrical modelling technique with computational fluid dynamics enhances the generation of detailed airway dynamic parameter assessment in patient specific geometries.

Majority of the healthcare practitioners are unequipped to the hi-tech, computational and simulation technique of generating patient specific models. There is an understandable scepticism to take advantage of the concept by the practitioner, probably because of the lack of a general validation protocol. Furthermore, the generation and construction of patient-specific models is a chronophagous process that relies on specific biological geometries, properties of material, and boundary conditions. Although, these demonstrate formidable requisitions, they provide significant opportunity to refine the clinical outcomes by edging in precision medicine into clinical practice. The effectiveness of simulation results must be further demonstrated, particularly in multi-centre clinical studies.

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