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Research Article
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Evaluating the effect of midpalatal corticotomy-assisted rapid maxillary expansion on the upper airway in young adults using computational fluid dynamics

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Abstract: Midpalatal corticotomy-assisted rapid maxillary expansion (MCRME) is a minimally invasive treatment of maxillary transverse deficiency (MTD) in young adults. However, the effect of MCRME on respiratory function still needs to be determined. In this study, we evaluated the changes in maxillary morphology and the upper airway following MCRME using computational fluid dynamics (CFD). Twenty patients with MTD (8 males, 12 females; mean age 20.55 years) had cone-beam computed tomography (CBCT) images taken before and after MCRME. The CBCT data were used to construct a three-dimensional (3D) upper airway model. The upper airway flow characteristics were simulated using CFD, and measurements were made based on the CBCT images and CFD. The results showed that the widths of the palatal bone and nasal cavity, and the intermolar width were increased significantly after MCRME. The volume of the nasal cavity and nasopharynx increased significantly, while there were no obvious changes in the volumes of the oropharynx and hypopharynx. CFD simulation of the upper airway showed that the pressure drop and maximum velocity of the upper airway decreased significantly after treatment. Our results suggest that in these young adults with MTD, increasing the maxillary width, upper airway volume, and quantity of airflow by MCRME substantially improved upper airway ventilation.

Key words: Maxillary transverse deficiency (MTD); Rapid maxillary expansion (RME); Upper airway; Computational fluid dynamics (CFD)

1 Introduction

Maxillary transverse deficiency (MTD) is a common clinical malocclusion in young adults, characterized mainly by a narrowing of the dental arch, crowded dentition, and negative overjet of the posterior dental region. Due to the high resistance of the mature midpalatal suture, it is not possible to perform ideal sutural separation without surgical osteotomies for expansion (Lee et al., 2014). Therefore, doctors often use surgically assisted rapid maxillary expansion (SARME) to correct MTD in young adults. The surgical procedure of SARME includes LeFort I osteotomy with or without the pterygomaxillary junction or midline palatal split under general anaesthesia (Menon et al., 2010). Published reports show that SARME involves potential postoperative risks, such as infection, pain, craniofacial fractures, paresthesia, occasional excess bleeding, sinusitis, and periodontal bone loss (Dergin et al., 2015; Pereira et al., 2018). The surgery also increases the psychological and economic burden for patients. Therefore, in this study we used a minimally invasive method of midpalatal corticotomy-assisted rapid maxillary expansion (MCRME) to correct MTD in young adults. A previous clinical study showed that MCRME was an effective micro-invasive treatment for young adults with MTD (Weng et al., 2017).

Recent studies have found that rapid maxillary expansion (RME) can increase the width and volume of the nasal cavity (Tausche et al., 2009; El and Palomo, 2014; Kim et al., 2018), reduce the resistance of the nasal airflow, and improve the nasal ventilation function

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(Warren et al., 1987; Iwasaki et al., 2012; Ghoneima et al., 2015). In a recent review, Buck et al. (2016) found that SARME could produce substantial short-term volume increases in the nasal cavity of non-growing patients, while evidence rarely showed no effect on oropharyngeal volume. Some scholars have suggested that RME can be used as a treatment option for nasal stenosis caused by nasal septum deformity, nasal infection, allergic rhinitis, and obstructive sleep apnea (Menegat et al., 2015; Vinha et al., 2016). However, most studies were evaluated as having a high risk of bias. The effect of such volume changes on respiratory function still needs to be determined. Recently, computational fluid dynamics (CFD) has been used for evaluation of airway ventilation (Iwasaki et al., 2013). Because it can simulate the flow of air and evaluate air current regardless of the shape of the upper airway, we speculated that CFD assessment may be a more accurate method for the complicated evaluation of the upper airway in MTD young adults. In this study, we investigated changes in the maxillary width and upper airway ventilation after MCRME using CFD.

2 Subjects and methods

2.1 Subjects

This study was approved by the Research Ethics Committee (No. 2019-580-1) of the First Affiliated Hospital of Zhejiang University (Hangzhou, China). A total of 20 consecutive patients with transverse maxillary deficiency underwent MCRME at the Department of Orthodontics from January 2015 to June 2019. The sample comprised 8 male and 12 female subjects with a mean age of (20.55±2.95) years.

The inclusion criteria were as follows: (1) according to cone-beam computed tomography (CBCT) measurements (NewTom VGi, Italy; FSV: 110 kV/4.11 mA; SSV: 110 kW/3.00 mA; pixel spacing: 0.300 mm; FOV: full), the difference in width between the mandible and maxilla was more than 5 mm before surgery (Fig. 1), and the diagnosis was transverse maxillary deficiency; (2) permanent dentition; (3) skeletal maturity (the lateral cephalogram shows at least cervical vertebra stage (Cvs) 4); (4) good periodontal condition; (5) no history of orthodontic or orthognathic treatment; (6) no craniofacial syndrome patients.

The exclusion criteria were as follows: (1) congenital maxillofacial deformities; (2) prior orthodontic and surgical treatment on the maxilla; (3) prior maxillary trauma; (4) transverse maxillary deficiency that could be corrected by orthodontic treatment alone; (5) there is a missing or large defect of bilateral maxillary first premolar and first molar.

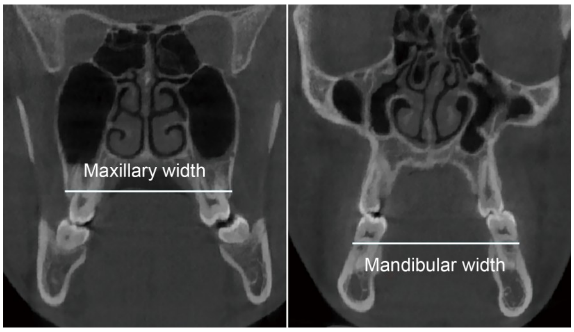

Fig. 1 Measurement of the difference in width between the maxillary and mandibular arches.

2.2 Surgical procedures and measurement

The surgery was carried out by one oral surgeon using the same surgical techniques. Surgical procedures were as follows (Weng et al., 2017): a corticotomy in the palate was performed under local anesthesia. The depth was about half of the cortical bone thickness at the midpalatal suture from the incisive canal to the transverse palatine suture (Fig. 2a). A periodontal dressing (Reso-PAC, HAGER WERKEN, Germany) was then applied to prevent infection and promote wound healing (Fig. 2b). One week after surgery, a tooth-borne hyrax maxillary expansion device was attached to the maxillary first premolar and the first molar (Fig. 2c). Each patient was instructed to rotate the device 1/4 turn each morning and evening (each quarter turn was 0.25 mm) for 21 d, then maintain for three months as a passive retainer. CBCT examinations were performed before treatment (t_1) and after three months of retention (t_2). Some landmarks and parameters (Fig. 3) were measured on the coronal CBCT images at t_1 and t_2, including the nasal cavity width (NCW), palatal bone width (PBW), and intermolar width (IMW).

2.3 Establishment of the upper airway three-dimensional (3D) model and CFD simulation

Two-dimensional tomographic images of computed tomography (CT) scans were imported into Mimics 20.0 software (Materialise Software, Belgium) in digital imaging and communication in medicine (DICOM)

Fig. 2 Surgical procedures and device. (a) Corticotomy in the palate; (b) A periodontal dressing was used to promote wound healing; (c) Hyrax rapid maxillary expansion (RME) device.

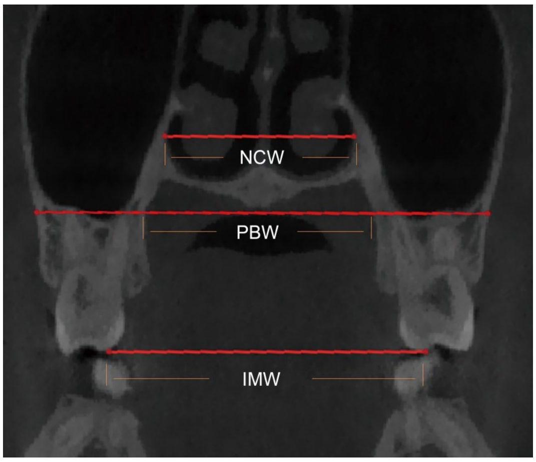

Fig. 3 Measurement of the maxillary and nasal cavity width. Nasal cavity width (NCW), palatal bone width (PBW) at the palatal root apex at the molar level, and intermolar width (IMW) between the molar palatal cusps were measured.

format. The CT threshold was adjusted from −1024 to −260, and then the upper airway model was created for the region between the nostrils and the hypopharynx. The frontal sinus, sphenoid sinus, ethmoid sinus, and maxillary sinus were removed by manual editing. After region growth and 3D calculation, a 3D model of the upper airway of the patient was established (Figs. 4a and 4b). In accordance with a recent systematic review (Guijarro-Martínez and Swennen, 2011), the upper airway was divided into four parts in the sagittal plane (Table 1), and their volumes were measured at t_1 and t_2.

The 3D model was imported into ANSYS 19.0 software (ANSYS, Inc., USA) in signal temporal logic (STL) format for meshing and boundary condition setting (Qian et al., 2013). The bilateral nostrils were set as velocity inlets, the volumetric flow rate was 275 mL/s, the hypopharynx plane was set at a static pressure of 0 Pa as the outlet, and standard atmospheric pressure was applied. The standard $\kappa-\varepsilon$ two-equation turbulence model was used to simulate the airflow field of the upper airway. This model was chosen because of its robustness, economy, and reasonable prediction of flow (Chang et al., 2018). The walls of the model, which were assumed to be rigid and noncompliant, were set at no-slip conditions, and simulations were carried out for 1000 times to calculate mean values. The pressure

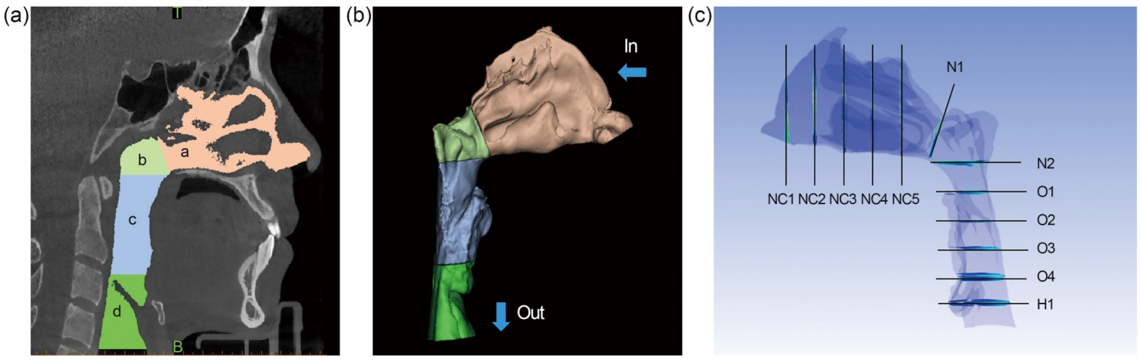

Fig. 4 Establishment of upper airway three-dimensional (3D) model and computational fluid dynamics (CFD) simulation. (a) Extraction and delimit of the upper airway data (a: nasal cavity; b: nasopharynx; c: oropharynx; d: hypopharynx); (b) Construction of a 3D upper airway model and numeric simulation (inspiration flow of the air mass, 275 mL/s); (c) Position of cross sections of the upper airway (NC1, NC2, NC3, NC4, NC5: nasal cavity cross section; N1, N2: nasopharynx cross section; O1, O2, O3, O4: oropharynx cross section; H1: hypopharynx cross section).

Table 1 Four parts of the upper airway in the sagittal plane

Part name	Boundary location
Nasal cavity	Anterior limit: anterior nostrils
	Posterior limit: line extending from S to the PNS
Nasopharynx	Superior limit: inferior limit of the nasal cavity
	Inferior limit: plane parallel to the FH plane passing through PNS
Oropharynx	Superior limit: inferior limit of the nasopharynx
	Inferior limit: plane parallel to the FH plane passing through the superior margin of the epiglottis
Hypopharynx	Superior limit: inferior limit of the oropharynx
	Inferior limit: plane parallel to the FH plane that passes through the most anteroinferior point of the 4th cervical vertebra

S: sella; PNS: posterior nasal spine; FH: Frankfort plane.

drop and maximum airflow velocity of the upper airway were recorded and assessed at t_1 and t_2 (Fig. 4c).

2.4 Statistical analysis

The means and standard deviations (mean±SD) of the measurements were calculated, and paired *t*-tests were performed on the maxillary width and relevant indicators of airflow characteristics during the t_1 and t_2 periods, using the SPSS software package (SPSS 23.0, IBM, USA). For all tests, $P<0.05$ was considered statistically significant.

3 Results

3.1 Widths of the maxillary and nasal cavities

Twenty patients achieved a significant transverse width expansion after MCRME. The IMW and PBW at the first molar and first premolar level exhibited significant increases ($P<0.01$). The width between the lateral walls of the nasal cavity was also expanded significantly ($P<0.01$; Table 2).

Table 2 Skeletal and dental changes

Position	Width (mm)		*D*-value
	Before treatment	After treatment	
PBW6	30.6±4.5	33.0±4.8	2.3±1.6**
IMW6	41.5±4.0	47.0±3.9	5.5±3.1**
NCW6	34.4±2.9	35.7±3.0	1.4±0.9**
PBW4	22.5±4.7	25.4±4.6	2.9±2.3**
IMW4	32.1±2.8	38.2±2.7	6.1±3.3**
NCW4	29.5±4.0	31.3±4.0	1.7±1.5**

The data are expressed as mean±standard deviation (n=20). PBW6 and PBW4: palatal bone widths at the first premolar and first molar regions, respectively; IMW6 and IMW4: intermolar widths at the first premolar and first molar regions, respectively; NCW6 and NCW4: nasal cavity lateral wall widths at the first premolar and first molar regions, respectively. ** $P<0.01$.

3.2 Upper airway volume

The total volume of the upper airway increased ($P<0.01$). In particular, there was a highly significant increase in the volumes of the nasal cavity and nasopharynx ($P<0.01$). No significant changes were found in the volumes of the oropharyngeal or hypopharynx airways after treatment ($P>0.05$; Table 3).

Table 3 Upper airway volume changes

Position	Volume (cm^3)		*D*-value
	Before treatment	After treatment	
Nasal cavity	16.29±3.33	18.24±3.61	1.95±1.68**
Nasopharynx	6.44±1.83	7.19±1.68	0.76±0.68**
Oropharynx	17.59±3.93	17.38±4.56	−0.21±2.51
Laryngopharynx	8.03±3.70	7.93±3.66	−0.09±1.41
Upper airway	48.35±9.53	50.75±9.92	2.40±4.07**

The data are expressed as mean±standard deviation (n=20). ** $P<0.01$.

3.3 Upper airway ventilation

The CFD results of upper airway pressure and velocity before and after MCRME are shown in Tables 4 and 5, respectively. The pressure drop and maximum velocity in the nasal cavity and nasopharynx decreased significantly after treatment ($P<0.01$). The pressure drop and maximum velocity in the oropharynx and hypopharynx also decreased after treatment ($P<0.05$). Figs. 5 and 6 show typical examples of the maximum velocities and pressures of the nasal cavity, nasopharynx, oropharynx, and hypopharynx before and after MCRME.

4 Discussion

Correction of MTD is more challenging for patients with a mature maxilla. SARME has gradually gained popularity as a treatment option to correct MTD in

Table 4 Upper airway pressure drop

Position	Pressure drop (Pa)		*D*-value
	Before treatment	After treatment	
Nasal cavity	23.99±11.83	13.08±7.42	−10.91±8.93**
Nasopharynx	11.19±7.21	5.64±3.38	−5.55±6.00**
Oropharynx	4.24±1.82	3.27±1.63	−0.98±1.72*
Laryngopharynx	2.92±2.11	1.96±1.96	−0.95±2.02*

The data are expressed as mean±standard deviation (n=20). * P<0.05; ** P<0.01.

Table 5 Upper airway velocity

Position	Velocity (m/s)		*D*-value
	Before treatment	After treatment	
Nasal cavity	5.23±1.09	3.99±0.84	−1.24±0.92**
Nasopharynx	3.81±0.88	2.81±0.88	−1.00±0.89**
Oropharynx	2.55±0.57	2.14±0.64	−0.41±0.72*
Laryngopharynx	2.07±0.52	1.71±0.64	−0.36±0.62*

The data are expressed as mean±standard deviation (n=20). * P<0.05; ** P<0.01.

young adults. Commonly used surgical procedures include separation of the midpalatal suture, separation of the pterygomaxillary sutures, and LeFort I corticotomy. The purpose of these procedures is to remove the resistance of the midface to lateral expansion. Lee et al. (2014) performed finite element analysis on these three surgical models and showed that they produced similar amounts of stress and displacement along the teeth, midpalatal sutures, and craniofacial sutures. Therefore, they recommended midpalatal suture separation to complement the use of a bone-borne rapid maxillary expander in adults, which requires minimal surgical intervention. Sant'Ana et al. (2016) compared surgically assisted RME with and without a midpalatal split and showed that without a midpalatal split, patients suffered greater discomfort. Therefore, in our study we used midpalatal corticotomy to assist RME.

As a result, a good expansion effect was achieved in 20 cases in our study. The data suggest that the maxillary width had increased significantly after maxillary expansion. The distance increases at the first premolars (6.1 mm) and the first molars (5.5 mm) were consistent with those of other studies (Kartalian et al., 2010; Chang et al., 2013). However, the average transverse expansion of 2.9 and 2.3 mm of the PBW was smaller than those of a previous study after rapid palatal expansion (4.4 and 3.9 mm, respectively) (Zandi et al., 2014). The reason may be that Zandi et al. (2014) performed osteotomy of the lateral maxillary wall from the piriform rim to the pterygomaxillary junction, and midline osteotomy between the central incisors and the pterygomaxillary disjunction, and released more resistance. The percentile increase ((level after RME/level before RME−1)×100%) at the first premolar level (average, 13.03%) was greater than that at the first molar level (average, 7.57%), as in a previous study (Seeberger et al., 2015). This indicates a V-shaped opening from anterior to posterior due to the mainly posterior resistance of the maxilla. Figueiredo et al. (2016) found bone expansion of up to 48% in children with RME. In this paper, the amount of palatal bone in the first molar region accounted for 43% of the increase. This result suggests that by using MCRME, young adults can have expansion effects similar to those of children treated with RME.

Previous studies that used acoustic rhinometry to assess the airway reported an increase in nasal volume. Babacan et al. (2006) and Wriedt et al. (2001) found that nasal airway volume increased by 14.09% and 21.20%, respectively. In a long-term study, Seeberger et al. (2010) found that nasal volume increased by 23.25% at 63 months after expansion. Recent studies which used CBCT and 3D model reconstruction reported a smaller increase in nasal cavity volume than that shown by acoustic rhinometry. Deeb et al. (2010) reported only a 5.1% increase in the nasal airway in bone-borne expansion using CT examination. Nada et al. (2013) found the nasal airway of a tooth-borne SARME group increased by 9.7%. Our result, that the nasal cavity volume increased by 12.0%, was consistent with previous studies. Our finding that the oropharynx and hypopharynx volumes did not change much was in agreement with the results of previous studies (Smith et al., 2012; Pereira-Filho et al., 2014). This indicates that MCRME may not influence the lower airway significantly. However, Liu et al. (2019) found a significant increase in the oropharynx airway after surgically assisted rapid palatal expansion (SARPE) combined with surgically facilitated orthodontic therapy (SFOT), and some studies (Zhao et al., 2010; Aloufi et al., 2012) found a significant increase in the retropalatal space. The main reasons for this discrepancy may be the difference in the measurement method and the boundary of the upper airway.

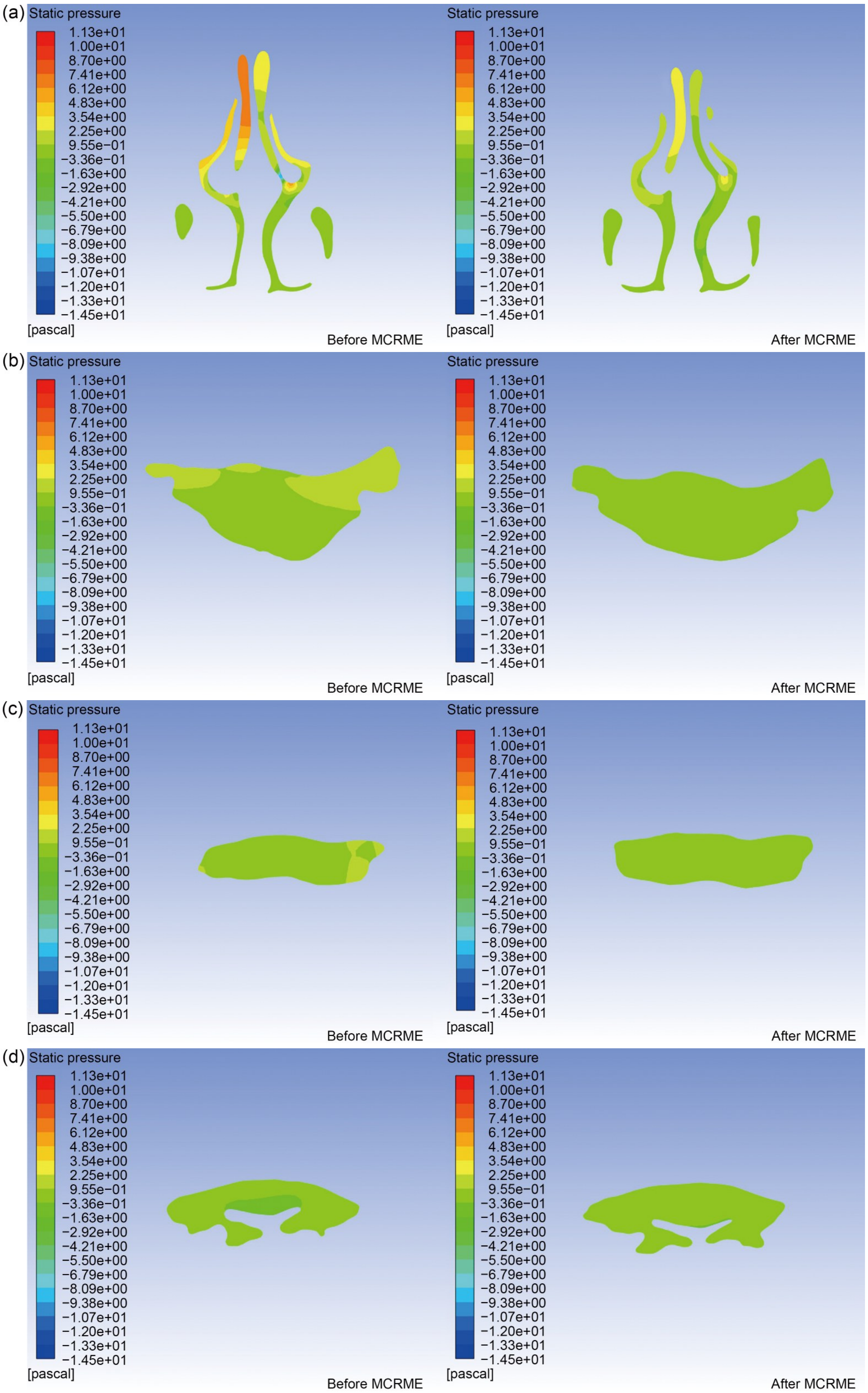

Fig. 5 Typical example of change in pressure drop of upper airway cross section from before to after midpalatal corticotomy-assisted rapid maxillary expansion (MCRME) via computational fluid dynamics (CFD). (a) Nasal cavity cross section; (b) Nasopharynx cross section; (c) Oropharynx cross section; (d) Hypopharynx cross section.

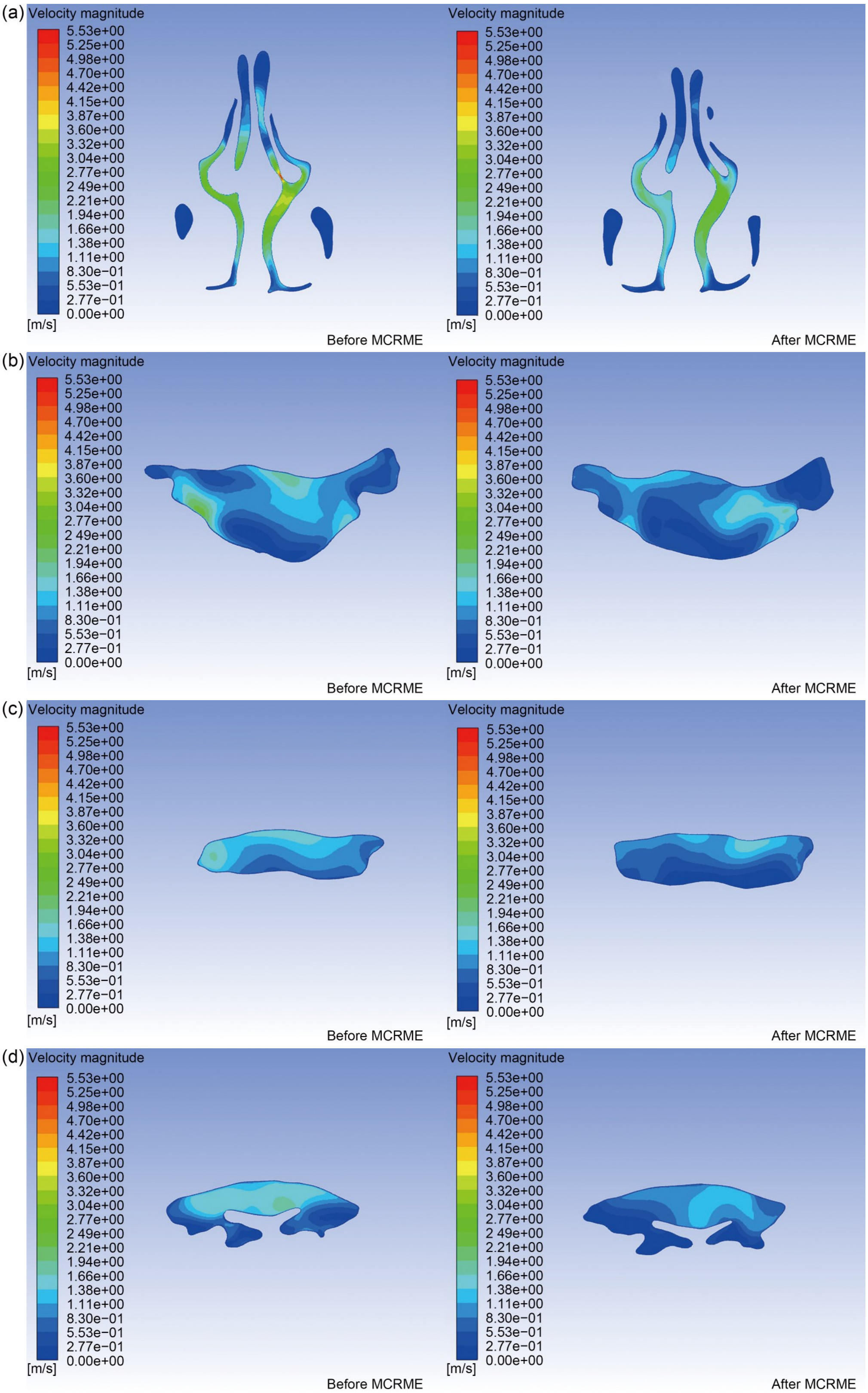

Fig. 6 Typical example of change in velocity of upper airway cross section from before to after midpalatal corticotomy-assisted rapid maxillary expansion (MCRME) via computational fluid dynamics (CFD). (a) Nasal cavity cross section; (b) Nasopharynx cross section; (c) Oropharynx cross section; (d) Hypopharynx cross section.

Our study used CFD to evaluate airway ventilation before and after treatment. Our results showed that the pressure drop and maximum velocity of the nasal cavity and nasopharynx were decreased after treatment (P<0.01). These results confirm those of previous studies (Iwasaki et al., 2012, 2014; Ghoneima et al., 2015) which investigated upper airway airflow characteristics by CFD, indicating that the nasal airflow was more gradual after treatment. Iwasaki et al. (2019) evaluated pharyngeal airway pressure during inspiration in young adolescents using CFD and found that the pharyngeal airway pressure was decreased with the significant reduction in nasal resistance following RME. Our results also showed that the pharyngeal airway velocity and pressure drop decreased. The reason for this may be that after the MCRME relieves the nasal resistance, the pressure of the pharyngeal airway also decreases, easing constriction in the pharyngeal airway and reducing pharyngeal airflow resistance.

Some scholars believe that MTD plays an important role in the pathophysiology of obstructive sleep apnea, because it is associated with low tongue posture, which may lead to narrowing of the oropharyngeal airway (Chang et al., 2013). MTD can also cause nasal obstruction, which in turn triggers obstructive sleep apnea syndrome (OSAS), because the negative pressure of the pharyngeal airway increases as the pharyngeal airway shrinks (Iwasaki et al., 2012). Our results suggest that MCRME in young adults can reduce the upper airway pressure and relieve the resistance of the upper airway. However, the functional benefit of SARME to the airway has not been fully determined (Neeley et al., 2007). Vinha et al. (2016) reported that OSAS symptoms are relieved after RME. Magnusson et al. (2011) reported that a subjective improvement in nasal function was significantly improved only in patients with an initial nasal obstruction. In addition, they found no correlation between the objective volume increase of the nasal cavity and the subjective perception of nasal function improvement. Thus, one limitation of the study was the absence of physical measurements to compare with CFD-derived values and to determine differences in the effects after treatment. Another limitation was that the three-month follow-up time was not enough. Smith et al. (2012) found that the volume increase was related to the length of the follow-up: at the first evaluation, the volume increased, but it then relapsed and the gain was lost.

5 Conclusions

The use of MCRME in the correction of maxillary deficiency in these adult patients improved both the maxillary width and upper airway volume, and reduced the upper airway pressure and velocity. In short, MCRME is a minimally invasive and effective treatment for MTD in adults and is useful for improving upper airway ventilation.

Acknowledgments

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Author contributions

Juan LI designed the study. Lingfang SHI collected the data. Xiayao ZHANG, Luxi WENG, and Hong CHEN performed the data processing and data analysis. Juan LI, Lingfang SHI, and Jun LIN wrote and edited the manuscript. All authors have edited and approved the final manuscript, and they have full access to all the data in the study and take responsibility for the integrity and security of the data.

Compliance with ethics guidelines

Juan LI, Lingfang SHI, Xiayao ZHANG, Luxi WENG, Hong CHEN, and Jun LIN declare that they have no conflict of interest.

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study. Additional informed consent was obtained from all patients for which identifying information is included in this article.

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