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Effects of maxillary skeletal expansion on upper airway airflow: a computational fluid dynamics analysis

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Introduction:

Upper airway obstructions that affect the breathing pattern can affect the width, length, and height of the maxillomandibular complex with a subsequent impact on the nasal cavity, retropalatal and retroglossal upper airway space¹⁻³. Craniofacial alterations of a narrowed maxilla, altered tongue position, and narrowed dentition in upper airway obstruction patients have been reported in numerous studies⁴⁻⁸. Besides, concomitant changes in the lower jaw and tongue may happen as an altered mandibular posture and counterclockwise rotation.

Rapid maxillary expansion (RME) is an orthopedic procedure that is routinely used by orthodontists to treat maxillary transverse discrepancies. The use of RME was first suggested as a therapy for treatment of adult obstructive sleep apnea or OSA⁽⁹⁾. It has been reported that RME separates the external walls of the nasal cavity laterally and causes lowering of the palatal vault and straightening of the nasal septum. This in turn increases the nasal volume, decreases nasal resistance, increases nasal airflow, and improves nasal breathing¹⁰.

Recently, Miniscrew assisted rapid palatal expansion (MARPE) provided a new alternative treatment modality for adolescent patients with maxillary transverse deficiency because of increased skeletal effects and decreased dental side effects compared with conventional RME¹¹⁻¹³. The treatment with MARPE appliance is thought to be helpful for relieving the symptoms of OSA in adult patients^{14,15}. In a randomized controlled trial it has proved that tooth-bone-borne (TBB) RME induced significantly higher nasal airway flow values and lower nasal resistance values than tooth-borne (TB) RME in a population from age 8–13 years¹⁶.

Computational fluid dynamics (CFD) is a non-invasive, convenient and reliable tool for simulating the internal flow dynamics of the upper airway. Numerical simulation has become an affordable research tool to study airflow in the human airway.

MSE is an effective method for the correction of maxillary transverse deficiency without surgery in adolescent patients¹⁷. The purpose of this study was to determine the effects of MSE on the upper airway of an adolescent patient using CFD analysis.

Materials and Methods

Segmentation of CT image data and 3D model reconstruction

The study was approved by the Ethics Committee of the School of Stomatology, Wuhan University. Pre- and post-treatment upper airway finite element models were constructed for a 13-year-old female with 6mm of transverse maxillary discrepancy measured using the method of Betts et al.¹⁸. This patient, cervical stage IV-V, had convex profile and high mandibular plane angle with severe crowding. She reported that she was used to mouth breathing with incompetent lips. She had no history of previous orthodontic or orthopedic treatment; systemic diseases, craniofacial anomalies, or temporomandibular joint disorders. This patient was treated with a MSE appliance as part of her comprehensive orthodontic treatment plan. Patient was instructed to turn the jackscrew 3 times a day (0.133mm per time) for 16 days resulting in almost 6 mm of maxillary midline diastema (Figure 1). Cone beam computed tomography (CBCT) images were taken before treatment and six months after the last activation of the appliance using the cephalostat (Soredex, Tuusula, Finland) according to a standard protocol (73kV, 10mA) using the following parameters: Width, 512 px; Height, 512 px; Pixel Size, 0.3 mm; Slice thickness 0.3mm; exposure conditions, 5 mA and 110 kVp for 10 seconds. Digital imaging and communications in medicine (DICOM) data obtained before (T0) and after treatment (T1) were exported to Mimics (MIMICS 16.0, Materialise, Belgium) to construct the surface model (STL file). Then, 3D computational models of airway, including nasal cavity and the pharynx, were constructed using a reverse modeling software (Geomagic Studio 12.0, Geomagic, Rock Hill, NC, USA). Two meshes with 4,689,761 cells at T0 and 4,532,389 cells at T1 were generated with tetrahedron elements in order to spatially discretize fluid domain. (ICEM CFD 12.0, ANSYS, Canonsburg, PA, USA).

Boundary conditions

Figure 2 shows the three-dimensional model of the upper airway at T0, T1 and superimposition. Each airway model was marked with 13 cross-sectional planes: six planes in the NC area, with an interplane distance of 10 mm from the aperture of the nostril to the beginning of the pharynx; and seven planes in the pharynx area, with an interplane distance of 10 mm from the beginning of the pharynx to the beginning of the larynx. A pressure outlet boundary condition with atmospheric pressure was defined on the nostrils, which was close to the Y-6 plane in Figure 2(C).

A velocity inlet boundary condition was defined on the lowest horizontal cutting plane of the larynx, which is close to Z-7 as shown in Figure 2(C). The periodic change of exhalation and inhalation was described by an unsteady air velocity or air flow rate. A time-dependent profile of breathing flow rate during one full breathing cycle used in our previous work was implemented in the present simulation as described in Figure 3.^{19,20} The profile is piecewise linear, and the exhalation duration (3 s) is longer than the inhalation duration (1.8 s). Consequently, the average respiratory rate is 12-13 breaths per minute. The peak exhalation flow rate is 30.54 L/min, and the peak inhalation flow rate is -27.49 L/min.

In the airflow simulation process, the flow was assumed to be incompressible. The governing differential equations, the Reynolds-averaged Navier–Stokes equation for turbulence with the $k - \varepsilon$ model, and constitutive equations for structure dynamics are shown in Table 1. Constant air density (1.185 kg/m³) and viscosity (1.831×10^{-5} kg/m·s) values were assumed. No-slip wall boundary conditions were imposed on the airway walls. The cross-sectional airway area at each plane was assessed at T0 and T1. In addition, airflow pressure and velocity, were measured at maximum inspiration (MI) and maximum expiration (ME). Changes in the total resistance of airflow were calculated on the basis of changes in each variable from T0 to T1.

Results

Comparison of cross-sectional airway area

Table 2 shows the comparison of cross-sectional airway area before and after MARPE on a teenager patient. In nasal cavity, each plane showed an increase of cross-sectional area, ranged from 1.35 mm² to 48.25 mm², 0.44% to 16.77%. Plane Y-2 to Y-6 showed a gradual growth of increase, plane Y-1 showed a strong increase. In the pharynx, changes in cross-sectional area appeared more significantly, plane Z-2 to plane Z-7 showed increase ranged from 90.83 mm² to 217.99 mm², 17.08% to 40.66%. The middle part of pharynx showed a strong increase, plane Z-4 and plane Z-5 showed increase of 212.81 mm² and 217.99 mm², 36.58% and 40.66%. The average increase of area is 7.42% in nasal cavity and 22.04% pharynx. These results implied that MARPE on teenagers primarily affected the anterior parts of NC, the nasopharynx (planes Y-5 and Y-6) and the middle part of the oropharynx (planes Z-4 and Z-5). The degree of increase in the cross-sectional airway area was higher for the pharynx than for NC, disregarding that the pharynx was located farther than NC from the MARPE appliance.

Comparison of airflow pressure and velocity

Table 3 shows the comparison of airflow pressure before and after MARPE on a teenager patient. It can be observed that at planes Y1 to Y6 in NC and planes Z1 to Z7 in the pharynx, the absolute values for airflow pressure were lower after MARPE than before MARPE.

During both inspiration and expiration, airflow pressure decreased in both NC and pharynx, the value of decrease in pharynx showed more stability, which ranged from -11.34% to -12.87% and from -16.87% to -17.25%, than that in NC, which ranged from -13.12% to -20.16% and from -18.28% to -23.68%.

Figure 4 shows the comparison of pressure distribution before and after MARPE. At ME and MI, the pharynx shows a strong decrease of pressure at T1 than that at T0.

Table 4 shows the comparison of airflow velocity before and after MARPE on the teenager patient. In NC, airflow velocity decreased after MARPE, the value of decrease ranged from -0.07 m/s to -0.46 m/s at ME, from -0.12 m/s to -0.31 m/s at MI, the average velocity decrease is -0.18 m/s at ME and -0.13 m/s at MI. In pharynx, the velocity shows a slight decrease, both of the averages at ME and MI are -0.07 m/s.

Figure 5 shows the comparison of velocity distribution before and after MARPE. In NC and pharynx, the velocity shows no significant variance both at ME and MI.

Discussion

Maxillary constriction is very common in patients exhibiting malocclusion. Previous research has indicated that transverse maxillary constriction happened in approximately 18% mixed-dentition patients.²¹ Maxillary transverse deficiency may cause functional interferences, and removing maxillary constriction may lead to spontaneous Class II improvement²².

RME is widely used by orthodontists to treat maxillary transverse discrepancies and is sometimes associated with improvement in the breathing patterns in patients with airway disorders. Literatures have reported the impact of RME on dental and skeletal structures, tongue posture, nasal morphology, and airway volume^{23,24}. Published studies describe the variable effects of maxillary expansion in treating children with narrow palates and/or retrognathic mandibles²⁵⁻³⁰, as well as the OSA by reducing their nasal airway resistance^{31,32}. And positive effects in terms of reduction of pressure, velocity, and resistance of airway help us understand the key mechanisms behind relieving the symptom of breathing disorders as a result of treatment with RME³³. The maxillary bones form approximately 50 percent of the nasal cavity's anatomic structure. Therefore, treatment modalities that alter the morphology of the maxillary dental arch, such as RME, can affect the geometry and function of the nasal cavity³⁴.

The CFD analysis is considered the most appropriate technique to simulate the internal flow dynamics of the upper airway. It provides accurate simulation to the magnitudes of air pressure and velocity and thus more precise evaluation of the airway function. Related studies reported that the pharyngeal airway pressure during inspiration decreases with the reduction of nasal resistance by conventional RME^{35,36}. Jae-Sik Hur et al¹⁵ investigated the effects of MARPE on airflow in upper airway of an adult patient with OSAS using 3D-CFD analysis and found that MARPE improves airflow and decreases resistance. The investigation of diseases involving the upper respiratory tract requires a good understanding of the complex interaction between the air flowing through the system and the tissues in the oropharyngeal region.

This study differs from all previous study by assessing the effect of MARPE on an adolescent female who were diagnosed with maxillary constriction using the CFD analysis. Adolescent (13-18 years) is in the process of developing from a child into an adult. Adolescent is different from children for the more matured skeletal development, thus teeth-borne RME is not suitable. The MARPE appliance is a bone-borne appliance effective in correcting maxillary transverse deficiency without surgery in more skeletally matured patients ¹⁷. Altered mandibular posture and counterclockwise rotation of the mandible may occur after maxillary expansion treatment in young patients and the change in lower jaw may also influence the upper airway dimensions ³⁷.

The subject in the present study showed reduction in upper airway resistance in the nasal cavity. This finding is in accordance with a previous review ³⁸, which suggested that expansion of the NC floor can benefit patients with a constricted maxillary arch and nasal airflow problem.

The amount of increase in the cross-sectional area was larger for the pharynx than for NC especially for oropharynx. The possible mechanism of oropharynx improved obviously is that after MSE the tongue posture may raise and enlarges the pharyngeal airway ²⁴.

Airflow pressure decreased in both NC and pharynx, but the value of decrease in pharynx is less obvious than NC, the reason maybe that the pharynx is made of soft tissue which is different from the NC that made of hard tissues such as the nasal septum, conchae, and palatal bone.

The current study has several limitations. Firstly, the patient was awake during the CBCT scans and standing in an upright posture. Secondly, the patient did not complete a sleep study or a sleepiness questionnaire. In addition, the airway is not a rigid structure, and the effect of the flaccidness of the soft tissue could not be taken into consideration in this study.

Despite these limitations, this is the first study that focus on the effect of MSE on the adolescent with maxillary constriction considering the difference between adolescent

and adult. And future studies can increase the sample size and lengthen the retention time to confirm the study outcome.

Conclusions

The use of MSE appliance in correction of maxillary deficiency in this patient shows positive effects in improvement of cross-sectional areas along the nasal and pharyngeal airway and reduction of upper airway resistance and velocity. The subject in the present study showed significant increase in the pharyngeal cross-sectional area together with reduction in upper airway resistance in the nasal cavity.

Availability of data and materials

The data supporting the conclusions of this article are included within the article.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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Authors' contributions

T.Z and X.Z. reviewed the related literatures, reconstructed the FME model, made the CFD analysis and wrote manuscript. The first two authors' contributions equally to the article. P.N and F.H assisted in design of the study and article revision. W.Y and X.C assisted in the boundary condition definition, CFD analysis and article revision. H.H carried out the study and reviewed the manuscript for publication. All authors read and approved the final manuscript.

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Figure Legends:

FIGURE 1. A) Pre-treatment intraoral photograph; B) Post-treatment intraoral photograph

FIGURE 2. Three-dimensional model of the upper airway. T0 (A, red), T1 (B, green) and superimposition (C) of the models showing the locations of six planes in the nasal cavity (Y1 to Y6) and seven planes in the pharynx (Z1 to Z7). The superimposition was performed with the best-fit method using the anterior cranial base of T0 and T1 models.

FIGURE 3. Respiratory rate used for computational fluid dynamic simulation. Total duration of one cycle is 4.8 seconds with maximum inspiration at 0.8 seconds, rest at 3 seconds, and maximum expiration at 4.2 seconds.

FIGURE 4. Comparison of pressure distribution before and after MSE

FIGURE 5. Comparison of velocity distribution before and after MSE

TABLE 1 The governing equations for numerical turbulence model

Conservation of mass (continuity)	$\frac{\partial u_i}{\partial x_i} = 0$
Momentum (Navier-Stokes)	$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$

where p is the pressure, Re is the Reynolds number, $u_i = U_i/U_{ir}$, $x_i = X_i/dir$, $p = P/P_{ir}$, U_{ir} is the velocity vector, U_{ir} is the outlet average velocity, dir is the narial diameter, ρ is the aerial density.

TABLE 2 Comparison of cross-sectional airway area before and after MARPE in a teenager patient

	Airway area (mm ²)			
	Before MARPE (T0)	After MARPE (T1)	$\Delta T1-T0$	Percentage of change $[(\Delta T1-T0)/T0] \times 100\%$
Nasal cavity				
Plane Y1	287.65	335.90	48.25	16.77%
Plane Y2	307.57	308.92	1.35	0.44%
Plane Y3	316.42	319.68	3.26	1.03%
Plane Y4	260.17	270.61	10.44	4.01%
Plane Y5	200.83	220.53	19.70	9.81%
Plane Y6	186.85	210.09	23.24	12.44%
Avergae	259.92	277.62	17.71	7.42%
Pharynx				
Plane Z1	528.47	489.22	-39.25	-7.43%
Plane Z2	531.95	622.78	90.83	17.08%
Plane Z3	562.75	703.59	140.85	25.03%
Plane Z4	581.69	794.50	212.81	36.58%
Plane Z5	536.18	754.17	217.99	40.66%
Plane Z6	599.22	724.17	124.95	20.85%
Plane Z7	563.42	684.76	121.33	21.54%
Average	557.67	681.88	124.22	22.04%

TABLE 3 Comparison of airflow pressure before and after MARPE.

Variable	Pressure (Pa)				Percentage of change [(ΔT1–T0)/T0] × 100%	
	Before MARPE (T0)		After MARPE (T1)			
	Max. expiration	Max. inspiration	Max. expiration	Max. inspiration	Max. expiration	Max. inspiration
Nasal cavity						
Plane Y1	36.95	-26.42	30.18	-22.46	-18.33%	-14.99%
Plane Y2	35.07	-25.17	27.19	-21.87	-22.44%	-13.12%
Plane Y3	32.24	-23.39	24.91	-20.28	-22.74%	-13.31%
Plane Y4	29.12	-19.61	22.22	-17.00	-23.68%	-13.33%
Plane Y5	24.05	-17.01	19.49	-13.58	-18.95%	-20.16%
Plane Y6	21.63	-7.97	17.67	-6.89	-18.28%	-13.51%
Avergae	29.84	-19.93	23.61	-17.01	-20.74%	-14.74%
Pharynx						
Plane Z1	38.73	-28.79	32.06	-25.52	-17.24%	-11.34%
Plane Z2	38.92	-28.52	32.30	-25.27	-17.01%	-11.42%
Plane Z3	38.92	-29.38	32.24	-25.74	-17.16%	-12.38%
Plane Z4	39.03	-29.06	32.38	-25.50	-17.02%	-12.25%
Plane Z5	39.22	-29.22	32.48	-25.45	-17.18%	-12.87%
Plane Z6	39.32	-29.24	32.54	-25.51	-17.25%	-12.76%
Plane Z7	39.53	-29.04	32.86	-25.36	-16.87%	-12.65%
Avergae	39.10	-29.03	32.41	-25.48	-17.11%	-12.24%

TABLE 4 Comparison of airflow velocity before and after MARPE.

Variable	Velocity(m/s)				$\Delta T1-T0$	
	Before MARPE (T0)		After MARPE (T1)			
	Max. expiration	Max. inspiration	Max. expiration	Max. inspiration	Max. expiration	Max. inspiration
Nasal cavity						
Plane Y1	1.87	1.59	1.80	1.40	-0.07	-0.20
Plane Y2	1.53	1.46	1.41	1.22	-0.12	-0.24
Plane Y3	1.48	1.53	1.34	1.36	-0.13	-0.17
Plane Y4	1.26	1.39	1.26	1.27	0.00	-0.12
Plane Y5	2.72	2.69	2.26	2.38	-0.46	-0.31
Plane Y6	3.58	2.80	3.26	3.05	-0.32	0.25
Avergae	2.07	1.91	1.89	1.78	-0.18	-0.13
Pharynx						
Plane Z1	0.87	0.94	1.08	0.88	0.21	-0.06
Plane Z2	0.74	1.15	0.66	0.85	-0.08	-0.30
Plane Z3	0.69	0.55	0.37	0.46	-0.33	-0.09
Plane Z4	0.63	0.84	0.57	0.69	-0.06	-0.14
Plane Z5	0.75	0.72	0.60	0.77	-0.15	0.05
Plane Z6	0.71	0.56	0.69	0.69	-0.02	0.13
Plane Z7	0.82	0.80	0.74	0.71	-0.08	-0.09
Avergae	0.75	0.80	0.67	0.72	-0.07	-0.07

A

B

A

B

C