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The effect of rapid maxillary expansion on pharyngeal airway pressure during inspiration evaluated using computational fluid dynamics

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ABSTRACT

Introduction: Recent evidence suggests that rapid maxillary expansion (RME) is an effective treatment of obstructive sleep apnea syndrome (OSAS) in children with maxillary constriction. Nonetheless, the effect of RME on pharyngeal airway pressure during inspiration is not clear. The purpose of this retrospective study was to evaluate changes induced by the RME in ventilation conditions using computational fluid dynamics.
Methods: Twenty-five subjects (14 boys, 11 girls; mean age 9.7 years) who required RME had cone-beam computed tomography (CBCT) images taken before and after the RME. The CBCT data were used to reconstruct 3-dimensional shapes of nasal and pharyngeal airways. Measurement of airflow pressure was simulated using computational fluid dynamics for calculating nasal resistance during exhalation. This value was used to assess maximal negative pressure in the pharyngeal airway during inspiration.
Results: Nasal resistance after RME, 0.137 Pa/(cm^3/s), was significantly lower than that before RME, 0.496 Pa/(cm^3/s), and the maximal negative pressure in the pharyngeal airway during inspiration was smaller after RME (−48.66 Pa) than before (−124.96 Pa).
Conclusion: Pharyngeal airway pressure during inspiration is decreased with the reduction of nasal resistance by the RME. This mechanism may contribute to the alleviation of OSAS in children.

1. Introduction

Abnormal growth of the tissues constituting the upper airway can constrict the airway, predisposing people to obstructive sleep apnea syndrome (OSAS) [1]. The influence of this type of obstruction on the development of many childhood disorders is increasingly recognized [1–3]. The OSAS in children is associated with excessive daytime sleepiness, hyperactivity, attention deficit disorder, poor hearing, physical debilitation, and failure to thrive [3].

Arens et al. [4] described changes in the upper airway area and shape during tidal breathing in children with OSAS and demonstrated differences with the changes in control subjects. They noticed significantly more fluctuation in the airway size, with narrowing during inspiration, and this effect was more prominent at the higher oropharyngeal levels. Hori et al. [5] reported significant correlations between the apnea index and both the size of the constricted area of the pharyngeal airway and its narrowing rate during forced inspiration. According to these reports, nasal obstruction is thought to be the trigger of OSAS because negative pressure in the pharyngeal airway increases as the area of the pharyngeal airway shrinks.

There are a few studies [6–8] evaluating the effects of rapid maxillary expansion (RME) on alleviation of OSAS in children (Fig. 1). Cistulli et al. [6] showed that RME is an effective treatment in 9 out of 10 young children with mild to moderate OSAS and maxillary constriction.

The mechanism underlying the effects of RME on OSAS in children is unclear. We believe that this mechanism can be

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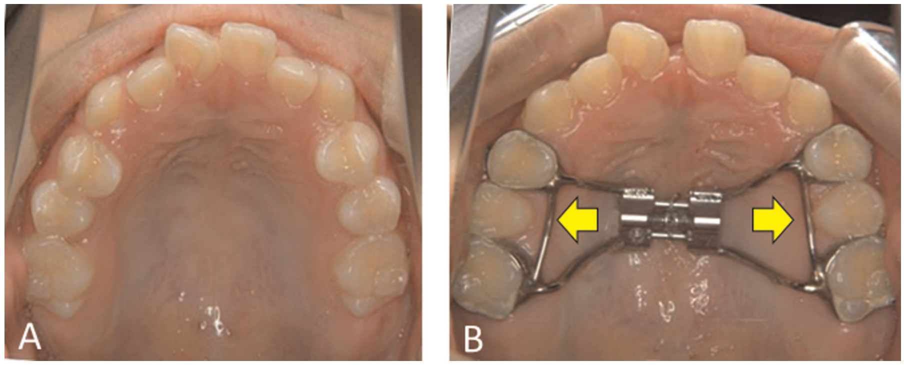

Fig. 1. The rapid maxillary expansion (RME) device and a change of dentition (A, before RME; B, after RME). A, constricted dentition. B, dentition expanded laterally by RME (yellow arrows) and concurrent maxillary midline dehiscence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

elucidated by evaluating nasal airway ventilation conditions (i.e., nasal resistance during exhalation that corresponds to the posterior method of rhinomanometry [9]) and the pharyngeal airway ventilation conditions (i.e., maximal negative pressure during inspiration) before and after RME. We also think that these ventilation conditions can be estimated using computational fluid dynamics (CFD). The purpose of this retrospective study was to use CFD to evaluate changes in ventilation conditions in the pharyngeal airway during inspiration after RME to clarify the mode of action of RME.

2. Methods

2.1. Subjects

A total of 44 patients who visited Orthodontic Office (Japan) to receive orthodontic treatment participated in this longitudinal retrospective study (23 boys, 21 girls). The eligibility criteria included (1) no previous orthodontic treatment, (2) no craniofacial or growth abnormalities, and (3) no enlargement of adenoids or tonsils. Cone-beam computed tomography (CBCT) images were acquired (which was not routine) before RME and after (RME group) or at the corresponding time points but without RME (control group). The RME group yielded serial CBCT images of 25 subjects (14 boys, 11 girls), with mean ages before and after RME of 9.96 ± 1.21 years and 11.23 ± 1.12 years, respectively (mean $\pm$ SD). Inclusion criteria were the following: mixed or early permanent dentition, a symmetrical sagittal position of first maxillary molars, moderately constricted maxilla, and insufficient maxillary arch circumference, with or without crossbite [10] The expander was a Hyrax (banded) device, shown in Fig. 1. The teeth required approximately 5 mm of maxillary expansion in the course of the orthodontic treatment. The expansion screw was turned 0.25 mm twice a day for 10 days or until a 5 mm expansion was achieved. Passive retention devices were not used before full orthodontic treatment. The mean treatment duration with an RME device was 5.5 ± 1.0 months. The control group consisted of serial CBCT images from 19 subjects (9 boys, 10 girls) with no history of RME. A pretreatment control CBCT image was taken in the RME group at 9.62 ± 1.12 years of age (before RME) and at 11.04 ± 1.21 years of age (after RME). The 2 CBCT scans were performed as follows. The first was performed at initial diagnosis. The second took place during careful examination for stage II treatment (final orthodontic treatment) after the orthodontic treatment that does not affect the airway shape without RME. The controls were approximately matched with the RME-treated subjects by gender, age, and dentition. The interval between the 2 CBCT scans was 1.27 years in the RME group and 1.42 years in the control group. The study was reviewed and approved by the Epidemiology Ethics Review Board of the University Graduate School of Medical and Dental Sciences, Japan.

2.2. Measurements

Each subject was seated in a chair with his or her Frankfort horizontal plane parallel to the floor. In this study, each subject was asked to hold his or her breath after the end of expiration because when awake, the pharyngeal airway diameter is smallest in this situation. Breath holding at this moment results in a static pharyngeal airway size that can be recorded consistently on all CT scans, thereby decreasing variation caused by changes in the pharyngeal airway diameter during the respiratory cycle [11]. A CBCT instrument (Alphard 3030; Asahi Roentgen Ind Co., Ltd., Kyoto, Japan) was set to maximum 80 kV, maximum 2 mA, collimation 22.7×22.7 mm; field of view (FOV) was $\phi 200 \times 179$ (H) mm, exposure time 17 s, and voxel dimensions $0.39 \times 0.39 \times 0.39$ mm. Because the volume of the pharyngeal airway is influenced by head posture, the craniocervical inclination of all subjects was examined to ensure that the inclination was between 90° and 105° [12]. The data were sent directly to a personal computer and stored in the DICOM (Digital Imaging and Communications in Medicine) format.

2.3. Morphological evaluation of intermaxillary molar width (Fig. 2)

For evaluation of intermaxillary molar width, a 3D coordinate system and 3D images were constructed using a medical image analysis system (ImagnosisVE; Imagnosis, Kobe, Japan) [13]. From the 3D reconstructed images, the intermaxillary molar width (i.e., the distance between the most medial points of the constricted part of the first maxillary molars) was measured to assess the morphological changes produced by RME (Fig. 2) [13].

2.4. Evaluation of the airway ventilation conditions (Figs. 3, 4)

Volume-rendering software (Intage Volume Editor; Cybernet, Tokyo, Japan) was used to generate 3D volume data of the upper airway [13–15]. Because the airway is a void surrounded by hard and soft tissues, inversion of 3D-rendered images is required, i.e., conversion of a negative value to a positive value and vice versa. We used threshold segmentation to select the CT units within the airway. The inverted air space exhibits significantly greater positive CT values than the denser surrounding soft tissue. The distinct high-contrast border produces clean segmentation of the airway. By modifying the threshold limits, we can use an appropriate range to define tissues of interest within a volume