R. Fastuca*, M. Meneghel*, P. A. Zecca**, F. Mangano**, M. Antonello***, R. Nucera****, A. Caprioglio*****

Department of Surgical and Morphological Sciences, University of Insubria, Varese, Italy
**Resident, Section of Orthodontics*
***Research Fellow, Section of Orthodontics*
****Research Fellow, Department of Mechanical Engineering, University of Padova, Italy*
*****Assistant Professor, Department of Orthodontics, University of Messina, Messina, Italy*
******Chairman, Section of Orthodontics*

e-mail: rosamariaf@hotmail.it

Multimodal airway evaluation in growing patients after rapid maxillary expansion

ABSTRACT

Aim *The objective of this study was to evaluate the airway volume of growing patients combining a morphological approach using cone beam computed tomography associated with functional data obtained by polysomnography examination after rapid maxillary expansion treatment.*

Materials and methods *Study design: 22 Caucasian patients (mean age 8.3 ±0.9 years) undergoing rapid maxillary expansion with Haas type expander banded on second deciduous upper molars were enrolled for this prospective study. Cone beam computed tomography scans and polysomnography exams were collected before placing the appliance (T0) and after 12 months (T1). Methods: Image processing with airway volume computing and analyses of oxygen saturation and apnoea/hypopnoea index were performed.*

Results *Airway volume, oxygen saturation and apnea/hypopnea index underwent significant increase over time. However, no significant correlation was seen between their increases.*

Conclusion *The rapid maxillary expansion treatment induced significant increases in the total airway volume and respiratory performance. Functional respiratory parameters should be included in studies evaluating the RME treatment effects on the respiratory performance.*

Keywords *maxillary expansion, airway, polysomnography, computational fluid dynamics.*

Introduction

The rapid maxillary expansion (RME) treatment has become popular to correct skeletal transverse maxillary discrepancy for several decades [Angell, 1860; Haas, 1961, 1980].

According to the anatomical proximity between nasal cavity and hard palate, an orthopaedic expansion of the former might occur as consequence of the RME treatment. In particular, earlier studies [Wertz, 1968, 1970] evaluated the advantages of RME treatment in improving nasal airflow in patients with nasal stenosis. It was later suggested that RME treatment triggers effects on nasal width [Brown, 1902; White et al., 1989; Ballanti et al., 2010] and volume [Haralambidis et al., 2009; Zhao et al., 2010; Görgülü et al., 2011; Ribeiro et al., 2012; Smith et al., 2012; Chang et al., 2013]. Indeed, some studies [Linder-Aronson et al., 1963; Hershey et al., 1976] showed a reduction in nasal airway resistance after RME treatment and an amount up to 45% increase in nasal cross-sectional areas after expansion has been reported [Warren et al., 1987]. In spite of this evidence, considering the V-shaped opening pattern of the midpalatal suture [Wertz, 1968, 1970], the only purpose of increasing respiratory performance has been reported as not sufficient to indicate an RME treatment [Wertz, 1970].

More in detail, airway changes upon RME treatment have been studied by using different methods including acoustic rhinometry [Doruk et al., 2007], 2D [Wertz, 1968, 1970] and 3D cephalometrics [Montgomery et al., 1979]. One of the most used morphological techniques nowadays is represented by cone beam computed tomography (CBCT) that allows a full 3D and reliable quantification of the anatomical changes of the airway compartments. Other functional diagnostic tools that can be employed to investigate the effects of RME on airflow include the polysomnography (PSG) examination. This recording widely employed in obstructive sleep apnoea (OSA) patients [Caprioglio et al., 1999, 2011; Zucconi et al., 1999; Villa et al., 2011; Nespoli et al., 2013] provides useful information about breathing pattern, showing quantitative data such as oxygen saturation (SpO_2) and apnea/hypopnea index (AHI). Indeed, a morphological modification of the airway spaces does not necessarily imply a greater respiratory performance (i.e. function) or vice versa, and studies including only the anatomical investigations of the RME treatment on airway compartments volume might be limited in their conclusions.

Therefore, through a combination of morphological and functional examinations, the aim of the present prospective study was to investigate the effects of RME on the airway volume and respiratory performance assuming that no correlation exists between airway volume and PSG examinations as null hypothesis.

Materials and methods

Population and study design

This study followed a prospective longitudinal design and enrolled subjects seeking orthodontic treatment and who had never been treated before, presenting at the Department of Orthodontics of University of insubria (Varese). As a routine procedure, a signed informed consent for releasing diagnostic records for scientific purposes was obtained from the parents of the patients prior to entry into the treatment. The protocol was reviewed and approved by the Ethical Committee, (Approval no. 5184) and procedures followed adhered to the World Medical Organization Declaration of Helsinki. Briefly, the including criteria were as follows: good general health according to medical history and clinical judgment; narrow maxillary arches, presence of unilateral or bilateral posterior crossbite; early mixed dentition with stages 1 or 2 in cervical vertebral maturation (CVM) [Baccetti et al., 2005] as assessed on lateral cephalograms derived from 3D CBCT recordings collected as detailed below; upper and lower first molars fully erupted.

Twenty-two patients (13 females and 9 males, mean age 8.3 ±0.9 years) were enrolled in the study. Each patient underwent two sessions of CBCT recording and of PSG examination at T0, prior to the beginning of the RME treatment, and again immediately after the removal of the maxillary expander, 12 months later (T1).

Rapid maxillary expansion therapy

The maxillary expander used for all subjects was a Haas-type expander with a 10-mm screw (A167-1439, Forestadent, Pforzheim, Germany) banded to the upper second deciduous molars. The maxillary expanders were banded using glass ionomer cement (Multi-Cure Glass ionomer Cement, 3M-Unitek, Monrovia, CA) in accordance with the manufacturer's instructions. The screw of the palatal expander was initially turned two times (0.45 mm initial transversal activation). Afterwards, parents of the patients were instructed to turn the screw once per each following day (0.225 mm activation per day). The maxillary expansion was performed until dental overcorrection, defined as when the lingual cusps of the upper first molars occluded onto the buccal cusps of the lower first molars, was achieved. The screw was then locked with light-cure flow composite (Premise Flowable; Kerr Corporation, Orange, CA) and the expander was kept on the teeth as a passive retainer. During this period, none of the patients underwent any further orthodontic treatment.

Image recording and post-processing

The CBCT scans (i-CAT, Imaging Sc. Int., Hatfield, PA, U.S.A.) were performed in the seated position (120 KV, 3.8 mA, 30 s). The DICOM files were processed in Mimics software (version 10.11, Materialise Medical Co, Leuven, Belgium). A reproducible position of head was obtained by reslicing procedure. The distance between the contralateral palatal foramens (Total Expansion) was used to assess the magnitude of the orthopaedic maxillary expansion (Fig. 1). The airway was segmented using a threshold-based procedure manually executed by an expert operator (RF) and corrected slice by slice from the nares to the base of the tongue (Fig. 2). The air space usually has significantly greater Hounsfield Unit (HU) values than surrounding tissues which are denser. Then the high-contrast border allowed to produce a clean enough segmentation. Therefore volumes were computed for the segmented airways.

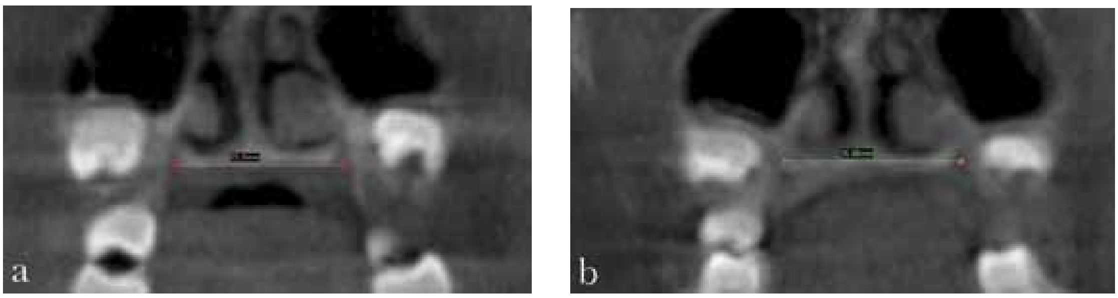

FIG. 1 Total Expansion measured at the Palatal foramens. 1A Before RME. 1B After RME.

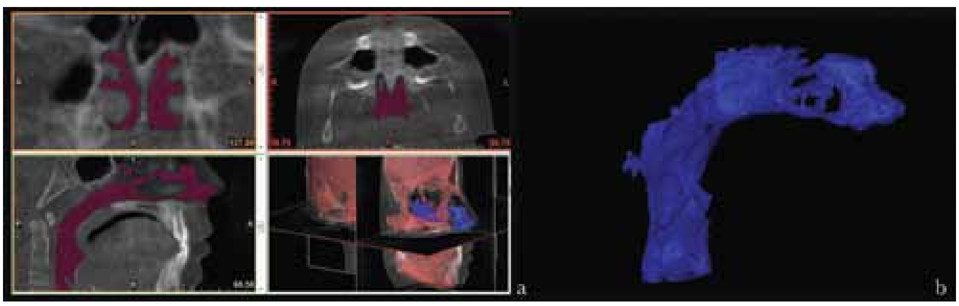

FIG. 2 Total airway segmentation. 2A Airway segmentation on the three planes of spaces. 2B Total Airway Volume 3D reconstruction.

Polysomnography examination

The PSG examination (Embletta - EMBLA, Thornton, CO, U.S.A.) was performed to collect SpO_2 and AHI parameters.

Sample size calculation and method error analysis

A sample size of at least 10 subjects was necessary to detect an effect size (ES) coefficient [Cohen, 1992] of 1.0 for each recorded parameter between the time points, with an alpha set at 0.05 and a power of 0.8. The ES coefficient is the ratio of the difference between the recordings of the two groups, divided by the within-subject standard deviation (SD). An effect size of at least 0.8 is regarded to as a large effect [Cohen, 1992], while a value of at least 1.0 is considered to be associated with good diagnostic potential [Perinetti et al., 2009].

With the aim of quantifying the full method error of the recordings the method of moments (MME) variance estimator was used [Springate, 2012]. Therefore, the mean error and 95% confidence intervals (CIs) between the repeated recordings were calculated using the MME variance estimator, and were expressed as percentages [Perinetti et al., 2012]. The MME variance estimator has the advantages of not being affected by any unknown bias, i.e. systematic errors, between pairs of measurements [Springate, 2012].

Data analysis

The SPSS software, version 13.0 (SPSS® Inc., Chicago, Illinois, USA) and Comprehensive Meta-Analysis, version 2 (BiostatTM, Englewood, New Jersey, USA) were used to perform the statistical analyses. Parametrical methods were used after having tested the existence of the assumptions through the Shapiro-Wilk test and Levene test for the normality of the distributions and equality of the variances between the time points, respectively. A paired sample t-test was employed to assess the significance of the difference of each parameter between the time points. Moreover, the ES coefficients (as Hedges's g coefficients) for each recorded parameter along the 95% CIs, were calculated between the time points, as previously described [Cohen, 1992]. In particular, the paired nature of the data was taken into account and, whenever negative, absolute values have been reported.

A p value <0.05 was set.

Results

Method errors as mean (95% CI) ranged from 0.4 mm (0.16-0.65) and 175.8 mm^3 (91.5-253.3) for the Total Expansion and Airway Volume, respectively.

Descriptive statistics for each recorded parameter are shown in tables 1 and 2. The Total Expansion, Airway Volume, SpO_2 and AHI (Table 1, 2) recorded at T1 were significantly greater than the corresponding T0 values ($p<0.05$, at least). The ES coefficients retrieved for all these parameters were statistically significantly greater than zero and ranging from 0.65 to 4.13 for the Airway Volume and AHI, respectively. However, only for the SpO_2 and AHI, the full 95% CI of the ES coefficients were above the threshold of 1.0.

Discussion

In the present study changes in airway volume, SpO_2 and AHI in patients undergoing RME treatment and their correlations were investigated. All of these variables underwent statistically significant differences between T0 and T1 consistent with an increase in airway volume and respiratory performance.

This study evaluated the combined respiratory anatomical and functional effects triggered by RME treatment. Indeed, while CBCT recording allows the measure of airway volume the SpO_2 and AHI recordings provide information on the respiratory performance.

Several findings [Bicakci et al., 2005] have been reported indicating increases in cross-sectional areas of airway after RME treatment using acoustic rhinometry. Meanwhile Enoki et al. [2006] showed no significant

Variable (n=22)	T0 mean±SD	T1 mean±SD	T1-T0 mean±SD	ES (95% CI)
Total Expansion (mm)	25.36±3.0	28.12±3.2	2.76±1.15**	0.75 (0.45-1.07)
Airway Volume (mm3)	11358.02±4391.2	15014.24±7143.4	3656±5915.1*	0.65 (0.12-1.41)
Data are shown as mean±SD. Total expansion, inter-palatal foramens distance; Airway Volume, total airway; ES, Hedges's g effect size; CI, confidence interval. Levels of significance: *p<0.05; **p<0.001.				

TABLE 1 Comparison of morphological CBCT changes before and after RME.

Variable (n=22)	T0 mean±SD	T1 mean±SD	T1-T0 mean±SD	ES (95% CI)
SpO_2 (%)	90.2±1.3	95.92±1.5	5.72±1.95**	4.12 (1.41-6.01)
AHI (events)	5.01±1.5	1.45±0.6	-3.56±1.32**	4.13 (1.51-6.45)
Data are shown as mean±SD. SpO2, oxygen saturation; AHI, apnea/ hypopnea index; ES, Hedges's g effect size; CI, confidence interval. Levels of significance: *p<0.05; **p<0.001.				

TABLE 2 Comparison of functional changes evaluated by PSG examination before and after RME.

difference for the minimal cross-sectional airway at the levels of the nasal valve and the inferior turbinate with the acoustic rhinometric evaluation suggesting that the benefits of RME might be a modest functional improvement based on bony expansion rather than a mucosal dimensional change. Recently CBCT evaluation showed not only bony expansion after RME, but also a significant cross-sectional area increase immediately posterior to the hard palate [Chang et al., 2013]. The effects of RME might be related to the local application of the forces and then with greater changes on the nasal cavity area [Cordasco et al., 2012; Caprioglio et al., 2014].

As based on our results both the SpO_2 and AHI showed significant increase in the present sample, demonstrating that RME treatment would have beneficial effects of the respiratory performance. These results may be compared with only little previous evidence. For instance, significant improvements in AHI were seen in OSA patients after RME by Villa et al. [2011] and they were stable 24 months after treatment.

Lacking of a control group should be considered as a limit of the present study. Zhao et al. [2010] included an untreated control group and saw no significant changes between treated and controls in airway volumes after RME treatment. Moreover threshold-based segmentation of airway might not be standardised as well as the difficulty of standardising CBCT acquisition and head position, although the present method errors were acceptable. The combination of morphological recording with functional respiratory analyses is therefore recommended.

The clinical usefulness of an indicator of successful rapid palatal expansion in individual patients is critically dependent upon the accuracy that such a diagnostic tool has. Therefore, a critical approach to assess the potential of any parameter as a diagnostic aid in orthodontics has to rely on the concept that to have high accuracy, the measurement outcomes recorded before and after treatment have to show large enough differences, as compared to their corresponding variances. A statistical approach to quantify this ratio (taking into account the size of the study population) is provided by the calculation of the ES coefficient [Cohen, 1992]. A theoretical pre-requisite for a diagnostic tool to be accurate is to show an ES coefficient at least equal to 1.0 [Perinetti et al., 2009]. In the present study, the ES retrieved for the total Airway Volume was 0.65 and, although significantly different than zero, it did not reach the desired threshold for diagnostic potential (Table 1). On the contrary, the ES coefficients for the SpO_2 and AHI were equal to 4.12 and 4.13, respectively (Table 2). This evidence is in favor of a reliable diagnostic use of both SpO_2 and AHI to assess a successful rapid palatal expansion in growing subjects in terms of respiratory performance. These data thus warrants further longitudinal study to better define diagnostic ranges and their accuracy.

This study compared morphological volumes to functional analyses and the above mentioned results showed the importance of combining functional data when a morphological evaluation is performed in investigating airway changes before and after maxillary expansion treatment. In fact the measurement of the volumes of airway compartments may be biased by several factors such as head and tongue position during CBCT scan acquisition, breathing, swallowing movements, repositioning of the tongue and the mandible after treatment. Therefore, the reliability and repeatability of the CBCT recording of airway compartment has been questioned [Ribeiro et al., 2012].

Conclusions

1. The RME treatment induced significant increases in total Airway Volume, SpO_2 and AHI with particular clinical relevance of the SpO_2 and AHI.
2. Total Airway Volume was not correlated with SpO_2 and AHI changes.
3. Functional respiratory parameters should be included in studies evaluating the RME treatment effects on the respiratory performance.

Addendum

Measuring the airway using computational fluid dynamics: multimodal clinical application

Recently computational fluid dynamics (CFD) was employed in the investigation of airway before and after orthopaedic maxillary expansion. Iwasaki et al. [2012] used CFD to evaluate airway changes on nasal cavity after RME, demonstrating that it allowed to model the upper airway flow field created with patient specific geometrical characteristics from CBCT volumes, hence providing a more accurate assessment of air flow without any additional functional examinations needed. The following case report shows how CFD was used for the evaluation of the airflow of upper airway in one of the patients comprised in the presented study sample.

Nasal cavities and rhinopharynx of a 7 years and 1 month old Caucasian female derived from the whole sample were separately segmented and separated from the other soft and hard tissues (Fig. 3).

Airflows in the nasal cavities feature a wide array of basic flow phenomena because of their complex geometries and inhalation/exhalation waveforms. Thus, in addition to being transient 3D, they may include laminar/turbulent flows, stagnation point and boundary-layer flows, and flow separation with recirculation zones and may be impacted by distensible walls and heat and mass transfer.

The CAD-like geometry of the 3D model of the nasal cavities has been exported in a suitable format for the mesh generation (Fig. 4). The air volume of the cavities was discretised with polyhedral cells, except for the near-

FIG. 3 Segmentation and separation of soft tissues 3A, hard tissues 3B, nose and airway 3C. Frontal view 3D and right sagittal view 3E.

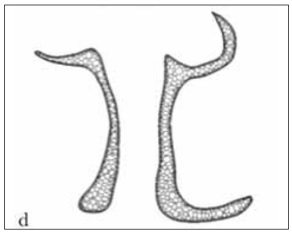

FIG. 4 3D CAD model of the nasal cavities. Axial 4A, isometric 4B, right sagittal 4C and frontal view 4D.

wall regions that were subdivided into prismatic layers. The flow inside the nasal cavities was assumed to be incompressible, steady and laminar (Fig. 5). Although the available experimental results did not reveal detailed flow fields, the observations indicated that the majority of airflows through nasal passages were laminar and quasi-steady. The governing equations were solved by the code Star-Ccm+ software, which is based on the finite volume method. Results showed that after the airflow enters the nasal cavity, the main part of flow passes through the middle-to-low portion of the main passageway between the middle and inferior meatuses. In particular, two high-speed regions were located under the middle and inferior meatuses.

For the CFD evaluation rhinopharynx (Fig. 6, 7) was segmented and analysed. The constructed 3D images were exported to the Project Falcon 2013 for Autodesk® freeware software which is a wind tunnel simulator that allows to interactively investigate the aerodynamic performance of a design at any stage using a robust meshing technique. The solver technology that drives Falcon utilizes the following CFD techniques to simulate the airflow over a body: transient, incompressible fluid flow solver, finite volume method, full 2D and 3D Navier-Stokes fluid solution, LES turbulence model. In the present case the flow was inserted inside the 3D model of the airway. The software allowed to obtain a qualitative evaluation of the airflow passing through the rhinopharynx and to compare the airflows before and after RME treatment.

In the presented simulation the air flows through the choanas toward the rhinopharynx and changes occur depending on the resistances due to the volume and the travelled path. The volume showed restrictions and smaller diameter in pre-treatment simulation corresponding to an enlargement of adenoids which partially blocked the entering airflow. The airflow would be blocked when meeting the posterior wall of the rhinopharynx and the flow would become gradually more turbulent increasing its velocity in some areas, especially in the lower portion of the flow, and stationary in some other areas. Moreover the whole amount of air would not seem able to overcome all the resistances due to the smaller volume at the adenoids level (Fig. 6).

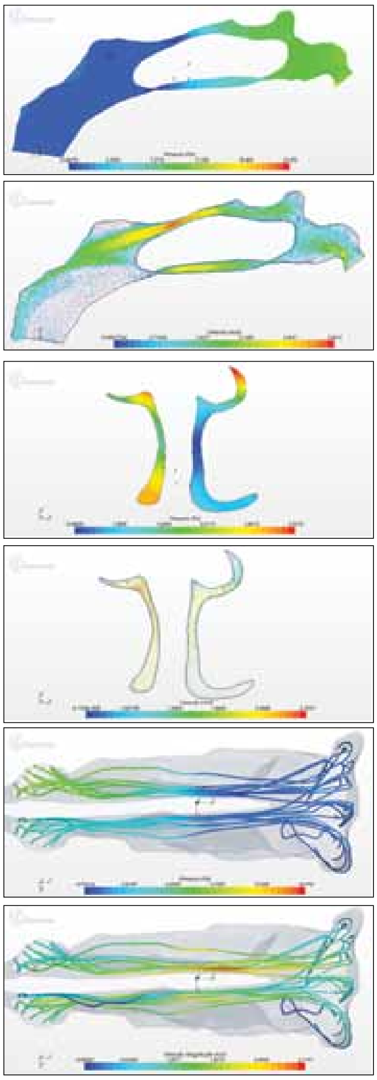

FIG. 5 Airflow passing through the nasal cavities. Pressure in the right sagittal, frontal and axial view (5 A, C, E) and velocity in the right sagittal, frontal and axial view (5 B, D, F).

After RME treatment an enlargement of the volume diameter was noticeable in addition to an apparent

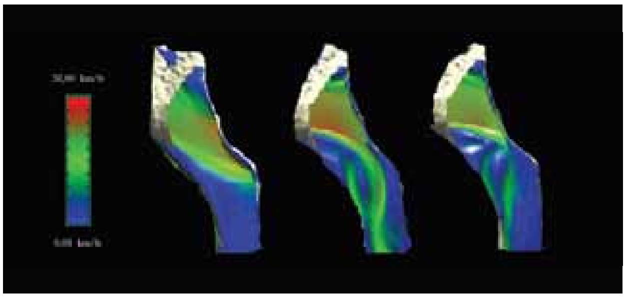

FIG. 6 Airflow passing through rhinopharynx before RME. Description in the text.

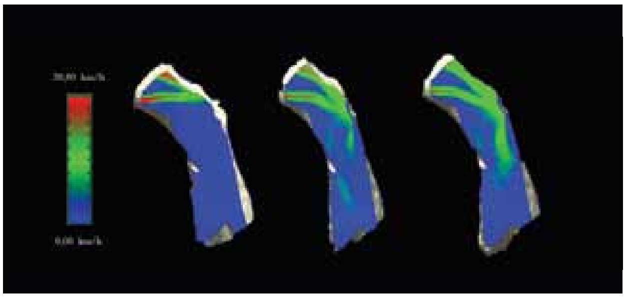

FIG. 7 Airflow passing through rhinopharynx after RME. Description in the text.

decrease of adenoid tissues in the posterior wall of the rhinopharynx. The airflow would become more steady and regular in velocity. As previously showed the flow would bump on the posterior wall of the airway but in this case it would not be blocked neither change its velocity and pathway (Fig. 7).

CFD allowed in the present case report to collect information about the dynamical characteristics of the airflow in addition to the morphological investigation gained from CBCT 3D reconstructions. As previously suggested for the analysis of nasal cavity airflow [Iwasaki et al., 2012] CFD would seem to be an exciting new high technology tool which should be further investigated and validated for the analysis of airway in orthodontics and dentofacial orthopaedics.

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