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SCIENTIFIC INVESTIGATIONS

Comparison of anatomic and aerodynamic characteristics of the upper airway among edentulous mild, moderate, and severe obstructive sleep apnea in older adults

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Study Objectives: First, to compare the upper airway's anatomic and aerodynamic characteristics of the edentulous older adults who experience mild, moderate, and severe obstructive sleep apnea (OSA). Second, to examine the correlation between the severity of OSA and the anatomic and aerodynamic characteristic(s) of the upper airway in these edentulous individuals.

Methods: NewTom5G cone beam computed tomography scans of 58 edentulous individuals with mild, moderate, and severe OSA were included in this analysis. 1) Computational models of the upper airway were reconstructed based on cone beam computed tomography images and the anatomical and aerodynamic characteristics of the upper airway were examined by an observer blind to OSA severity. 2) Pearson correlation analysis was used to determine the correlation between apnea-hypopnea index and the anatomic and aerodynamic characteristics of the upper airway.

Results: Compared with edentulous patients with mild and moderate OSA, those with severe OSA have a more hourglass-shaped upper airway. The severity of OSA, namely, apnea-hypopnea index, was significantly correlated with the length, shape, and minimum cross-sectional area of the upper airway. During inspiration, the mean velocity of the airflow within the upper airway of the edentulous patients with severe OSA was higher than that of patients with mild and moderate OSA. During both inspiration and expiration, apnea-hypopnea index was found to be significantly correlated with maximum velocity (P = .05) and airway resistance (P = .024, 0.038).

Conclusions: The edentulous patients with severe OSA have a more hourglass-shaped upper airway. The findings also suggest that, during inspiration, the airflow travels faster in edentulous patients with severe OSA than in those with mild or moderate OSA.

Clinical Trial Registration: Registry: ClinicalTrials.gov; Name: The Effect of Nocturnal Wear of Dentures on Sleep and Oral Health Related Quality of Life; URL: https://clinicaltrials.gov/ct2/show/NCT01868295; Identifier: NCT01868295.

Keywords: edentulism, older adults, obstructive sleep apnea, cone beam computed tomography, computational fluid dynamics, upper airway, apnea-hypopnea index

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BRIEF SUMMARY

Current Knowledge/Study Rationale: The world population is rapidly aging. The upper airway plays an important role in the pathogenesis of obstructive sleep apnea (OSA). The pathogenesis of OSA, especially in older adults who are edentulous, is still unknown.

Study Impact: Our study found that the edentulous patients with severe OSA have a more hourglass-shaped upper airway. The airflow travels faster in edentulous patients with severe OSA than in those with mild or moderate OSA during inspiration. These findings could help to clarify the pathogenesis of OSA in edentulous individuals.

INTRODUCTION

Obstructive sleep apnea (OSA) is a sleep-related breathing disorder, often associated with a compromised upper airway space and an increase in upper airway collapsibility.[1] According to the American Academy of Sleep Medicine Task Force and based on the apnea-hypopnea index (AHI) obtained from polysomnography recording, patients with OSA are classified as mild (AHI of 5–15 events/h), moderate (AHI of 15–30 events/h), and severe (AHI > 30 events/h).[2,3] Complete tooth loss (edentulism) is considered to worsen upper airway obstruction during sleep.[4,5] In this study, we focus on edentulous individuals with OSA syndromes.

Over the last few decades, cone beam computed tomography (CBCT) has been used to analyze the upper airway anatomy in patients with OSA. Furthermore, computational fluid dynamics

(CFD) has been used to simulate airflow in OSA research using 3-dimensional datasets from CBCT.[6–9] Accordingly, a systematic review on this subject indicated that the minimum cross-sectional area (Min-CSA) is an anatomical landmark of the upper airway that is related to the pathogenesis of OSA in dentulous individuals.[10] However, no findings were reported in regard to edentulous individuals. Therefore, this study used CBCT images to compare the upper airway's anatomic and aerodynamic characteristics of the edentulous individuals with mild, moderate, and severe OSA. Comparison of the anatomic and aerodynamic characteristics of the upper airway, among patients with mild, moderate, and severe OSA can add insight into understanding the progression of OSA in edentulous individuals. Furthermore, the correlation between the severity of OSA and the anatomic and aerodynamic characteristic(s) of the upper airway in edentulous patients with OSA were examined.

METHODS

Study design

This is a secondary data analysis of a randomized clinical trial designed to investigate the effect of nocturnal wear of complete dentures on sleep and oral health-related quality of life (ClinicalTrials.gov. Identifier: NCT01868295). The protocol and the details of the clinical trials have been published previously.[11,12] This trial provided support to usual practice guidelines to remove dentures at night in edentulous older adults with sleep apnea.[12] Informed consent was obtained from each eligible participant before proceeding with the trial.

Inclusion and exclusion criteria

The inclusion criteria for the clinical trial were: 1) being aged 65 years or older; 2) having worn a complete set of removable dentures in the past year but not during sleep in that period; 3) having an AHI score of at least 10 events/h at screening; 4) having an adequate understanding of written and spoken English or French; 5) being able to understand and respond to the questionnaires used in the study; 6) agreeing to follow the research study instructions. Participants were excluded if they: 1) had an AHI score less than 10 events; 2) had any severe cardiologic, neurologic, psychological, or psychiatric condition, respiratory disease, acute airway infection, or any other health condition that jeopardizes sleep; 3) score 24 or less on the Mini-Mental State Examination[13]; 4) regularly consumed more than 2 (for women) or 3 (for men) alcoholic beverages per day; 5) were taking medication or any illicit drug that affects sleep architecture or respiratory muscle activity (that is, hypnotics, psychostimulants, anticonvulsant, or antipsychotics); 6) were receiving regular continuous positive airway pressure therapy or nocturnal supplemental oxygen; 7) had sleepiness deemed to be unsafe and requiring urgent treatment.

Polysomnography recording

Polysomnography (Embla Titanium, Denver, CO) was collected with dentures in situ by the sleep technologist by means of 1 portable overnight recording.[14,15] Portable overnight polysomnography recordings included the following variables: electroencephalogram (F3, F4, C3, C4, O1, O2), electrooculogram, leg and chin electromyograms, electrocardiogram, pulse oximetry, neck microphone, and nasal cannula pressure transducer. The polysomnography recordings were scored manually in a standard fashion.[16] Apnea was defined as cession of airflow ≥ 90% for at least 10 seconds. Hypopnea was defined as a decrease in airflow of more than 30% for at least 10 seconds and an oxygen desaturation greater than 3%.[16] The mean AHI of the patient with OSA was defined as the number of apneas and hypopneas per hour of sleep. Patients with OSA are classified as mild (AHI = 5–14 events/h), moderate (AHI = 15–30 events/h), and severe (AHI > 30 events/h).[17]

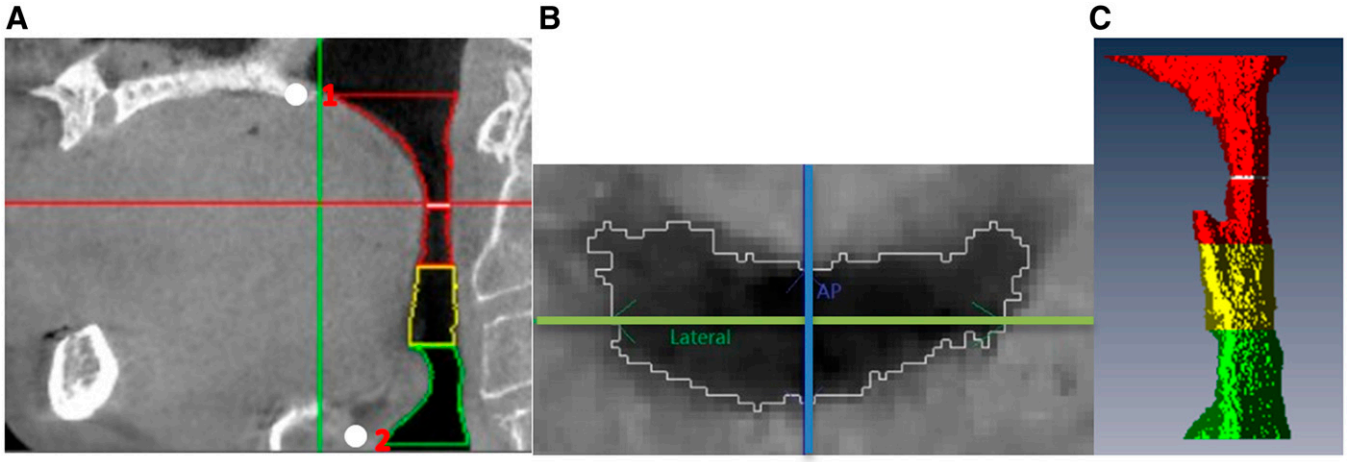
Cone beam computed tomography

The CBCT datasets of the participants were obtained using a NewTom 5G CBCT system (QR Systems, Verona, Italy). During the imaging procedure, the patients were positioned in a supine position with the Frankfort horizontal plane perpendicular to the floor.[18] They were instructed to wear their dentures with the upper and lower teeth in contact in a normal occlusal position during the scanning period. They were also instructed to breathe quietly and to avoid swallowing and other movements. The exposure settings were 110 kV, 4 mA, 0.3 mm voxel size, 3.6 seconds exposure time (pulsed radiation), and 18–36 seconds scanning time, depending on the weight of the patient.[18] The CBCT scans were imported into NNT software (QR Systems, Verona, Italy) and rotated to a standard head orientation.[19] For further analysis, the images were saved as digital imaging and communications in medicine (DICOM) files. The observer was blind to the severity of OSA while doing the analysis.

Procedures to obtain anatomical characteristics of the upper airway

Using Amira (v4.1l Visage Imaging, Inc., Carlsbad, CA), automatic processing of the upper airway segmentation was performed following the same protocol as in a previous study.[18] First, a voxel set was built to include all upper airway information; second, a new mask was built with its thresholds ranging from −1,000 to −500 Hounsfield units; and third, the superior boundary (ie, the plane across the posterior nasal spine (PNS) parallel to the Frankfort horizontal plane) and the inferior boundary (ie, the plane across the base of the epiglottis parallel to the Frankfort horizontal plane) of the upper airway were selected in the corresponding axial planes and put into the voxel set. Finally, all the slices between the upper and lower boundaries were selected and put into the voxel set. The shape of upper airway was defined as the ratio between Min-CSA and mean CSA (Mean-CSA) of upper airway, and described as hourglass-shaped or cylinder-shaped. The Min-CSA, the anterior-posterior dimension of Min-CSA, the lateral dimension of Min-CSA, the volume of the upper airway, and the length of the upper airway were calculated based on the segmented upper airway (**Figure 1**).[18]

Figure 1—The 3-dimensional anatomic analysis of the upper airway.



(A) The midsagittal plane of the CBCT image (1 = PNS, posterior nasal spine; 2 = BEP, base of epiglottis). **(B)** The minimum cross-sectional area (Min-CSA) on an axial slice of the CBCT image. **(C)** The segmented upper airway. AP = anterior-posterior dimension of the Min-CSA, CBCT = cone beam computed tomography, Lateral = lateral dimension of the Min-CSA.

Procedures to obtain aerodynamic characteristics of the upper airway

The procedure of CFD analysis is based on our previous study.[9] The upper airway from the posterior section of the nasal cavity to the base of epiglottis was segmented (**Figure 2**). By surface triangulation, the segmented models were subsequently converted into 3-dimensional standard tessellation language models. The segmented standard tessellation language models of the upper airway were exported into ANSYS ICEM CFD 17.0 (ANSYS, Inc., Canonsburg, PA) to generate tetrahedral volume meshes. Depending on the complexity of the upper airway model, a typical grid consisted of about 1,000,000 tetrahedral cells. ANSYS Fluent (ANSYS, Inc.) was used to conduct flow simulation within the upper airway. The steady-state Reynolds Averaged Navier-Stokes formula with the κ-ω shear stress transport turbulence model was used to model aerodynamic characteristics within the upper airway.[20] The air within the upper airway was considered adiabatic.[21] A least-squares cell-based gradient was used for spatial discretization.[22,23] Second-order discretization schemes were used for the pressure and momentum equations. The coupling between the velocity and pressure fields was realized using the SIMPLE algorithm.[8,21,24] Air density within the upper airway was set as 1.225 kg/m^3 and air viscosity as 1.79E-05 kg/m/s. One boundary was set at the coronal plane through PNS point and another boundary at the base of the epiglottis. The boundary condition consisted of axial velocity at the inlet plane, and no-slip boundary conditions for the upper airway wall. An inlet volume flow rate of 166 ml/s (10 L/min) was used in the flow simulation.[25,26]

The aerodynamic characteristics, namely velocity, wall shear stress, and wall static pressure, were calculated in the upper airway model of each edentulous patient with OSA during both inspiration and expiration. The inspiration phase was simulated by setting the inlet plane at the coronal plane across the PNS point and the outlet plane at the base of epiglottis. Conversely, the expiration phase was simulated by setting the inlet plane at the base of epiglottis and the outlet plane at the coronal plane across the PNS point.[9]

The inlet velocity was determined using the following equation V_{inlet} (m/s) = Q (mL/s)/A_{inlet} (mm^2). A_{inlet} is cross-sectional area of upper airway at the inlet plane. During inspiration, A_{inlet} is the cross-sectional area of the upper airway at the coronal plane across the PNS point. During expiration, A_{inlet} is the cross-sectional area of the upper airway at axial plane across the base of epiglottis.

Based on CFD calculations, airway resistance R was determined using the following formulation: $r = \Delta P/Q$, where ΔP is the total pressure drop between the inlet and outlet boundaries of the upper airway; Q is the volume flow rate within the upper airway. The aerodynamic characteristics, namely velocity and static pressure of the midsagittal plane of the upper airway model, were also calculated during both inspiration and expiration.[9]

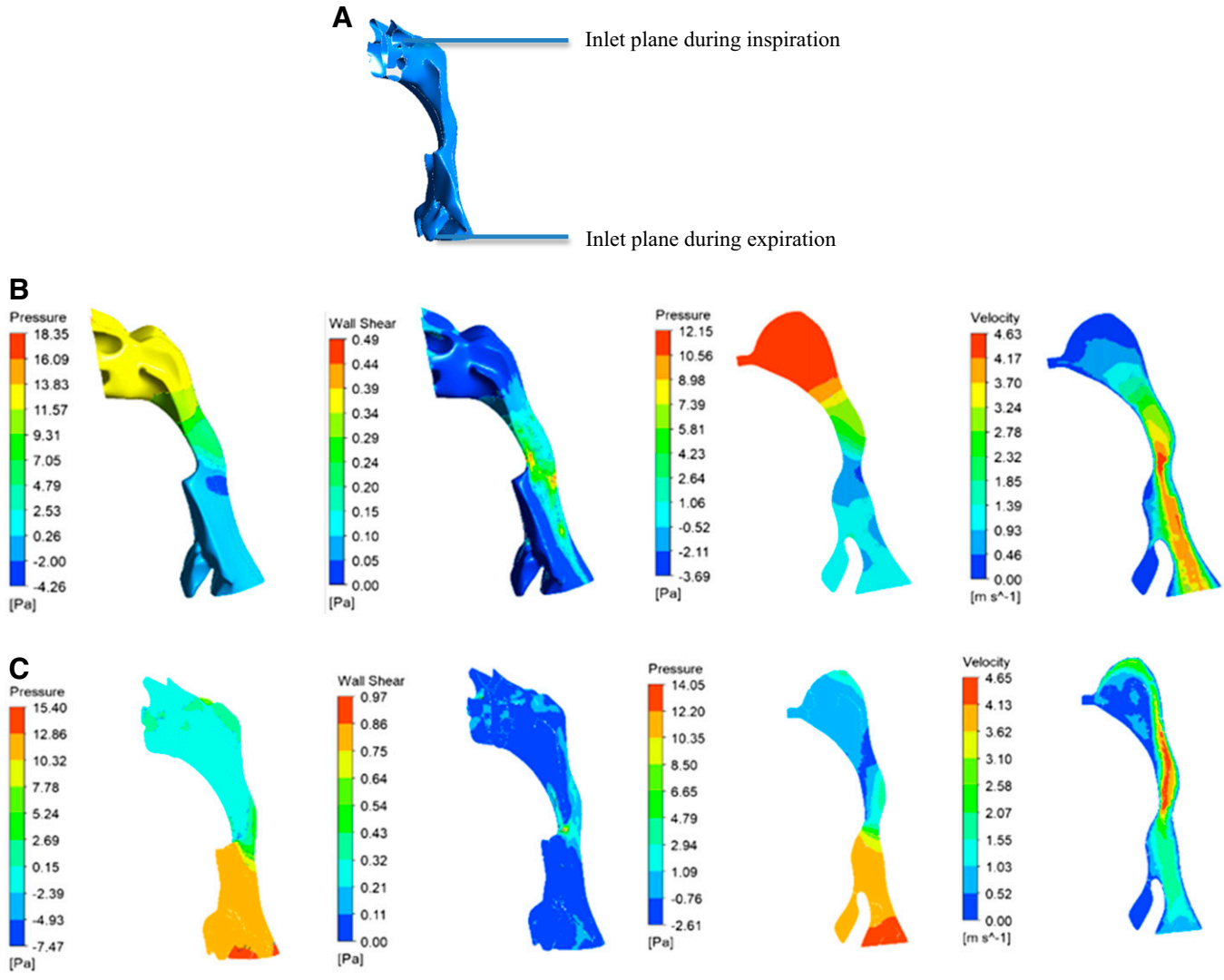
Statistical analysis

To determine the differences between patients with mild, moderate, and severe OSA with respect to the demographic characteristics, the Kruskal-Wallis (for nonnormally distributed variables) or chi-squared test (for categorical variables) or 1-way analysis of variance (for normally distributed variables) were used, with a significance level set at $P < .05$. Pearson correlation analysis was performed to assess the relationships between AHI and demographic characteristics, between AHI and the anatomic characteristics, and between AHI and aerodynamic characteristics. The IBM Statistical Package for Social Sciences for Windows (SPSS version 21; Chicago, IL) were used to analyze the data.

RESULTS

From a total of 70 patients included in the clinical trial,[12] only the data of 58 patients (19 mild OSA, 18 moderate OSA, and 21

Figure 2—The aerodynamic analysis of the upper airway.



(A) The upper airway model used for CFD analysis. **(B)** Contours of wall static pressure (Pa), wall shear stress (Pa), and velocity (m/s) and static pressure (Pa) at the midsagittal plane of a typical edentulous patient with OSA during inspiration. **(C)** Contours of wall static pressure (Pa) and wall shear stress (Pa), and velocity (m/s) and static pressure (Pa) at THE midsagittal plane of a typical edentulous patient with OSA during expiration. CFD = computational fluid dynamics, OSA = obstructive sleep apnea.

severe OSA) were subject to this secondary analysis. The data of 12 patients were excluded for the following reasons: 1) upper airway totally blocked by the uvula (n = 1); 2) CBCT images did not include the lower part of the hypopharynx (n = 2); 3) floating point error appeared during CFD analysis (n = 1); 4) abnormal position of the tongue (n = 1); 5) missing data (n = 7).

The characteristics of the edentulous individuals with mild, moderate, and severe OSA are shown in **Table 1**. There was no significant difference in sex among the edentulous mild, moderate, and severe OSA patients ($\chi 2 = 2.05$, $P = .360$). There were significant differences in age and body mass index (BMI) among the edentulous patients with mild, moderate, and severe OSA ($\chi 2 = 6.16$, $P = .046$, $\chi 2 = 9.55$, $P = .008$ separately). The edentulous patients with moderate OSA, with a mean age of 72.8 (standard deviation 7.8) years, were significantly younger than those edentulous patients with mild and severe OSA, with a mean age of 77.2 (standard deviation 6.4) years and 73.6 (standard deviation 5.1) years, respectively. The mean BMI of patients with severe OSA (32.5 ± 4.9 kg/m^2) was higher than in patients with mild (28.9 ± 6.2 kg/m^2) and moderate (27.8 ± 4.3 kg/m^2) OSA.

Anatomic characteristics of the upper airway

Table 2 shows the comparative measurements of anatomic characteristics of the upper airway between the edentulous patients with mild, moderate, and severe OSA. Significant differences in the shape of the upper airway were found in edentulous patients with mild and moderate OSA compared to those with severe OSA ($\chi 2 = 3.13$, $P = .051$). Edentulous individuals with severe OSA had a more hourglass-shaped upper airway, while in edentulous patients with mild and moderate OSA, the upper airway is less hourglass-shaped. No significant

Table 1—Characteristics of the edentulous patients with mild, moderate, and severe OSA.

Variable	Mild	Moderate	Severe	$\chi 2$	*P*
Age (year)	77.2 ± 6.4	72.8 ± 7.8	73.6 ± 5.1	6.16	.046
BMI (kg/m^2)	28.9 ± 6.2	27.8 ± 4.3	32.5 ± 4.9	9.55	.008
Female (%)	14/19 (73.7%)	12/18 (66.7%)	11/21 (52.4%)	2.05	.360
Hip circumference (cm)	109.1 ± 12.4	104.9 ± 17.4	114.5 ± 14.4	2.65	.266
Waist circumference (cm)	103.5 ± 17.8	99.2 ± 21.0	111.4 ± 13.8	5.26	.063
Neck circumference (cm)	38.7 ± 4.3	38.7 ± 3.8	41.4 ± 6.9	2.62	.270

BMI = body mass index, OSA = obstructive sleep apnea.

Table 2—The mean (± SD) of the anatomical characteristics of the upper airway of the edentulous patients with mild, moderate, and severe OSA.

Variable	Mild	Moderate	Severe	χ^2	*P*
Min-CSA of upper airway (mm^2)	109.5 ± 66.5	92.9 ± 53.3	70.6 ± 47.0	3.05	.22
Volume of upper airway (cm^3)	14.5 ± 7.4	15.4 ± 6.9	14.5 ± 7.6	0.49	.78
Mean-CSA of upper airway (mm^2)	230.1 ± 96.8	231.8 ± 92.2	208.4 ± 97.2	1.28	.53
Shape of upper airway (Min-CSA/Mean-CSA)	0.45 ± 0.16	0.41 ± 0.17	0.34 ± 0.12	3.13	.051
Anterior-posterior dimension of Min-CSA (mm)	6.6 ± 2.8	6.1 ± 4.0	5.7 ± 3.0	1.71	.43
Lateral dimension of Min-CSA (mm)	16.0 ± 7.7	16.2 ± 7.4	13.5 ± 5.4	1.03	.59
Length of upper airway (mm)	61.6 ± 8.6	64.7 ± 9.8	68.0 ± 11.8	1.99	.147

Mean-CSA = mean cross-sectional area, Min-CSA = minimum cross-sectional area, OSA = obstructive sleep apnea, SD = standard deviation.

differences in other anatomic characteristics were found among patients with mild, moderate, and severe OSA.

Aerodynamic characteristics of the upper airway

Table 3 shows the measurements of aerodynamic characteristics of the upper airway in edentulous individuals with mild, moderate, and severe OSA during inspiration and expiration.

During inspiration, there was a significant difference in the mean velocity of the airflow within the upper airway between edentulous patients with mild, moderate, and severe OSA ($\chi 2$ = 7.13, P = .028). The mean velocity of the airway within the upper airway of the edentulous patients with severe OSA (0.63 ± 0.24 m/s) was significantly higher than that in patients with mild (0.49 ± 0.23 m/s) and moderate (0.48 ± 0.14 m/s) OSA (P = .028). No significant differences were found in other aerodynamic characteristics of the upper airway in edentulous patients with mild, moderate, and severe OSA during inspiration. During expiration, there were no significant differences in the aerodynamic characteristics of the upper airway between edentulous patients with mild, moderate, and severe OSA.

Correlation between AHI with denture in situ and the anatomic/aerodynamic characteristics of the upper airway

Table 4 shows the correlation between AHI with denture in situ and the anatomic/aerodynamic characteristics of the upper airway. Weak but significant correlations were found between AHI and BMI (r = .316, P = .017) and between AHI and neck circumference (r = .307, P = .022). Similarly, weak but significant correlations were found between AHI and length of the upper airway (r = .29, P = .027), between AHI and Min-CSA of the upper airway (r = −.33, P = .012), and between AHI and shape of the upper airway (r = −.384, P = .003).

During inspiration, there was a weak but significant correlation between AHI and maximum velocity (r = .26, P = .050) and between AHI and airway resistance (r = .30, P = .024). During expiration, AHI was also significantly correlated with maximum velocity and airway resistance. In addition, there was a weak but significant correlation between AHI and mean wall pressure (r = .29, P = .028), between AHI and mean pressure at midsagittal plane (r = .297, P = .024), and between AHI and maximum pressure at midsagittal plane (r = .30, P = .022).

DISCUSSION

In this descriptive study, both the anatomical and aerodynamic characteristics of edentulous individuals with mild, moderate, and severe OSA were compared. Compared with edentulous patients with mild and moderate OSA, the edentulous patients with severe OSA have a more hourglass-shaped upper airway. The mean air velocity of the patients with severe OSA was

Table 3—The mean (± SD) of the aerodynamic characteristics of the upper airway of the edentulous patients with mild, moderate, and severe OSA.

Variable	Mild	Moderate	Severe	F/χ^2	*P*
Inspiration					
Maximum velocity (m/s)	4.2 ± 1.9	3.7 ± 1.6	5.2 ± 2.2	5.31	.07
Maximum wall shear stress (Pa)	1.0 ± 0.7	1.3 ± 1.4	1.6 ± 1.4	4.06	.13
Minimum wall static pressure (Pa)	−5.8 ± 6.3	−4.5 ± 4.3	−8.6 ± 7.8	4.65	.098
Airway resistance (Pa/mL/s)	0.68 ± 0.46	0.61 ± 0.46	1.11 ± 0.85	5.19	.074
Mean velocity (m/s)	0.49 ± 0.23	0.48 ± 0.14	0.63 ± 0.24	7.13	.028
Mean wall static pressure (Pa)	3.3 ± 2.3	3.0 ± 2.8	5.5 ± 4.6	3.98	.14
Maximum wall static pressure (Pa)	16.8 ± 19.4	30.0 ± 41.2	26.1 ± 20.3	5.41	.067
Mean velocity of midsagittal plane (m/s)	0.85 ± 0.39	0.78 ± 0.27	0.92 ± 0.33	0.91	.41
Maximum velocity of midsagittal plane (m/s)	3.3 ± 1.7	3.0 ± 1.3	4.0 ± 1.8	3.74	.15
Minimum pressure of midsagittal plane (Pa)	−2.8 ± 2.6	−2.8 ± 2.9	−4.6 ± 4.6	2.17	.34
Mean pressure of midsagittal plane (Pa)	3.3 ± 2.4	2.8 ± 2.7	5.2 ± 4.6	2.52	.28
Maximum pressure of midsagittal plane (Pa)	9.0 ± 13.3	5.5 ± 3.8	9.8 ± 8.1	3.23	.20
Expiration					
Maximum velocity (m/s)	3.5 ± 1.4	3.6 ± 1.5	5.0 ± 2.8	3.6	.165
Maximum wall shear stress (Pa)	0.95 ± 1.03	0.84 ± 0.50	1.38 ± 1.14	3.20	.20
Minimum wall static pressure (Pa)	−4.8 ± 4.1	−5.3 ± 4.8	−10.8 ± 12.8	2.79	.25
Airway resistance (Pa/mL/s)	0.6 ± 0.43	0.65 ± 0.50	1.08 ± 0.90	3.21	.20
Mean velocity (m/s)	0.62 ± 0.25	0.61 ± 0.24	0.72 ± 0.30	1.56	.50
Mean wall static pressure (Pa)	1.74 ± 1.9	2.12 ± 2.30	3.6 ± 3.9	3.40	.18
Maximum wall static pressure (Pa)	9.5 ± 7.0	10.1 ± 8.90	16.3 ± 17.6	1.41	.50
Mean velocity of midsagittal plane (m/s)	1.01 ± 0.42	0.94 ± 0.37	1.04 ± 0.50	0.27	.88
Maximum velocity of midsagittal plane (m/s)	3.15 ± 1.3	3.2 ± 1.39	3.8 ± 1.70	1.59	.45
Minimum pressure of midsagittal plane (Pa)	−2.7 ± 1.95	−3.4 ± 4.4	−3.8 ± 3.8	0.42	.81
Mean pressure of midsagittal plane (Pa)	1.46 ± 1.61	1.95 ± 2.19	3.37 ± 3.77	4.46	.11
Maximum pressure of midsagittal plane (Pa)	5.94 ± 4.5	6.4 ± 4.5	11.4 ± 9.5	3.93	.14

OSA = obstructive sleep apnea, SD = standard deviation.

higher than that of patients with mild and moderate OSA. Additionally, we found that the severity of OSA in edentulous individuals is correlated with several anatomic and aerodynamic characteristics of the upper airway.

Obesity and age of edentulous patients with mild, moderate, and severe OSA

Obesity has been hypothesized to alter breathing during sleep via multiple mechanisms, including alteration of upper airway morphology.[27,28] In this study, we found that patients with severe OSAs have a higher BMI than do edentulous patients with mild and moderate OSA. Additionally, BMI is significantly correlated with severity of OSA (**Table 4**).Thus, obesity could be a risk factor for the progress of OSA.[29] Weight loss and prevention of weight gain can be solutions to reducing the occurrence and severity of OSA. On the other hand, there are individuals with high BMI but no OSA. Therefore, the role of obesity in the pathogenesis of OSA in edentulous individuals should be addressed in a well-designed study in future. Age is a risk factor for both OSA and tooth loss.[30,31] Leppanen et al[30] concluded that severity of OSA increases with age. In this study we found a significant difference in age among edentulous patients with mild, moderate, and severe OSA, although the increase in the severity of OSA in edentulous individuals was not parallel to an increase in age. Based on these findings, there is a tendency that both tooth loss and OSA may progress over time. This should be taken into consideration when planning a treatment or evaluating its long-term effects, especially in older edentulous patients with OSA.[30]

Anatomical characteristics

It is suggested that complete tooth loss (edentulism) could produce prominent anatomical changes, such as mandible rotation, which may influence upper airway size and function.[31] Moreover, Bucca et al[5] found that there is a decrease in retropharyngeal space in edentulous individuals and this may favor upper airway obstruction and negatively influence sleep. In this study, we found that the upper airway of the edentulous patients with severe OSA is shaped more like an hourglass than it is in patients with mild and moderate OSA. Moreover, we also found

Table 4—Correlation analysis between AHI with denture in situ and the anatomic and aerodynamic characteristics of the upper airway in edentulous patients with OSA.

Variable	*r*	*P*
BMI (kg/m^2)	.316	.017
Hip circumference (cm)	.145	.197
Waist circumference (cm)	.053	.260
Neck circumference (cm)	.307	.022
Anatomical characteristics of the upper airway		
Min-CSA of upper airway (mm^2)	−.33	.012
Volume of upper airway (cm^3)	−.02	.91
Mean-CSA of upper airway (mm^2)	−.11	.40
Shape of upper airway (Min-CSA/Mean-CSA)	−.384	.003
Anterior-posterior dimension of Min-CSA (mm)	−.18	.17
Lateral dimension of Min-CSA (mm)	−.25	.063
Length of upper airway (mm)	.29	.027
Inspiration		
Maximum velocity (m/s)	.26	.05
Maximum wall shear stress (Pa)	.25	.06
Minimum wall static pressure (Pa)	−.23	.09
Airway resistance	.30	.024
Mean velocity (m/s)	.24	.067
Mean wall static pressure (Pa)	.24	.067
Maximum wall static pressure (Pa)	.15	.25
Mean velocity of midsagittal plane (m/s)	.13	.33
Maximum velocity of midsagittal plane (m/s)	.20	.13
Minimum pressure of midsagittal plane (Pa)	−.23	.08
Mean pressure of midsagittal plane (Pa)	.22	.10
Maximum pressure of midsagittal plane (Pa)	.028	.835
Expiration		
Maximum velocity (m/s)	.26	.049
Maximum wall shear stress (Pa)	.187	.16
Minimum wall static pressure (Pa)	−.22	.096
Airway resistance	.273	.038
Mean velocity (m/s)	.11	.42
Mean wall static pressure (Pa)	.289	.028
Maximum wall static pressure (Pa)	.175	.188
Mean velocity of midsagittal plane (m/s)	.008	.954
Maximum velocity of midsagittal plane (m/s)	.22	.093
Minimum pressure of midsagittal plane (Pa)	−.133	.32
Mean pressure of midsagittal plane (Pa)	.297	.024
Maximum pressure of midsagittal plane (Pa)	.300	.022

AHI = apnea-hypopnea index, BMI = body mass index, Mean-CSA = mean cross-sectional area, Min-CSA = minimum cross-sectional area, OSA = obstructive sleep apnea.

that OSA severity in edentulous patients is correlated with upper airway morphology, such as the length, shape, and Min-CSA of the upper airway. Similarly, in the dentate patients, fat deposit around the neck could narrow the upper airway and worsen OSA condition.[32,33] However, for both edentulous and dentate patients with OSA, it is still unclear which upper airway anatomic characteristic can be used as predictor to help us recognize the severity of the OSA. Moreover, as the etiology of OSA is obviously multifactorial and varies considerably between individuals,[34] we hypothesized that in addition to the

anatomical factors, the effect of neuromuscular factors, such as genioglossus muscle activity, is also related to the severity of OSA in edentulous individuals.[35–37] It is suggested that the interaction of the above factors related to the severity of OSA needs further investigation in order to fully understand the progression of OSA in edentulous individuals.[38,39]

Aerodynamic characteristics and their correlation with AHI

This study investigated the aerodynamic characteristics of the upper airway, such as velocity and pressure measurements among edentulous patients with mild, moderate, and severe OSA during inspiration and expiration following a protocol published in our previous study.[9] It is shown in a previous study that, for OSA in children, a rapid decrease in pressure occurs in the narrow region of the upper airway.[40] It is also found that the airway negative pressure greatly contributes to the severity of OSA in children.[41] Therefore, it would be interesting to investigate if it is still the case in edentulous in patients with OSA. Additionally, if the wall static pressure (Pa) is lower, assuming that the atmospheric pressure is constant, it means that the pressure difference between inside and outside of upper airway is higher and, therefore, the upper airway is easier to collapse.

We found that the mean velocity of the upper airway is higher in patients with severe than in patients with mild and moderate OSA. One explanation could be as follows. All CFD simulations were run at the same volumetric flowrate (Q = 166 ml/s). Air velocity (V), cross-sectional area (A), and flowrate (Q) are related by the equation Q = A*V or V = Q/A. Since the flowrate (Q) is constant, there is an inverse relationship between air velocity and cross-sectional area. It is shown in **Table 2** that the severe OSA group tends to have the smallest cross-sectional area, thus it is expected that the air velocity would be highest in the severe OSA group. Another hypothesis is that the age-related changes of the tissue surrounding the upper airway in patients with OSA could narrow the upper airway, and, therefore, the velocity of the airflow increases while traveling through the upper airway. These hypotheses need further investigation.

We found that the OSA severity of edentulous patients is correlated with many aerodynamic characteristics of the upper airway, such as airway resistance. It seems that airway resistance could be an important factor in the progression of OSA in edentulous individuals. However, the above correlation is relatively weak. Therefore, studies with larger sample size using CFD analysis should be carried out in the future.

Limitations of the study

This analysis has certain limitations. CBCT images were taken while the participants were awake, but in supine position, which is as close as one can get to the sleeping situation. We hypothesize that the difference between edentulous mild, moderate, and severe OSA groups is influenced in a comparable way during sleep and while awake, which would minimize the effect of sleep on the comparison of these groups. Further research is required to support this hypothesis. Another limitation is that CBCT imaging was performed with dentures in situ. Previous studies, based either on cephalometric images[5] or CBCT images,[42] suggested that there is a significant increase in upper airway dimensions with the denture in situ compared to the situation when the denture is not worn. In our pilot study, CBCT images was obtained without dentures in situ. However, even with customized wax record to achieve jaw relation, it is difficult for the participants to keep their mandible stable, and this can bias the image.

Clinical relevance and future directions

OSA is an heterogenous disorder; risk factors and causes remain under investigation in the era of precision and personalized medicine. Yet, there is limited literature on the progression of OSA with aging. Our study investigated the characteristics of the upper airway in older adults wearing dentures for more than 36 years from both anatomical and aerodynamic perspectives. CBCT images of edentulous patients with severe OSA presented a more hourglass-shaped upper airway. Future studies may investigate the changes of anatomical parameters in relation to OSA exacerbation with aging in both dentate and edentate individuals. In addition, it remains unanswered if edentate individuals with OSA and treated with positive airway pressure device should sleep with or without their dentures. This needs future investigation.

CONCLUSIONS

The edentulous patients with severe OSA have a more hourglass-shaped upper airway. Furthermore, the study results showed that, during inspiration, the airflow travels faster in edentulous patients with severe OSA than in those with mild or moderate OSA.

ABBREVIATIONS

AHI, apnea-hypopnea index
BMI, body mass index
CBCT, cone beam computed tomography
CFD, computational fluid dynamics
Mean-CSA, mean cross-sectional area
Min-CSA, minimum cross-sectional area
OSA, obstructive sleep apnea
PNS, posterior nasal spine

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