

Biomechanical Evaluation of Pre- and Post-bilateral Sagittal Split Mandibular Osteotomy on Three-Dimensional Models for Obstructive Sleep Apnea Using Finite Element Analysis

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Abstract Obstructive sleep apnea syndrome (OSA) is the hindrance of upper airway during sleep, associated with curtailment in blood oxygen saturation. It is characterized by subdual flow of oxygen to vital organs causing irregular heart rhythms. One of the triumphant surgeries to treat OSA is maxillo-mandibular advancement (MMA) which is found to be 90% successful for OSA patients (Phee 2015). In MMA, the lower jaw and the mid-face are progressed to augment the posterior airway space facilitating trouble-free breathing. In this research, we attempted to contemplate the von Mises stresses due to mastication in normal and osteotomed 3D models and identify the maximum stress that can be tolerated by the mandible using finite element analysis (FEA). FEA has been extensively used to solve complex problems in dentistry and researchers have found a high correlation between FEA simulation results and in vitro measurements for mandibular specimens (Erkmen et al. 2005). The location of screws and miniplate fixation in the 3D osteotomed models was determined by Champy's lines in order to ensure stable fixation (Erkmen et al. 2005). We first evaluated the extent of movement of the posterior airway space that is mandatory for the OSA patients to breathe normally. It was evident that the airway constriction was corrected in the upper respiratory tract by the advancement of the mandible. The von Mises stress and displacement in the mandible before and after MMA by applying three different loads, incisal, contralateral compressive molar loads, and one-sided molar loads were analyzed to rule out the fixation and orthognathic issues. The stress distributions during mastication were furthermore compared for mandibular osteotomy models with two distinct lengths of advancement. In addition, the deflection by virtue of mastication on molars, incisors, and canines was also assessed. In line with the above-mentioned evaluation, we performed the computational fluid dynamics

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(CFD) analysis of the upper airway model with the pre- and post-surgical conditions to predict the airflow dynamics accordingly.

State of the Art

Obstructive sleep apnea (OSA) is the most prevalent type of sleep apnea, caused by partial or complete blockage of upper respiratory tract during sleep. It is indicated by continual episodes of shallow or paused breathing during sleep and is usually associated with the reduction in blood oxygen saturation.

According to the statistical study by International Society of Aesthetic Plastic Surgery (ISAPS) of 2015, for around 0.4 million face and head procedures are performed globally. There are several surgical treatments to modify airway anatomy that, known as sleep surgery, are varied and must be tailored to the specific airway obstruction needs of a patient. For those obstructive sleep apnea sufferers unable or unwilling to comply with front line treatment, a properly selected surgical intervention will be the result of considering an individual's specific anatomy and physiology, personal preference and disease severity (Sato et al. 2012). There is little randomized clinical trial evidence for all types of sleep surgery. One of the triumphant surgeries to treat OSA is maxillo-mandibular advancement (MMA), a type of orthognathic surgery which is found to be 90% successful for OSA patients (Phee 2015). Further this surgery offers an equally efficacious alternative in mild to moderate OSA patients who are not compliant or refuse CPAP therapy. The lower jaw and the mid-face are progressed in MMA to augment the posterior airway space and facilitate trouble-free breathing. The most common orthognathic surgical procedure is bilateral sagittal split osteotomy (BSSO).

Trauner and Obwegeser in 1957 gave the first description of this orthognathic technique Takahashi et al. (2010). Since then, Dal Pont introduced many modifications with the aim of improving surgical convenience, minimizing morbidity, and maximizing procedural stability, which is generally recognized that the buccal osteotomy cut of the Obwegeser–Dal Pont method is positioned more anteriorly than that of the Obwegeser method (Takahashi et al. 2010), thus increasing the cancellous bone contact.

The proximal and distal segments after the procedure of BSSO can be stabilized by rigid internal fixation for speedy bone healing triggering promptly postoperative mandibular function, and decreasing the amount of relapse (Takahashi et al. 2010). For an ideal stable osteotomy design, there are certain primary factors affecting the stability. Not only the miniplate orientation and shape and the location of the osteotomy cut, but also the location of the miniplates (superior, middle, or inferior) was considered to be the main parameter by using finite element analysis (FEA) (Champy et al. 1978). Champy et al. (1978) ascertained “the ideal line of osteosynthesis in the mandible” where miniplate fixation is the most stable.

The complex problems in dentistry can be solved using FEA. Vollmer et al. (2000) have found quite a high correlation between FEA simulation and in vitro

measurements of mandibular specimens. FEA is thus an efficacious research tool which can endow clear-cut insight into the mandible's complex mechanical behavior, which is quite hard to assess by other means.

In this research, we attempt to compute the biomechanical behavior of the mandible and screw-miniplate system. We applied incisal and contralateral molar compressive loads to contemplate the deflection as well as the maximum von Mises stresses in the mandible before and after the surgery. Two models with distinct levels of advancement in the MMA were done and the same was compared and analyzed.

Materials and Methods

Modeling of the Mandible

The aim of modeling is to simulate the original scenario of BSSO. We have two different types of models; one is the normal mandible and the other is the osteotomized model of the mandible with fixation of screws and miniplates.

(i) *Volume rendering of the mandible:*

A stack of 2D computed tomography (CT) images with each image having 1 mm thickness were processed to render a 3D mandibular model.

(ii) *Levels of progression in the BSSO models:*

The various levels of advancement, viz., 5 and 7 mm in BSSO for the treatment of obstructive sleep apnea patients were modeled to evaluate the biomechanical behavior of the mandible post-surgery.

(iii) *Screws and miniplates modeling:*

Monocortical screws and miniplates are placed during osteotomy to withstand the loads exerted in the bone after surgery. As aforementioned, two pairs of monocortical plates are placed in the osteotomized model where six-screw-miniplates and two-screw-miniplates on each side of the mandible. The miniplates are approximately 40 mm in length and 1 mm in thickness. The screw with head dimensions of 2.5 mm width and 1 mm height, and its body dimensions of 2 mm width and 5 mm height was modeled. As per AO Foundation (www2.aofoundation.org), if the height of the screw goes beyond 6 mm, it might affect the tooth's roots. So the height of the screw is maintained at an optimum range (Fig. 1).

(iv) *Considerations for fixation of the implant:*

The oblique line is the line which passes just below the mental foramen. We looked upon this oblique line as reference for the osteotomy cut and constructed the mandibular advancement in the model. Fixing the screws and miniplates in the mandible should come hand-in-hand with experience of the surgeon as the

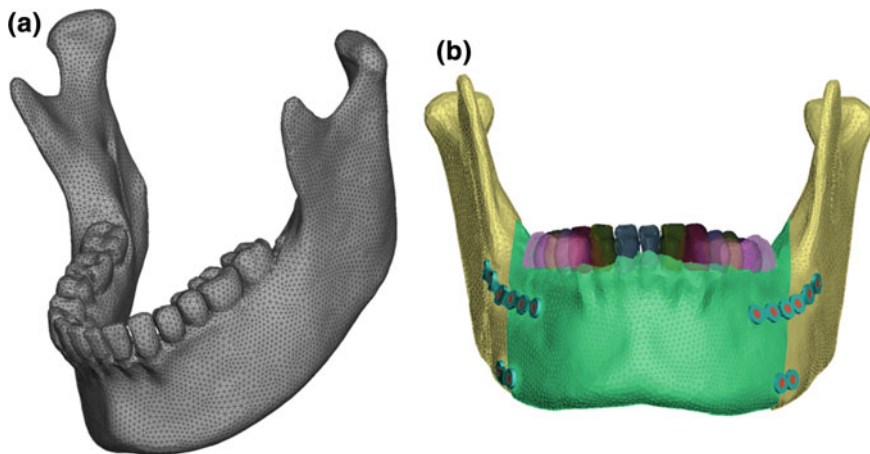


Fig. 1 a Normal mandible. b Osteotomized mandible

placement of the implant should not affect the roots of tooth, nerve, blood vessels, etc. We also have taken into account the ideal line of osteosynthesis, Champy's line before fixation of the implant on the osteotomized mandible (Champy et al. 1978).

(v) *Contouring of miniplates:*

Contouring is the process of twisting the miniplates with the help of two pliers at both ends to ensure matching of the underneath bone surface. Surgeons usually contour the miniplate according to the surface anatomy which is adjacent to the fraction line for a perfect and stable fixation. This ensures adaptation of the plate with the surface from one end to the other end. The intermediate bone surface which does not get along with the miniplate surface is excised during the surgery that is also followed during our modeling of the implant. We performed contouring through our in silico pre-processing methods.

Upper Airway path Modeling

The 3D model of upper pharyngeal airway is obtained from the same BSSO case. The airway region is segmented using threshold function with Simpleware Scan IP software. The model is meshed with approximately 0.7 million polyhedral volume elements. The fluid volume model is meshed with three boundary layers. Airway path extracted in this study extends from nostrils till the trachea and the thyroid gland. Two different airway paths were considered in this study: the pre-surgical airway path and the extended path. The extension is performed at the constriction from the oropharynx to laryngopharynx synching with the mandibular advancement (Fig. 2).

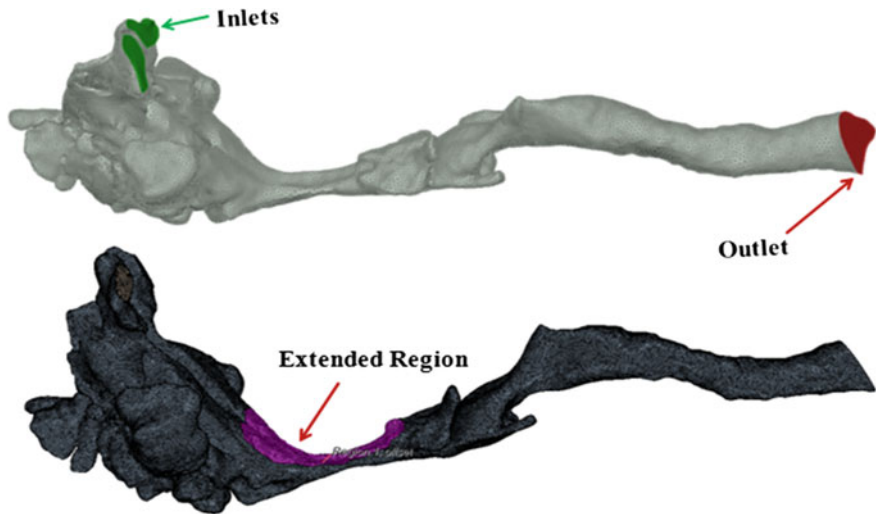


Fig. 2 Upper airway path

Materials used for the Modeling

(i) Software tools utilized for modeling and analysis:

The segmentation process of the region of interest (mandible) of DICOM images from CT scan was performed using Simpleware, ScanIP 7.0. The processed 3D image was exported in the stereolithography (STL) format. The rendered STL files of the mandible were imported into a finite element pre-processing tool for discretization for finite element meshing. The resulting model consisted of 0.4–0.5 million tetra elements in the model. The simulations and analysis were executed using Abaqus Implicit solver.

Boundary Conditions—BSSO

(i) Constraints:

The temporo-mandibular joint (TMJ) is bilaterally constrained in all degrees of freedom. The goal of constraining TMJ is to simulate the masticatory movement of the mandible only.

(ii) Material properties:

The material used for different types of teeth in the pre-surgical model is the dentin which is of more composition mimicking the teeth properties. We considered the properties of titanium for the screws and miniplates that are in the post-

Table 1 Material properties of various materials used

Material	Young’s modulus (MPa)	Poisson ratio	Density (ton/mm ³)
Tooth (dentin)	1400	0.32	2.65e ^{−9}
Mandible (cortical bone)	9000	0.3	1.98e ^{−9}
Implant (titanium)	115,000	0.33	4.43e ^{−9}

Table 2 Loads applied to incisors (Biswas et al. 2013)

Tooth	Incisal loads (N)	
	Right side	Left side
Central incisor	200	
Lateral incisor		
Canine		

Table 3 Loads applied to molars (Biswas et al. 2013)

Tooth	Contralateral molar loads (N)	
	Right and left side	One-sided
First premolar	300	
Second premolar		
First molar		
Second molar		

surgical model. The properties of various materials, viz., Young’s modulus, Poisson ratio, and density are given (Table 1):

(iii) *Applied masticatory loads:*

The three different types of loads, i.e., incisal, contralateral molar loads, and one-sided contralateral molar loads are applied according to the anatomy of the tooth. Loads are applied perpendicular to the occlusal plane. The human mastication is a complex biomechanical process. During mastication, it is obvious that persons masticate harder substances with higher pressure and strength using the molars when compared to incisors (Tables 2 and 3).

Boundary Conditions—Airflow Dynamics

Airflow inside the human nasal cavity at rest and at dynamic state is taken under consideration. During normal breathing 15 l/min of air is inhaled; in this study the upper pharyngeal airway is simulated in normal breathing condition. The flow is kept steady throughout the simulation and air is modeled with K-epsilon turbulence model. Airflow inlet was modeled with mass flow rate inlet, outlet to be pressure outlet, and the wall to be with no-slip boundary condition (Table 4).

Table 4 Boundary conditions

Descriptions	Quantity	Air properties	
Space	Three dimensional		
Time	Steady state	Density	1.225 kg/m ³
Material	Air		
Flow	Segregated flow, constant density	Dynamic viscosity	1.85508E−5 Pa s
Model	Realizable K-epsilon turbulence		
Boundary conditions			
Inlet		Mass flow rate	
Outlet		Pressure outlet	
Wall		No-slip	

Results

To obtain the responses of mastication in mandible before and after the BSSO, we have analyzed the subject based on three main types of loading according to the tooth morphology. Molars are meant to bear heavy loading where as incisors are sharp ones used to cut and tear food and canines are at corners to cut food and position food in equilibrium. We also analyzed the airflow patterns in the upper pharyngeal airway at pre- and post-surgical conditions.

Baseline Model

There are three models which can be classified according to the loading condition (see Fig. 3). The mandible in the pre-surgical level is considered as the baseline model to compare with. Tooth displacements were interpreted in the vertical direction in accordance with loading direction.

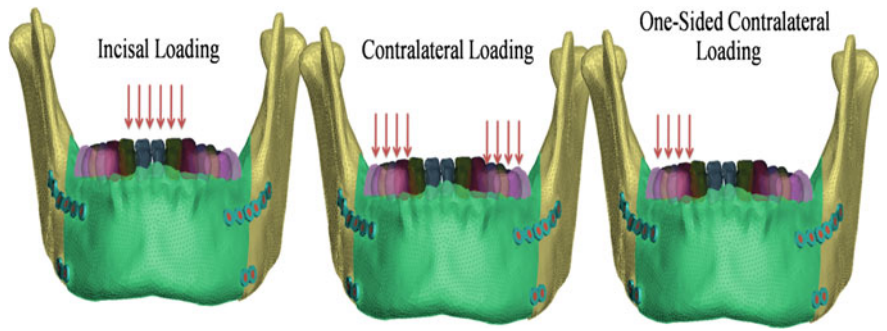


Fig. 3 Types of masticatory loads applied

5 mm BSSO Model

There are several factors that will determine the optimal modification for BSSO surgery like the position of the third molar, position if the mandibular foramen, and the alveolar nerve locations. We have modeled the BSSO model with all these surgical considerations as mentioned. The 5 mm advancement is one of the levels of mandibular advancements done in this study.

7 mm BSSO Model

The 7 mm advancement is the second level of advancement which is done in this study. We modeled perfect adaptation on the contacting surfaces with a viewpoint of high mechanical stability due to the complex biomechanical behavior of mandible and implant system.

Displacements Due to Loading, Maximum Bone Stress, Maximum Monocortical Miniplate Stress

Comparison of all the three loading conditions in the following baseline, 5 and 7 mm model is done in Figs. 3, 4 and 5 mentioned above. On comparing the three loading conditions maximum vertical deflection were found in the contralateral loading and one-sided contralateral loading with values nearly 1.9–2 mm, whereas incisal loading showed deflection of 1.7 mm (see Fig. 7). Miniplates and screws

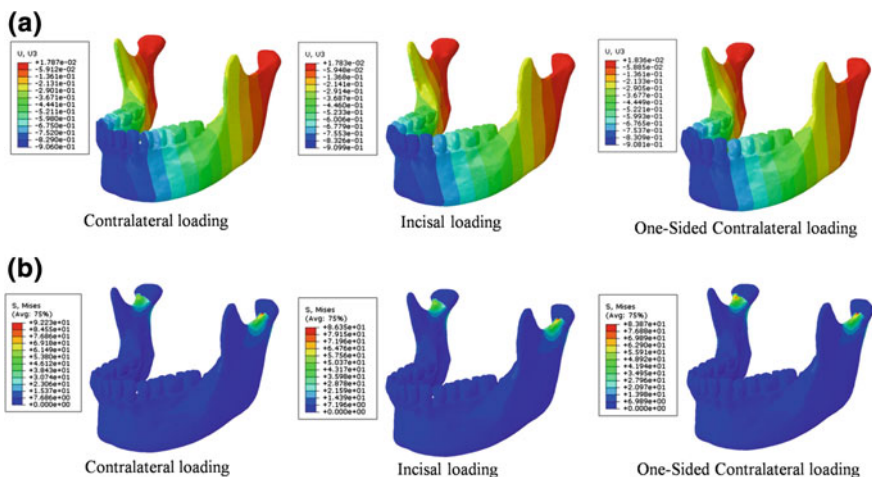


Fig. 4 a Vertical displacement and b bone stress (Von Mises stress)

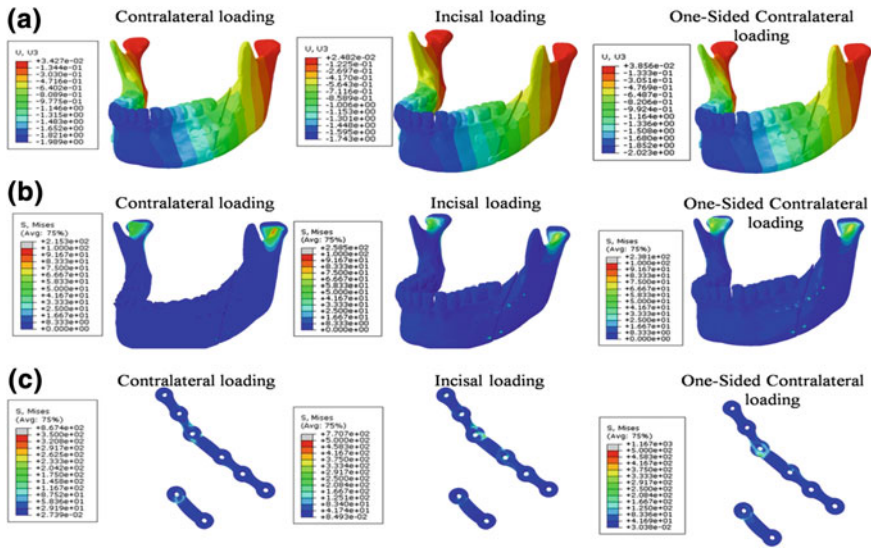


Fig. 5 **a** Vertical displacement, **b** stress at bone (Von Mises stress) and **c** stress at miniplates

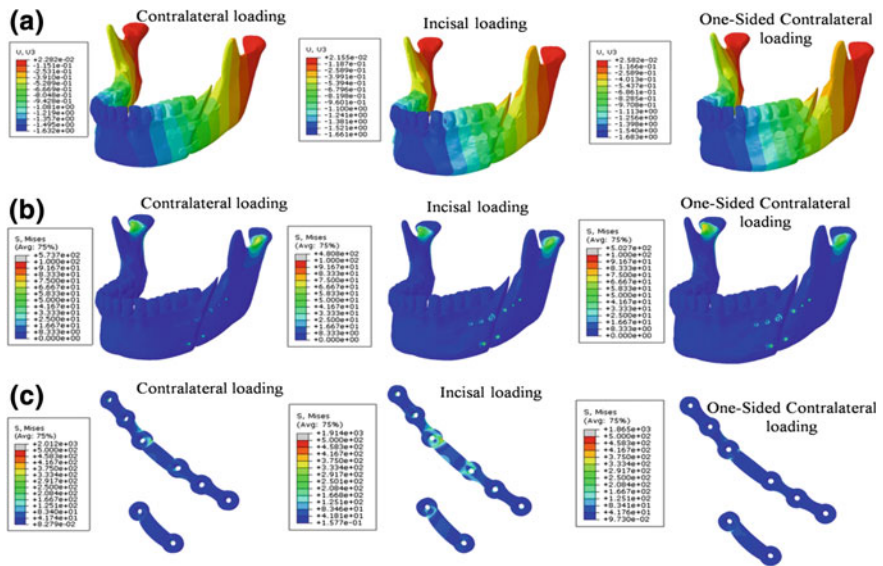


Fig. 6 **a** Vertical displacement, **b** stress at bone (Von Mises stress) and **c** stress at miniplates

were inferred with increase in stress with respect to increase in the level of advancement in BSSO (see Fig. 8). We can observe in Fig. 8 that maximum stress in miniplate is lower than material yield strength (895 MPa) and thus the implant had good strength to withstand the applied masticatory load (Fig. 6).

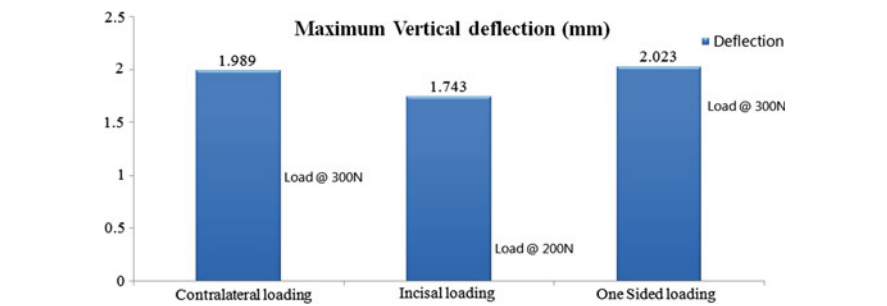


Fig. 7 Maximum vertical deflection

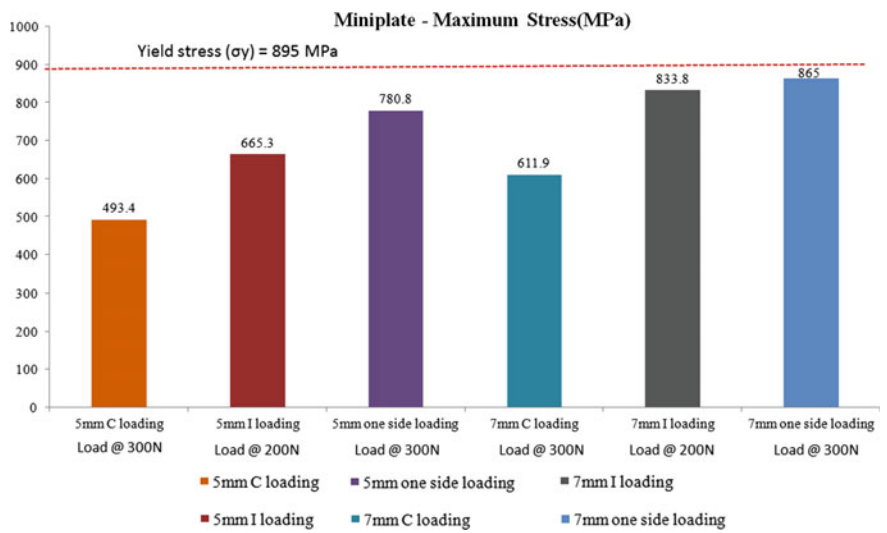


Fig. 8 Maximum miniplate stress

Airflow Dynamics in the Upper Airway Path

Considering the two different upper pharyngeal airway models, we can predict the pre- and post-operative airflow dynamics during inhalation. The extended airway model mimics the post-surgical airway path as the oropharyngeal region is expanded by considering the mandibular advancement. The velocity of airflow during inhalation increased in the areas of constriction in the upper airway volume near oropharynx. There were few areas of recirculation near the palatine tonsils and the laryngopharynx. Velocity reduces with the level of extension and increase of the cross-sectional area of the constriction. Pressure increased at the extended regions and few pressure drop areas occurred due to recirculation zones (Figs. 9 and 10).

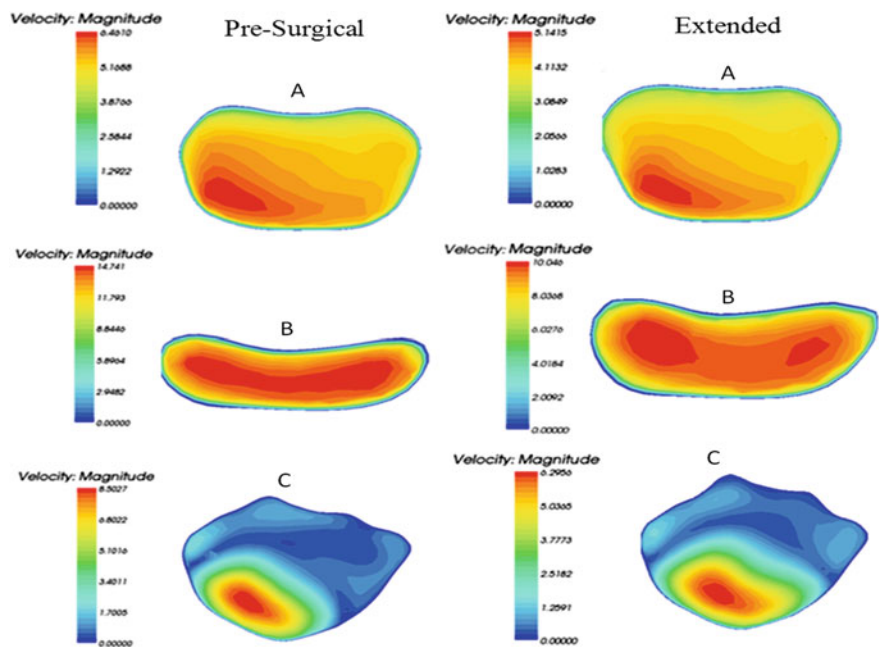


Fig. 9 Velocity contours on cross-sections

Discussion

The assessment of airway and its airflow dynamics is important to predict sleep disorders. Nowadays doctors and surgeons predict the breathing disorders only from the morphology of the airway path taken from the MRI sleep study or CT scan. The literature states that sleep disorders due to breathing are affected by factors like dental structures, bone structures, tongue volume, nasal morphology, and the airway volume. There is always lack of information on the flow patterns of air inside the upper airway path. The obstructive sleep apnea patients need refractive surgical management on jaw bone to improve the volume of air flowing into lower airway and its gas exchange.

Surgeons mostly perform cephalometric plan to enable orthodontic and maxillofacial surgical treatment’s planning. But interestingly patients with normal cephalometric measurements sometimes had abnormal breathing rates and sleep disorders. Also it is clearly established that abnormal cephalometric measurements post-surgery are quite striking than the original pre-surgical cephalometric measurements.

The BSSO technique performed in our study is the most common orthognathic procedure for OSA patients. For modeling the BSSO surgery there are several factors that are maintained to attain significant placements of miniplates and screws. Basically osteotomy is decided according to the morphology of the bone and

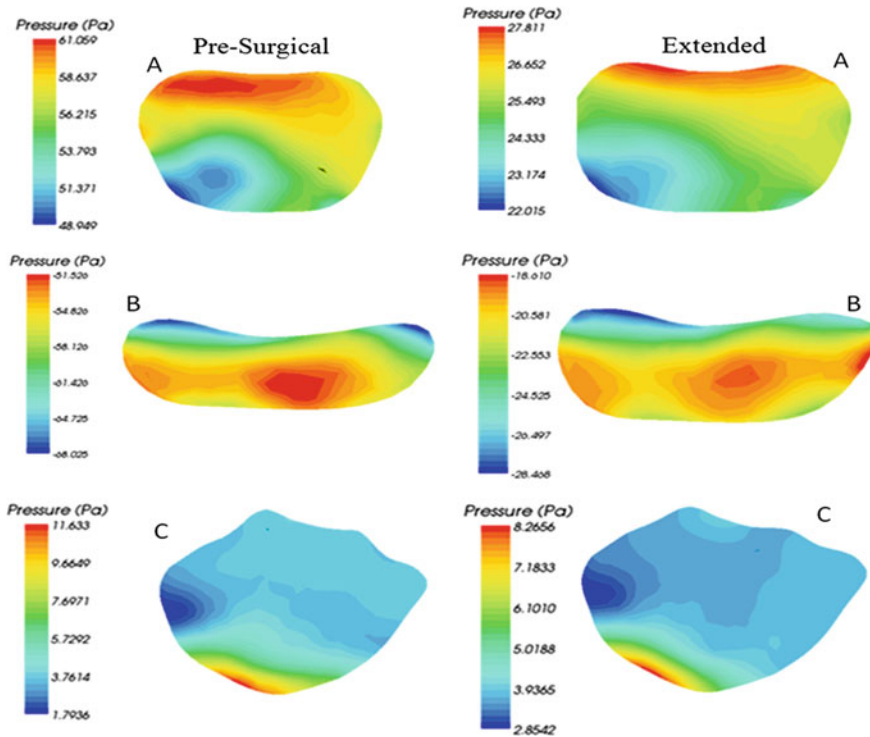


Fig. 10 Pressure contours on cross-sections

the need. In order to have better stability and reduced trauma surgeons has to focus on the location of the fixation system. We followed the Champy's lines which are the ideal line of osteosynthesis, performed to introduce stable fixation without risks due to screws and miniplates. Another advantage of Champy's lines is that we can find the exact area of placement without damaging the roots of the teeth. Volmer et al. have proved high correlation (>0.992) between FEA simulation and in vitro specimens under surgery.

We have shown the maximum vertical displacement in justice to the masticatory tooth loads. The idea of our study is to analyze a few major factors such as the exact fixation for the osteotomy, the level of masticatory loads which the implant system and the bone can withstand with less deformation and CFD of airflow patterns after the FEA in silico surgical setup. The expected result is said to have high stability in fixation as the displacement is less (<2.2 mm) when compared to literature and adding the fact that the implant system did not fail (see Fig. 8). A successful BSSO surgery for OSA patients is determined by the level of patency for airflow in airway after the surgery. In order to analyze the flow streamlines and the nature of flow after our virtual surgery for which we performed CFD of the upper airway region. The BSSO surgery helped to understand the airway patterns and the key areas of

risk in which airway path gets constricted. When volume of airway path increases the level of breathing patency increases, thus leading to better sleep for OSA patients.

The most constricted areas of airway passages in the upper airway anatomy were the nasal cavity, nasopharynx, oropharynx, and hypopharynx. The model is extended in the areas of airflow challenges. We found that turbulence occurred at the nasal and oropharyngeal areas formed recirculation zones; as a result there was an increase in turbulent kinetic energy, velocity, and pressure at the constricted zone. At a flow rate of 15 l/min as given in this study is to understand the normal adult breathing patterns during rest. Due to the increase in the cross-sectional area in the plane C when compared to plane B the pressure drop is reduced and controlled to be equipoise between plane B and C. The plane B which is near the oropharyngeal region was found to be with higher (≈ 4.25 Pa) WSS due to largest frictional loss in flow. But this WSS is reduced for extended model (≈ 2.8 Pa). Therefore, we can agree to the fact that the increase in the advancement in BSSO can decrease the workload of breathing for OSA patients.

Conclusion

The stress and deflection at the implant–bone interface and the airflow dynamics before and after BSSO surgery was analyzed computationally. The actual surgical scenario was depicted and the implants were placed on the mandibular bone. The virtual BSSO surgery was performed in accordance with the standard surgical methods followed by maxillofacial surgeons. Masticatory loads were considered for assessing better fit and durability of the implant system. In addition to this, the airflow dynamics inside the upper pharyngeal airway volume was evaluated before and after mandibular advancement. Inhalation of air in the extended airway was found to have reasonable ranges of pressure, velocity, and wall shear stress as per the surgeon's expectation and better airflow results were inferred. Thus we suggest, virtual planning of BSSO paves way for prediction of possible airway patency that can be found at the pre-surgical level.

Acknowledgements We would like to thank for support and clinical guidance given to us. Dr. Manikandan BDS, MDS, FDSRCS, FFDRCSI, FTPRM Oral And MaxilloFacial Surgeon, Implantologist, Dentist, Meenakshi Ammal Dental College and Hospital.

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Computer Methods in Biomechanics and Biomedical
Engineering

Proceedings of the 14th International Symposium

CMBBE, Tel Aviv, Israel, 2016

Gefen, A.; Weihs, D. (Eds.)

2018, VIII, 263 p. 135 illus., 113 illus. in color.,

Hardcover

ISBN: 978-3-319-59763-8