Anatomic Predictors of Retropalatal Mechanical Loads in Patients with Obstructive Sleep Apnea

Yanru Li^a Jingying Ye^a Tianzuo Li^b Na Lin^b Zhenchang Wang^c
Chenyang Liang^c Al Sperry^d Demin Han^a

^aDepartment of Otolaryngology Head and Neck Surgery, Beijing Tongren Hospital, Capital Medical University; Key Laboratory of Otolaryngology Head and Neck Surgery (Capital Medical University), Ministry of Education,

^bDepartment of Anesthesia, Beijing Tongren Hospital, Capital Medical University, ^cMedical Imaging Center, Beijing Tongren Hospital, Capital Medical University, and ^dAir Liquide Healthcare, Beijing, China

Key Words

Sleep apnea · Upper airway · Anatomy · Magnetic resonance imaging · Collapsibility · Closing pressure

Abstract

Background: The retropalatal airway is one of the most collapsible sites during sleep in patients with obstructive sleep apnea (OSA). The primary anatomical contributors to increased collapsibility in the retropalatal segment remain unclear. **Objectives:** This study seeks to investigate how the balance between pharyngeal soft tissues and the bony enclosure influences retropalatal mechanical loads in patients with OSA. **Methods:** The segmental mechanical load of the retropalatal pharynx was determined by the region's critical closing pressure in 30 anesthetized, paralyzed and intubated subjects with OSA. The volumetric anatomical parameters of the retropalatal airway were evaluated using magnetic resonance imaging, and their associations with retropalatal closing pressures were analyzed. **Results:** Increased retropalatal closing pressure was associated with the increased proportion of volumetric pharyngeal soft tissues to the surrounding cervicomandibular bony frame ($r = 0.791$, $p < 0.001$), enlarged soft tissues of the lateral wall ($r = 0.752$, $p < 0.001$) and soft palate ($r = 0.726$, $p < 0.001$). The decreased volume of

the nasopharynx ($r = -0.650$, $p < 0.001$) and pharyngeal cavity ($r = -0.653$, $p < 0.001$) indicated a relatively higher retropalatal closing pressure. The multivariate linear regression model demonstrated that the proportion of retropalatal soft tissues to the bony frame and volume of the soft palate predicted 69.4% of the variability in closing pressure ($F = 30.674$, $p < 0.001$). **Conclusions:** The increased volumetric proportion of pharyngeal soft tissue to the bone enclosure may be an important contributor to increased retropalatal mechanical loads.

Copyright © 2011 S. Karger AG, Basel

Introduction

The retropalatal airway is one of the most collapsible sites during sleep in patients with obstructive sleep apnea (OSA) [1–3]. To explore more effective and targeted treatments for OSA, it is important to address the primary anatomical contributors to increased mechanical loads in the retropalatal area (RP). Previous studies have shown that patients with OSA have smaller retropalatal airways, more lateral pharyngeal wall soft tissues and larger parapharyngeal fat pads than controls [4–7], implying that these anatomical features may be associated with in-

creased airway mechanical loads. However, individuals may have varied upper airway (UA) collapsibility even if they have the same airway size, suggesting that UA mechanical loads cannot be attributed exclusively to narrowed pharyngeal cavities.

The anatomical imbalance in the volume of the rigid craniofacial bony frame and the volume of enclosed collapsible soft tissue may provide a better explanation for increased UA collapsibility [8–13]. Suratt and coworkers [8] found that the enlargement of soft tissue structures within the bony enclosure increased pharyngeal resistance in pigs. Animal models have recently been used to suggest [9, 10] that the mass loading of extraluminal tissue space results in increased resistance in UA, whereas mandibular advancement decreases the extraluminal tissue pressure. Isono and coworkers [11] found that a narrow bony enclosure is associated with a positive closing pressure in the oropharynx in OSA patients. Moreover, the anatomical imbalance between the volume of the soft tissues and the surrounding bony enclosure has recently been further documented in OSA patients compared to nonsnorers [12, 13]. Increased volume of the bony structures and changes in the surrounding soft tissues were found to be the mechanisms of action of mandibular advancement surgery in improving sleep apnea [14]. However, the predictive value of the anatomical balance for segmental mechanical loads in RP remains unclear.

The objective of this study is to test the hypothesis that the balance between the amount of soft tissues and the volume of the surrounding bony enclosure has great predictive value for retropalatal mechanical loads. In addition, the relative contributions of other specific anatomical risk factors to the static mechanical loads of RP are evaluated.

Methods

The research protocol was approved by the ethics committee of Beijing Tongren Hospital (where the study was conducted). The aim and potential risks of the study were fully explained to each subject, and written consent was obtained from each.

The following design was utilized. First, the segmental closing pressure in RP was measured to quantify the segmental mechanical loads. To eliminate the influence of the neural control mechanism on UA collapsibility, the segmental closing pressures were determined under passive conditions [12]. The retropalatal anatomical balance as well as the other pharyngeal anatomical parameters were subsequently evaluated using magnetic resonance imaging (MRI). Their associations with mechanical loads of RP were analyzed to determine their contribution to collapsibility of the corresponding pharyngeal segment.

Subjects

A total of 30 participants of the Chinese Han population who were undergoing UA surgery were studied. Subjects who had undergone previous pharyngeal surgery were excluded. The 30 subjects (27 males) were 37.8 ± 7.7 years (20.1–59.0) old on average, and their body mass index (BMI) was 28.5 ± 4.3 (20.5–35.8). All subjects underwent overnight polysomnography with an apnea-hypopnea index (AHI) >5 ; AHI was 53.5 ± 24.1 events/h (6.1–102.2), while AHI in a supine position was 68.9 ± 23.6 events/h (10.7–130.0).

MRI of UA

UA imaging was performed in all subjects during an awakened state using a 1.5-T MRI scanner (Signa Excite; General Electric, Wisc., USA). The subject's head was in a supine position in the soft tissue Frankfort plane (tragus of the ear to orbital fissure), perpendicular to the scanner table, and fixed prior to the scan [4]. Throughout the scanning, subjects were instructed to keep their mouths closed, breathe normally through their noses, and assume a normal relaxed bite. They were instructed not to move their head or swallow. The following parameters were used during the scanning:

- (1) Sequential T1-weighted spin-echo axial sections, spanning from the most superior aspect of the nasopharynx to the false vocal cords (spin-echo repetition time = 500.0 ms, echo time = 11.5 ms, 320×192 matrix, number of signal averages = 2 NEX, FOV = 20.0 cm, slice thickness of 4.0 mm and 0.0 mm skip).
- (2) Sagittal T1-weighted spin echo MR sequence, scanning range from one mandibular rami to the other (spin-echo repetition time = 640.0 ms, echo time = 14.5 ms, 320×224 matrix, number of signal averages = 2, FOV = 20.0 cm, slice thickness of 4.0 mm and 0.0 mm skip).

The mean acquisition time for each sequence was 3.5 min. The UA volumetric reconstructions were performed using the analysis system of Volume Viewer Vxtool 3.0.64z (General Electric).

Anatomic Definitions, Measurements and Analyses

The UA was divided into three parts: the nasopharynx cavity, the RP (from the level of the hard palate to the tip of the uvula), and the retroglossal region (RG, from the tip of the uvula to the top margin of the epiglottis) [4, 13]. The three parts of the pharyngeal cavity, their surrounding soft tissues and the bony frame were evaluated separately using the following measurements.

The anatomical parameters for the three-dimensional volumetric measurements included (1) the airway in the RP, RG and nasopharynx, (2) the soft tissues of the lateral and posterior pharyngeal wall, (3) the parapharyngeal fat pad, (4) the space surrounded by the cervicomandibular bony frame (fig. 1) and (5) the tongue, soft palate and tonsils. The volumetric proportions of the soft tissues to the surrounding cervicomandibular frame at RP and RG were calculated by dividing the volume of soft tissues (total soft tissues of the lateral and posterior pharyngeal wall and the soft palate) by the volume of the cervicomandibular bony frame and multiplying the result by 100%. The structural constitution of the lateral pharyngeal wall was evaluated by the proportion of the parapharyngeal fat pad to the volume of total lateral pharyngeal soft tissues (in percent).

Measurement of Retropalatal Pharyngeal Mechanical Load

The retropalatal mechanical load was quantified by the segmental critical closing pressure (P_{close}) of the RP. P_{close} was defined as the intraluminal pressure as the airway just closed (cross-sectional area = zero). A higher retropalatal P_{close} indicates a more collapsible retropalatal pharynx.

To eliminate the influence of the neural control mechanism on UA collapsibility, retropalatal P_{close} was evaluated under general anesthesia with complete muscle paralysis [12, 15]. Each subject was placed in the supine position, with the neck in a neutral position. After intubation through the nasal passage (outer diameter 9.5 mm and inner diameter 7.0 mm), general anesthesia was induced through the intravenous administration of propofol (0.5 mg/kg) and vecuronium (0.08 mg/kg), which produced complete paralysis for the duration of the experiment. Two to three percent sevoflurane and mixed oxygen as well as nitrous oxide were given through inhalation to maintain the anesthesia. Subjects were ventilated using an anesthetic machine, and their SpO_2 , electrocardiogram and blood pressure were monitored.

The positive intraluminal pressure was delivered nasally and controlled by a pressure control system in steps of 1 cm H_2O using a modified CPAP machine (Knight Star 330; Puritan Bennett, Pleasanton, Calif., USA). A modified anesthetic nasal mask and nasal plugs were used to prevent air leaks. Pressure monitoring was used to ensure that the intraluminal pressure was correctly delivered (SSD1057; Millar Instrument Co., Houston, Tex., USA).

Pharyngeal images at each step of the decreased pressure were recorded and analyzed using computer-assisted fiberoptic pharyngoscopy. The method of endoscope calibration and measurement has been described in previous reports [16]. Briefly, the fiberoptic pharyngoscope (ENF-P4; Olympus, Tokyo, Japan; diameter 3.6 mm) was passed through the naris to the level of the soft palate and fixed (at a distance of 2 cm above the level of the uvula). The image of the pharynx at each level of P_{AW} was recorded and transferred into the computer (fig. 2). All measurements included in this study were done when both the intraluminal pressure and the cross-sectional area of the airway were steady to ensure the measurement of the static pharyngeal mechanics.

With the scatter plot, the retropalatal pressure cross-sectional area in each subject was plotted. Closing pressure was defined as the intraluminal pressure corresponding to no open area [12, 15]. As described by Isono and coworkers [11], the static pressure-area relationships for the oropharynx could be denoted as the exponential function $A = A_{max} - B \times \exp(-K \times P_{AW})$, where B, K and A_{max} are constants and A was the cross-sectional area. Using this function, the model pressure-area relationship of each subject could be estimated using the curve-fitting tool (Matlab 7.1; Mathworks Inc., Natick, Mass., USA). The pressure-area relationship of each subject was imported into the software for curve fitting. The medians of A_{max} , B and K for the 30 subjects were 214.95 (185.30, 244.03), 606.05 (400.58, 1,232.00) and 0.14 (0.11, 0.23), respectively. The retropalatal critical P_{close} (cross-sectional area = 0 mm²) could be calculated using the following equation: $P_{close} = K - 1 \times \ln(B/A_{max})$. In addition, to test the accuracy of the P_{close} estimated by curve fitting after intubation, we compared the closing pressure measured without intubation ($P_{close-0}$) and with intubation ($P_{close-1}$) in 12 patients with mild sleep apnea in our preliminary experiment. The mean $P_{close-0}$ was 2.12 ± 2.25 cm H_2O ; the median of A_{max} , B and K measured without intubation was 241.80 (202.45, 309.60), 335.95 (273.95, 420.13) and 0.20 (0.15, 0.23), respectively.

Fig. 1. The range of the surrounding cervicomandibular bony frame and its enclosed soft tissues of the airway on one slice of the image (white line). * = Lateral pharyngeal soft tissue within the parapharyngeal fat pad; P = internal pterygoid muscle; SP = soft palate; F = parapharyngeal fat pad. The posterior and lateral parts of the bony frame were surrounded by the two mandibular ramus and vertebrae. The anterior range was the edge of the hard palate and the soft palate.

The mean $P_{close-1}$ was 2.24 ± 2.50 cm H_2O ; the median of A_{max} , B, and K measured with intubation was 236.30 (201.97, 314.77), 340.25 (273.12, 430.15) and 0.19 (0.15, 0.21), respectively. Intubation did not appear to affect the results of individual P_{close} of RP as paired sample t tests showed that no significant difference existed between $P_{close-0}$ and $P_{close-1}$ ($t = 1.081$, $p = 0.303$).

Analyses

Statistical analyses were completed using the software package SPSS 13.5. A single-sample Kolmogorov-Smirnov test was used to test whether the variables were normally distributed. Descriptive statistics were presented as means $\pm$ SD. The association between parameters was evaluated using the Pearson correlation coefficient. Linear regression analyses were performed on independent variables against the retropalatal P_{close} . All the variables that were correlated to retropalatal P_{close} were included as candidates for the analyses. The stepwise algorithm was subsequently used to choose the predictors for the dependent variable (P_{close}). $p < 0.05$ was considered to be significant.

Results

Anatomical Balance and Its Correlations with Retropalatal P_{close}

During muscle paralysis at atmospheric pressure, pharyngeal cavity collapse at the retropalatal airway was observed in all subjects. The mean retropalatal P_{close} was

Fig. 2. A sample of the corresponding cross-sectional area of steps of intraluminal pressure (the scatter plot) and pharyngeal images. The pressure monitoring tube and intubation tube can be seen in the images. The curve is plotted according to the exponential function of the subject. The area-pressure relationship below the cross-sectional area of the tracheal tube is plotted as a dashed line. The point of intersection of the curve and the x axis was the estimated P_{close} (cross-sectional area = 0 mm²).

7.15 ± 3.57 cm H₂O. The mean proportion of soft tissues to bony frame in RP was 96.09 ± 2.00%. Increased retropalatal closing pressure was associated with an increased proportion of volumetric pharyngeal soft tissues to the surrounding cervicomandibular bony frame in RP ($r = 0.791$, $p < 0.001$). Figure 3 shows the scatter plots of individual values of retropalatal P_{close} and proportion of soft tissues to bony frame in RP.

Figure 4 shows a representative example of volumetric reconstructions of pharyngeal cavities and surrounding tissues in RP from two subjects with different retropalatal mechanical loads. With the same volume of pharyngeal cavities, the subject with a larger proportion of soft tissue to the bony frame had higher retropalatal P_{close} .

The mean volumetric proportion of parapharyngeal fat pad to the total lateral pharyngeal soft tissues was 23.41 ± 6.88%. No relationship existed between the proportion and retropalatal P_{close} ($r = -0.043$, $p = 0.821$), indicating that, with the same volume of soft tissues, the structural constitution of the lateral pharyngeal wall did not affect retropalatal mechanical loads.

Fig. 3. Scatter plot of retropalatal P_{close} and proportion of soft tissues to bony frame in retropalatal segment. A strong positive association existed ($r^2 = 0.626$).

Fig. 4. Volumetric reconstructions of soft tissues surrounded by cervicomandibular bony frame in RP in subject A ($P_{\text{close}} = 8.3$ cm H₂O) and subject B ($P_{\text{close}} = 0.2$ cm H₂O). The volume of airway caliber (marked in blue; dark gray in the print version) was similar in subjects A and B (2.436 and 2.545 cm³, respectively). The proportion of soft tissue to the bony frame was higher in subject A than in subject B (96.9 and 92.6%, respectively), which caused a higher retropalatal P_{close} in subject A.

Color version available online

Table 1. Volumetric measurements in RP and their correlations with retropalatal P_{close}

Factors	Volume, cm ³	r	p
Soft palate	8.54 ± 1.63	0.726	<0.001**
Tonsils	9.86 ± 5.24	0.248	0.187
Retropalatal pharyngeal cavity	1.83 ± 0.67	-0.653	<0.001**
Parapharyngeal fat pad	12.00 ± 5.04	0.396	0.030*
Total soft tissues of the lateral wall	51.03 ± 14.38	0.752	<0.001**
Space within the cervicomandibular bony frame	61.11 ± 14.92	0.766	<0.001**

Data are shown as means ± SD. n = 30. * p < 0.05; ** p < 0.01.

Table 2. Volumetric measurements in RG and their correlations with retropalatal P_{close}

Factors	Volume, cm ³	r	p
Retroglossal pharyngeal cavity	3.08 ± 1.20	-0.560	0.001**
Parapharyngeal fat pad	7.95 ± 4.09	0.220	0.250
Total soft tissues of the lateral wall	28.93 ± 6.49	0.340	0.070
Space within the cervicomandibular bony frame	259.69 ± 85.77	0.320	0.080
Tongue	105.27 ± 23.26	0.563	0.001**

Data are shown as means ± SD. n = 30. ** p < 0.01.

Volumetric Anatomical Parameters and Their Correlations with Retropalatal P_{close}

Other volumetric anatomical measurements of UA and their correlations with retropalatal P_{close} are listed in tables 1 and 2. Decreased volume of the pharyngeal cavity in the nasopharynx indicated a relatively higher segmental P_{close} in RP ($r = -0.650$, $p < 0.001$). BMI, which may affect the amount of the soft tissue volume surrounding airway, was positively correlated with retropalatal P_{close} in RP ($r = 0.575$, $p = 0.001$). The increased seg-

mental closing pressure of RP was also associated with the decreased cross-sectional area at both the level of the hard palate ($r = -0.446$, $p = 0.014$) and the uvula ($r = -0.609$, $p < 0.001$).

Regression Model for Factors Contributing to Mechanical Loads of the Retropalatal Airway

All three-dimensional anatomy parameters previously correlated with P_{close} were considered as candidates for the regression model. Two variables were ultimately se-

lected using the stepwise algorithm. The model was as follows: $P_{\text{close}} = -122.936 + 1.172 \times (\text{proportion of the soft tissues to bony frame in RP}) + 0.792 \times (\text{volume of the soft palate})$. The standardized coefficients for these variables were 0.552 and 0.355, respectively. The following variables were not included in the model: BMI, volume of the tongue and parapharyngeal fat pad, volume of the soft tissues of the lateral wall, and volume of the pharyngeal cavity in RP, RG and nasopharynx. The multivariate linear regression model using stepwise protocol demonstrated that anatomical parameters could explain 69.4% of the variability in P_{close} ($F = 30.674$, $p < 0.001$).

Discussion

Anatomical Balance and Its Contribution to Retropalatal Mechanical Loads

The concept of the anatomical balance of the UA was proposed in 1995 by Suratt and coworkers [8], who found that the enlargement of soft tissue structures within the bony enclosure was responsible for the narrowed airway and increased pharyngeal resistance. Isono and coworkers [11] pointed out that the partially enclosed bony frame was constituted by the mandible and cervical vertebrae. They further assessed the UA anatomical balance by measuring tongue size and craniofacial dimension using cephalometric radiograph [12]. The three-dimensional pharyngeal anatomical balance recently described by Suzuki and coworkers [13] was calculated by dividing the sum of the lateral pharyngeal wall and tongue volumes by the craniofacial volume. The previous study documented the significant difference in anatomical balance between OSA patients and control groups [12, 13]. However, the predictive value of the anatomical balance for segmental mechanical loads in the RP remains unclear. Both increased mechanical loads and compromised UA dilator muscle function contributed to sleep apnea. Although many anatomy parameters were found to be correlated with severity of AHI, the correlation may be obscured due to different levels of UA dilator activities among individuals. Thus, we chose to examine the relationship between mechanical loads and anatomical parameters.

To our knowledge, this study is the first to prove that the segmental anatomical imbalance in RP is of significant predictive value to static mechanical loads of the corresponding pharyngeal segment. Therefore, the volumetric proportion of pharyngeal soft tissue to the bony enclosure should be considered when doctors try to de-

crease the mechanical loads of RP. For patients with a higher proportion of soft tissues to the surrounding bony frame, more soft tissues might be reduced or more CPAP pressure might be needed to open the retropalatal airway.

How does the balance between the pharyngeal soft tissue and the bony enclosure influence the mechanical loads in RP? The answer is twofold. Primarily, in a fixed volume bony frame, more pharyngeal cavity would be occupied if there were more soft tissues within the bony enclosure, which results in a smaller baseline airway size [8]. Once all space in the pharyngeal cavity is occupied, a further increase in the amount of soft tissues will squeeze together and lead to increases in soft tissue pressure and mechanical loads. Isono and coworkers [11] demonstrated the theory in their models.

Meanwhile, the amount of the baseline volume of collapsible soft tissues would affect the segmental mechanical loads of the pharynx despite the baseline volume of the pharyngeal cavity, although this is a relatively minor aspect because the greater the baseline volume of the collapsible soft tissues, the greater the increase in total soft tissue volume per unit of extraluminal tissue pressure decrease. Briefly, in a segment of static pharynx, the intraluminal pressure should be positively related to the compressive pressure exerted by the surrounding tissues (for the balance of the constrictive and dilated forces). When the intraluminal pressure (proportional to extraluminal pressure) decreases, if the baseline volume of collapsible soft tissues is greater in a subject, the increases in the soft tissue volume will be greater, thereby occupying more of the pharyngeal cavity. This possible explanation is consistent with the findings of Kairaitis et al. [9, 10]. The soft tissue pressure in the pharyngeal wall decreases with the advancing mandible in rabbits, suggesting that decreased proportions of soft tissues to the bony frame may lead to decreased tissue pressure.

In the current study, all participants were from the Chinese Han population. The BMI and age of the subjects in this study were similar to those in previous Asian studies [3, 11]. Ethnic differences in OSA, especially cephalometry measurements, have been mentioned in many studies [17, 18]. Previous interethnic cephalometry studies found that Asian men were more likely to have severe OSA at a nonobese level of BMI when using Caucasian standards for obesity; Asian men were also noted to have a significantly shorter cranial base and a smaller anterior cranial base angle [17]. In another interethnic comparison, the Chinese group showed a shorter and

steeper anterior cranial base, smaller midface, smaller and more posteriorly positioned mandible, and larger total and upper facial height compared to Caucasians matched for age, BMI and AHI [18]. These results indicate that UA anatomical factors may be of increased importance in contributing to sleep apnea among the Asian population.

Some parameters of RG (such as the volume of the tongue) were also associated with retropalatal mechanical loads. One possible interpretation is the overlapping of the tongue and the soft palate in the RP. Structurally, the dorsum of the tongue is located anterior to the soft palate. Isono et al. [19] found that the pressure between the dorsum of the tongue and anterior wall of the soft palate, which changes during the obstruction, significantly depends on the collapsibility of the retroglossal airway, indicating that posterior displacement of the tongue pushes the anterior wall of the soft palate backwards and possibly maintains the closure at the retropalatal airway. Thus, it is possible that a relatively large tongue in the oral cavity may add compressive pressure to the soft palate and increase the mechanical loads in RP.

Influence of the Constitution of the Pharyngeal Wall on Retropalatal Mechanical Loads

The soft tissues of the pharyngeal wall associated with increased mechanical loads in RP included pterygoid muscles, the soft palate, parapharyngeal fat pads, prevertebral muscles, mucosa and some lymphatic tissues. However, whether their different rigidities lead to differences in the mechanical loads of the airway is not known. Davidson and colleagues [5] did not find an association between the density of fat content in the posterior tongue and severity of OSA. However, an increased volume in parapharyngeal fat pads was reported to be an important risk factor for OSA [4]. The results in the current study did not indicate a relationship between retropalatal P_{close} and the proportion of parapharyngeal fat pads, implying that the volume of total lateral pharyngeal soft tissues – rather than the amount of fat content – influences the retropalatal mechanical loads.

Limitations of the Current Study

Anatomy parameters were evaluated during an awakened state in the current study. Thus, different levels of UA dilator activities among subjects may obscure the relationship between size of the pharyngeal cavity and retropalatal P_{close} . For the shape and the volume of the pharyngeal cavity during wakefulness, the anterior-

posterior diameters in particular may have been affected by the activities of the UA muscles [20, 21] as such, it can be deduced that the correlation between the anterior-posterior diameter of the pharynx and retropalatal P_{close} of the RP segment was most affected. This is why we did not include the analysis of these relationships in this study.

The measurement of P_{close} according to the linear relationship between upstream nasal pressure and maximal inspiratory flow also allows evaluation of the mechanical properties of the pharynx by greatly reducing neuromuscular factors [21–23]. Since the segmental P_{close} cannot be measured using abbreviated methods, this study chose to measure the static retropalatal mechanical loads in muscular paralysis. Some limitations are inherent in the measurements. First, the endotracheal tube might impact the pharyngeal collapsibility measurements due to the area occupied by the tracheal tube. The area-pressure relationship below the cross-sectional area of the nasal tracheal tube could not be measured directly. Thus, retropalatal P_{close} was estimated using the static pressure-area relationship and curve fitting to eliminate the bias to the measurement. Although the closing pressure measured without intubation and the estimated P_{close} by curve fitting after intubation were compared in our preliminary experiment, additional factors such as surface tension, which was reported to be an independent factor that can affect both opening pressure and P_{close} [24–26], were not taken into consideration in the analyses. Whether the difference of the surface tension of the pharyngeal mucus and endotracheal tube between individuals attributes to the measurement was not clear. As all subjects were examined under the same condition, the estimated P_{close} by curve fitting did not appear to have introduced a bias to the associations between mechanical loads of RP and anatomical parameters.

Furthermore, endoscopies were used to evaluate the cross-sectional area of the pharynx. Although image sampling and calibration were standardized in this study, it is difficult to avoid the examiner's subjective judgment in the measurement of pharyngeal images. All images were measured by one investigator who was blind to the MRI parameters to minimize the subjectivity in this study.

Further studies are needed to determine the anatomical risk factors for increased mechanical loads in RG as well as to investigate the influence of upstream resistance to dynamic mechanical loads of UA.

Conclusion

In conclusion, the proportion of the volume of the pharyngeal soft tissues to the bony enclosure correlates to static retropalatal mechanical loads in patients with OSA. Enlarged volumes of the soft palate and the lateral pharyngeal wall soft tissues as well as decreased volume of the retropalatal airway indicate increased retropalatal mechanical loads.

Financial Disclosure and Conflicts of Interest

Funding for this project came from Chinese National Scientific Fund No. 30730100 (key project) and No. 30672304, and the Science and Technology Key Projects of the Beijing Municipal Commission of Education (No. KZ201010025020). Al Sperry works for Air Liquide.

References

- 1 White DP: The pathogenesis of obstructive sleep apnea. *Am J Respir Cell Mol Biol* 2006; 34:1–6.
- 2 Arens R, Marcus CL: Pathophysiology of upper airway obstruction: a developmental perspective. *Sleep* 2004;27:997–1019.
- 3 Han D, Ye J, Wang J, et al: Determining the site of airway obstruction in obstructive sleep apnea with airway pressure measurements during sleep. *Laryngoscope* 2002;112: 2081–2085.
- 4 Schwab RJ, Pasirstein M, Pierson R, et al: Identification of upper airway anatomic risk factors for obstructive sleep apnea with volumetric MRI. *Am J Respir Crit Care Med* 2004;168:522–530.
- 5 Barkdull GC, Kohl C, Patel M, Davidson TM: Computed tomography imaging of patients with obstructive sleep apnea. *Laryngoscope* 2008;118:1486–1492.
- 6 Verbraecken JA, De Backer WA: Upper airway mechanics. *Respiration* 2009;78:121–133.
- 7 Hsu PP, Tan BY, Chan YH, et al: Clinical predictors in obstructive sleep apnea patients with computer-assisted quantitative video endoscopic upper airway analysis. *Laryngoscope* 2004;114:791–799.
- 8 Winter WC, Gampper T, Gay SB, Suratt PM: Enlargement of the lateral pharyngeal fat pad space in pigs increases upper airway resistance. *J Appl Physiol* 1995;79:726–731.
- 9 Kairaitis K, Howitt L, Wheatley JR, et al: Mass loading of the upper airway extraluminal tissue space in rabbits: effects on tissue pressure and pharyngeal airway lumen geometry. *J Appl Physiol* 2009;106:887–892.
- 10 Kairaitis K, Stavrinou R, Parikh R, et al: Mandibular advancement decreases pressures in the tissues surrounding the upper airway in rabbits. *J Appl Physiol* 2006;100: 349–356.
- 11 Watanabe T, Isono S, Tanaka A, et al: Contribution of body habitus and craniofacial characteristics to segmental closing pressures of the passive pharynx in patients with sleep-disordered breathing. *Am J Respir Crit Care Med* 2002;165:260–265.
- 12 Tsuiki S, Isono S, Ishikawa T, et al: Anatomical balance of the upper airway and obstructive sleep apnea. *Anesthesiology* 2008;108: 1009–1015.
- 13 Saigusa H, Suzuki M, Higurashi N, et al: Three-dimensional morphological analyses of positional dependence in patients with obstructive sleep apnea syndrome. *Anesthesiology* 2009;110:885–890.
- 14 Chan AS, Sutherland K, Schwab RJ, et al: The effect of mandibular advancement on upper airway structure in obstructive sleep apnoea. *Thorax* 2010;65:726–732.
- 15 Isono S, Remmers JE, Tanaka A, et al: Anatomy of pharynx in patients with obstructive sleep apnea and in normal subjects. *J Appl Physiol* 1997;82:1319–1326.
- 16 Ye J, Han D, Wang J, et al: Computer-assisted fiberoptic pharyngoscopy in obstructive sleep apnea syndrome. *J Oto-Rhino-Laryngology and Rel Spec* 2007;69:153–158.
- 17 Li KK, Kushida C, Powell NB, et al: Obstructive sleep apnea syndrome: a comparison between Far-East Asian and white men. *Laryngoscope* 2000;110:1689–1693.
- 18 Liu Y, Lowe AA, Zeng X, et al: Cephalometric comparisons between Chinese and Caucasian patients with obstructive sleep apnea. *Am J Orthod Dentofacial Orthop* 2000;117: 479–485.
- 19 Isono S, Tanaka A, Nishino T: Dynamic interaction between the tongue and soft palate during obstructive apnea in anesthetized patients with sleep-disordered breathing. *J Appl Physiol* 2003;95:2257–2264.
- 20 Litman RS, McDonough JM, Marcus CL, et al: Upper airway collapsibility in anesthetized children. *Anesth Analg* 2006;102:750–754.
- 21 Jordan AS, White DP: Pharyngeal motor control and the pathogenesis of obstructive sleep apnea. *Respir Physiol Neurobiol* 2008; 160:1–7.
- 22 Smith PL, Wise RA, Gold AR, Permutt S: Upper airway pressure-flow relationships in obstructive sleep apnea. *J Appl Physiol* 1988;64: 789–795.
- 23 Schwartz AR, O'Donnell CP, Baron J, et al: The hypotonic upper airway in obstructive sleep apnea: role of structures and neuromuscular activity. *Am J Respir Crit Care Med* 1998;157:1051–1057.
- 24 Kirkness JP, Eastwood PR, Szollosi I, et al: Effect of surface tension of mucosal lining liquid on upper airway mechanics in anesthetized humans. *J Appl Physiol* 2003;95: 357–363.
- 25 Kirkness JP, Christenson HK, Garlick SR, et al: Decreased surface tension of upper airway mucosal lining liquid increases upper airway patency in anaesthetized rabbits. *J Physiol* 2003;547:603–611.
- 26 Kirkness JP, Madronio M, Stavrinou R, et al: Relationship between surface tension of upper airway lining liquid and upper airway collapsibility during sleep in obstructive sleep apnea hypopnea syndrome. *J Appl Physiol* 2003;95:1761–1766.