Computed Tomography Characterization and Comparison With Polysomnography for Obstructive Sleep Apnea Evaluation

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Purpose: We hypothesized that computed tomography (CT) combined with portable polysomnography (PSG) might better visualize anatomic data related to obstructive sleep apnea (OSA). The present study evaluated the CT findings during OSA and assessed their associations with the PSG data and patient characteristics.

Patients and Methods: We designed a prospective cross-sectional study of patients with OSA. The patients underwent scanning during the awake state and apneic episodes. Associations of the predictor variables (ie, PSG data, respiratory disturbance index [RDI]), patient characteristics (body mass index [BMI], neck circumference [NC], and waist circumference [WC]), and outcome variables (ie, CT findings during apneic episodes) were assessed using logistic regression analysis. The CT findings during apneic episodes were categorized regarding the level of obstruction, single level (retropalatal [RP] or retroglossal [RG]) or multilevel (mixed RP and RG), degree of obstruction (partial or complete), and pattern of collapse (complete concentric collapse [CCC] or other patterns).

Results: A total of 58 adult patients with OSA were scanned. The mean $\pm$ standard deviation for the RDI, BMI, NC, and WC were 41.6 ± 28.55, 27.80 ± 5.43 kg/m^2, 38.3 ± 4.3 cm, and 93.8 ± 13.6 cm, respectively. No variables distinguished between the presence of single- and multilevel airway obstruction in the present study. A high RDI ($\geq$30) was associated with the presence of complete obstruction and CCC (odds ratio 6.33, 95% confidence interval 1.55 to 25.90; and odds ratio 3.77, 95% confidence interval 1.02 to 13.91, respectively) compared with those with a lesser RDI.

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This research project was supported by Mahidol University.

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Received June 8 2017

Accepted September 2 2017

0278-2391/17/31170-9

https://doi.org/10.1016/j.joms.2017.09.006

Conclusions: An increased RDI appears to be an important variable for predicting the presence of complete obstruction and CCC during OSA. Scanning during apneic episodes, using low-dose volumetric CT combined with portable PSG provided better anatomic and pathologic findings of OSA than did scans performed during the awake state.

J Oral Maxillofac Surg 76:854-872, 2018

Obstructive sleep apnea (OSA) syndrome is a common disorder affecting at least 2 to 4% of the adult population. Repetitive cessation of breathing during sleep due to collapse of the upper airway results in signs, symptoms, and consequences, such as an increased risk of cardiovascular disease.[1] Full-night polysomnography has been recommended as a standard method for the diagnosis of the sleep-related breathing disorder OSA.[2] The diagnosis of OSA is confirmed by a respiratory disturbance index (RDI) greater than 15 or greater than 5 for a patient who reports any OSA symptoms.[3] The RDI is defined as the number of obstructive events (apneas, hypopneas, respiratory event-related arousals) per hour on PSG. OSA severity is defined as mild (RDI ≥5 but <15), moderate (RDI ≥15 but ≤30), and severe (RDI >30).[1]

When choosing the appropriate OSA therapeutic approach, patients should be included in the discussion of the treatment options.[1] Continuous positive airway pressure (CPAP) is the standard treatment of moderate to severe OSA and is an optional therapeutic method for mild OSA.[4] However, CPAP can only be effective if used regularly (ie, ≥4 hours each night).[5] CPAP failure can occur in 25 to 50% of patients because they discontinue therapy, largely within the first 4 weeks.[6] Alternative non-CPAP therapies for OSA, such behavioral treatments, oral appliances, upper airway surgery, maxillomandibular advancement (MMA), and implanted upper airway stimulation (UAS), have been recommended for patients who decline to use CPAP.[1,7] The behavioral treatment options include weight loss (≥10% of body weight), exercise, positional therapy, and avoidance of alcohol and sedatives before bedtime.[1] Custom-made oral appliances are indicated for use in patients with mild to moderate OSA for whom both CPAP and behavioral strategies fail.[8] Upper airway surgery can be considered as a primary treatment in patients with mild OSA who have severely obstructing airways that are surgically correctible (eg, tonsillar or adenoid hypertrophy).[1] MMA (ie, pharyngeal space enlargement by moving the maxilla and mandible forward to reduce pharyngeal collapsibility[9,10]) is currently the most effective craniofacial surgical technique for the treatment of OSA in adults.[11,12] The diagnosis of OSA and its severity should be determined using PSG before any surgery. Implanted UAS therapy (ie, closed-loop hypoglossal nerve implants) offers an alternative for patients with moderate to severe OSA and CPAP failure.[7] The clinical indications for UAS require the absence of complete concentric collapse (CCC) of the upper airway during drug-induced sleep endoscopy (DISE; ie, nasopharyngoscopic visualization of the upper airway with the patient under sedation).[13]

Owing to the inability of real-time monitoring devices to localize obstruction levels within the upper airway, level-specific treatment approaches, such as various upper airway surgeries and oral appliances, have shown relatively low success rates compared with CPAP.[14-16] Recent advanced imaging modalities of upper airway geometry, such as DISE[17] and computational fluid dynamic analyses based on magnetic resonance imaging (MRI)[18] or computed tomography (CT),[19] have been used to evaluate treatment success. DISE, MRI, and CT can also be used to define possible surgical sites in the upper airway. DISE is an alternative diagnostic tool for locating the obstruction site in patients[20] that generates qualitative information regarding the level, degree, and direction of upper airway collapse.[21] MRI is a nonionizing radiation scanner providing high-resolution imaging, including upper airway soft tissue; however, it is slow and costly.[22-25] CT is a fast method of scanning, revealing the causes and sites of obstruction.[26,27] Nonetheless, limited research assessing upper airway changes during sleep apnea has been reported.

The purpose of the present study was to evaluate the CT findings, including the level of obstruction, degree of obstruction, and pattern of collapse, in patients during OSA. We hypothesized that the CT findings observed during apneic episodes would demonstrate greater and more relevant upper airway pathologic findings than those observed during the awake state and would be associated with OSA severity. The specific aim of the present study was to identify associations between PSG data (RDI) or patient characteristics (body mass index [BMI], neck circumference [NC], and waist circumference [WC]) and CT variables of interest (CT findings during apneic episodes) using logistic regression analysis.

Materials and Methods

STUDY DESIGN AND SAMPLE

To address the research purpose, we designed and implemented a prospective cross-sectional study. The study population included all patients presenting for evaluation and management of OSA from August 2011 through November 2016. To be included in the study sample, the patients were required to have a diagnosis of OSA (sleep-related symptoms[1] and an RDI >5) using standard overnight in-laboratory PSG (Sandman Elite; Nellcor Puritan Bennett, Pleasanton, CA) at the Ramathibodi Hospital Sleep Disorder Center. The RDI was interpreted according to the American Academy of Sleep Medicine diagnostic criteria.[28] Patients were excluded as study subjects if they had an infiltrative lesion in the upper airway. Before participating in the research study, all patients gave written consent using the forms and processes approved by the Committee on Human Rights Related to Research Involving Human Volunteers, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, in accordance with the Declaration of Helsinki.

VARIABLES

The predictor variables were PSG data (RDI) and other variables (ie, patient characteristics [BMI, NC, and WC]) that might influence the outcome. The outcome variables were abnormal CT findings during apneic episodes. The CT findings during the apneic episodes were categorized regarding the level of obstruction, degree of obstruction, and pattern of collapse.

DATA COLLECTION METHODS

Signal Triggering, CT Image Acquisition

Before CT scanning, a portable PSG recorder (Titanium; Embla System, Broomfield, CO) was used for the assessment of sleep by recording the electroencephalogram, electro-oculogram, nasal/oral airflow, thoracoabdominal efforts, oxygen saturation, and heart rate. After confirming that the patients met the minimal requirements for the diagnosis of OSA,[29] they were induced to sleep in the supine position on the CT table using 10 mg of zolpidem hemitartrate. This drug is commonly used in PSG studies because it does not affect the apnea/hypopnea index, oxygen desaturation index, or the lowest oxygen saturation.[30] A low-dose, volumetric axial CT scan without contrast, using 80 kVp and 20 mAs (500 ms, 40 mA) and resulting in only 0.07 mSv per scan, was performed using a 320-slice CT scanner (Aquilion ONE; Toshiba Medical Systems, Nasu, Japan) at the Advanced Diagnostic Imaging Center, Ramathibodi Hospital, Bangkok, Thailand. The CT image resolution was 512×512 pixels (0.39×0.39 mm^2), and the shift between one cross-sectional image and the subsequent image was 1 mm. Scout images (anterior and lateral views) were obtained to determine the scanning area covering the upper wall of nasal cavity and the hyoid bone. Patients could maintain their sleep cycle phases during the examination because volumetric scanning (ie, acquisition of 16 cm of anatomy in a single rotation) was performed to eliminate the effect of CT table movement. Axial images of the patients' upper airways were scanned in 2 states (ie, awake and during apneic episodes). The PSG technician interpreted the physiologic signals that distinguished the awake state and apneic episodes and informed the radiographer in the CT console room using RemLogic software, version 2.0. Multiplanar, reformatted sagittal and coronal images were then generated. Finally, 3-dimensional (3D) images were created using Vitrea fX postprocessing software, version 3.0.1 (Toshiba Medical Systems).

Image-Based, Upper Airway Evaluation

We evaluated the following qualitative upper airway outcome variables: level of obstruction, degree of obstruction, and pattern of collapse. The level of obstruction was defined as either single-level (airway obstruction observed in the retropalatal [RP] or retroglossal [RG] region) or multilevel (airway obstruction observed in both RP and RG regions). The RP region was defined as the uvulopalatal complex region (ie, the airway from the paranasal sinus to the tip of uvula). The RG region was defined as the tongue base area (ie, the airway from the tip of uvula to the lower border of the hyoid bone). The degree of obstruction was categorized as partial or complete. The patterns of collapse included CCC and other patterns (eg, anteroposterior [AP] or lateral collapse).

STATISTICAL ANALYSIS

The commercial statistics software package SPSS, version 18.0 (IBM Corp, Armonk, NY) was used for the statistical analyses. We used the Pearson χ^2 test to assess the relationships between the predictor variables of RDI, BMI, NC, and WC and the qualitative CT OSA outcome variables (ie, level [single-level or multilevel], degree [partial or complete], and pattern [CCC or other]). $P < .05$ was considered statistically significant for the between-group comparisons and was used to select the terms as initial candidates for bivariate logistic regression analysis. Finally, multivariate logistic regression analysis was used to find independent associations between these 2 groups of variables using a forward, stepwise selection method.

Results

A total of 58 adult patients with OSA were scanned during both awake states and apneic episodes. The mean ± standard deviation (SD) RDI of the patients was 41.68 ± 28.55. The mean ± SD of the patient characteristics, including BMI, NC, and WC, was 27.80 ± 5.43 kg/m^2, 38.3 ± 4.3 cm, and 93.8 ± 13.6 cm, respectively. During apneic episodes, we observed the level (single-level or multilevel), degree (partial or complete), and pattern (CCC or other) of airway obstruction in the 58 patients. Single-level obstructions in the RP region (Fig 1) was observed in 44.8% of the patients and multilevel obstruction (mixed RP and RG obstruction; Fig 2) in 55.2%. The CT images revealed anatomic findings related to narrowing or obstruction of the airways, such as an enlarged soft palate and uvula (Fig 1),

FIGURE 1. Single-level complete obstructions in retropalatal region (*arrows*) presented as sagittal and 3-dimensional (3D) images in the same patient. *A*, Sagittal computed tomography (CT) scan during the awake state; *B*, sagittal CT scan during an apneic episode; **(Fig 1 continued on next page.)**

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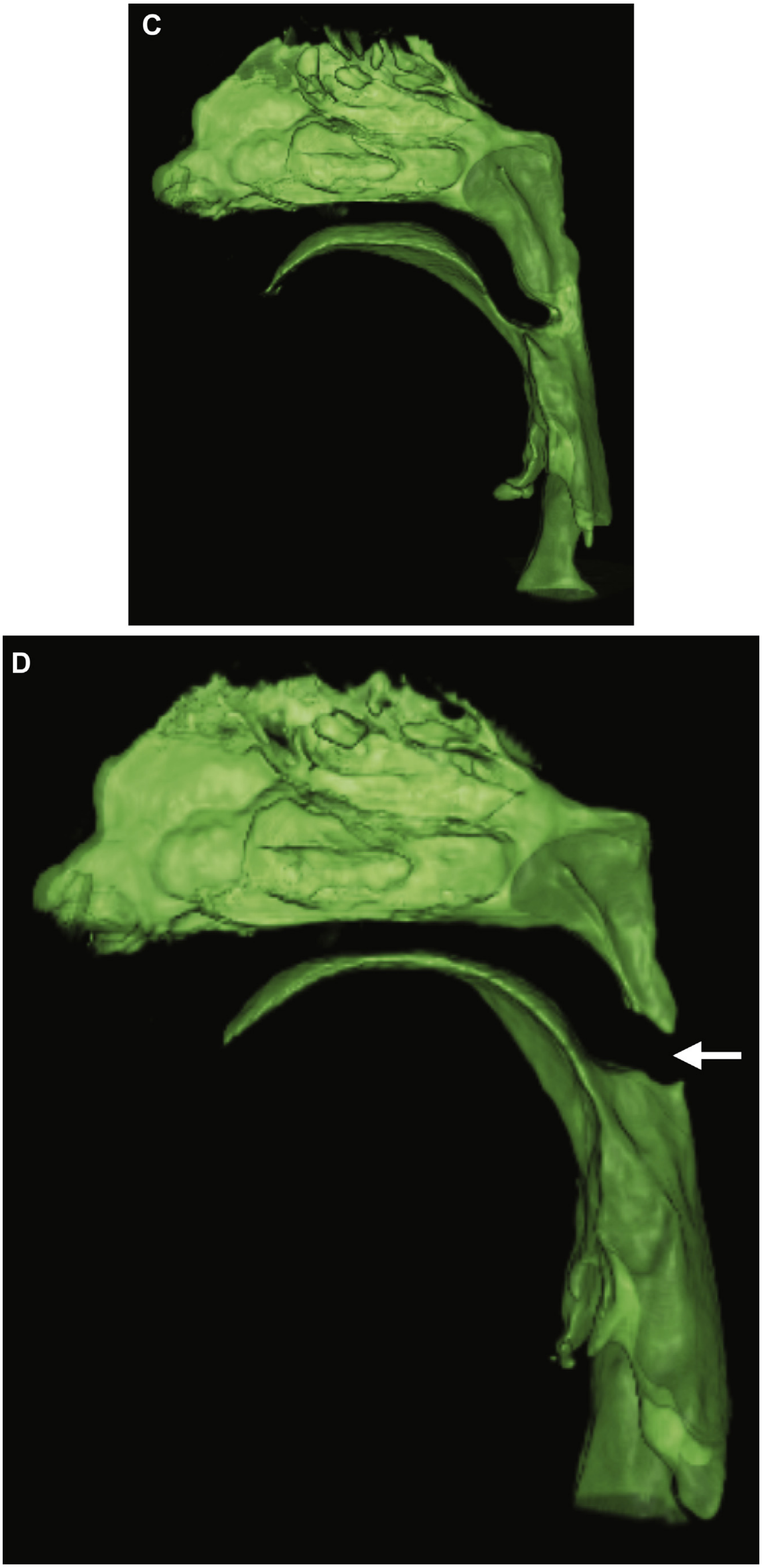

FIGURE 1 (cont'd). *C*, 3D image during the awake state; and *D*, 3D image during an apneic episode.

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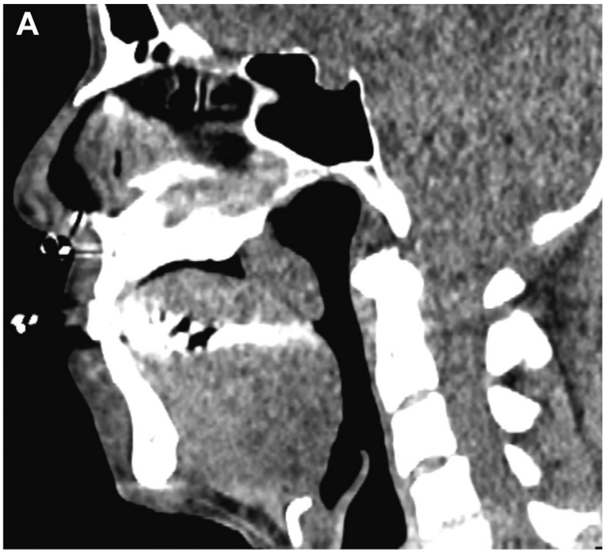

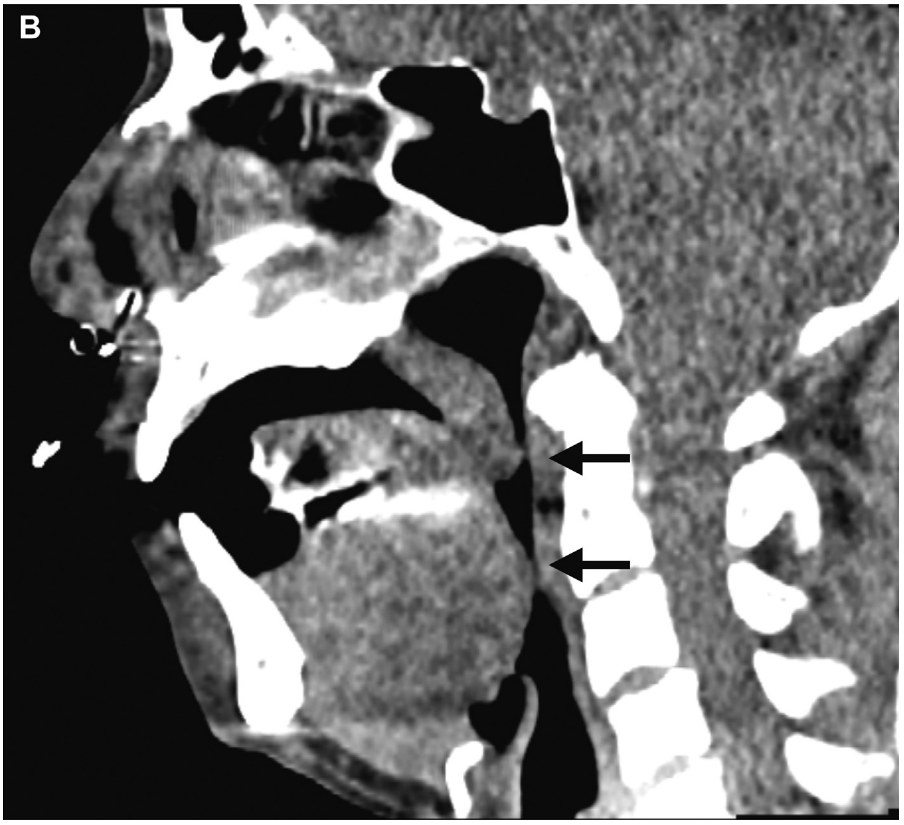

FIGURE 2. Multilevel complete obstruction in the retropalatal and retroglossal regions (*arrows*) presented as sagittal and 3-dimensional (3D) images in the same patient. *A*, Sagittal computed tomography (CT) scan during the awake state; *B*, sagittal CT scan during an apneic episode; **(Fig 2 continued on next page.)**

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tongue displacement (Fig 2), and enlarged palatine tonsils (Fig 3). Complete obstruction was observed more frequently than partial obstruction (74.1 vs 25.9%). Complete obstruction was commonly associated with CCC (53.4%), followed less frequently by complete AP collapse (19.0%) and complete lateral collapse (1.6%). CCC was multilevel in 67.7% (Fig 4) and single-level in 32.3% (Fig 5). Partial obstruction was most often associated with partial concentric collapse (73.3%), and less often with partial AP collapse (20.0%) or partial lateral collapse (0.7%). Three-dimensional images of the upper airways from

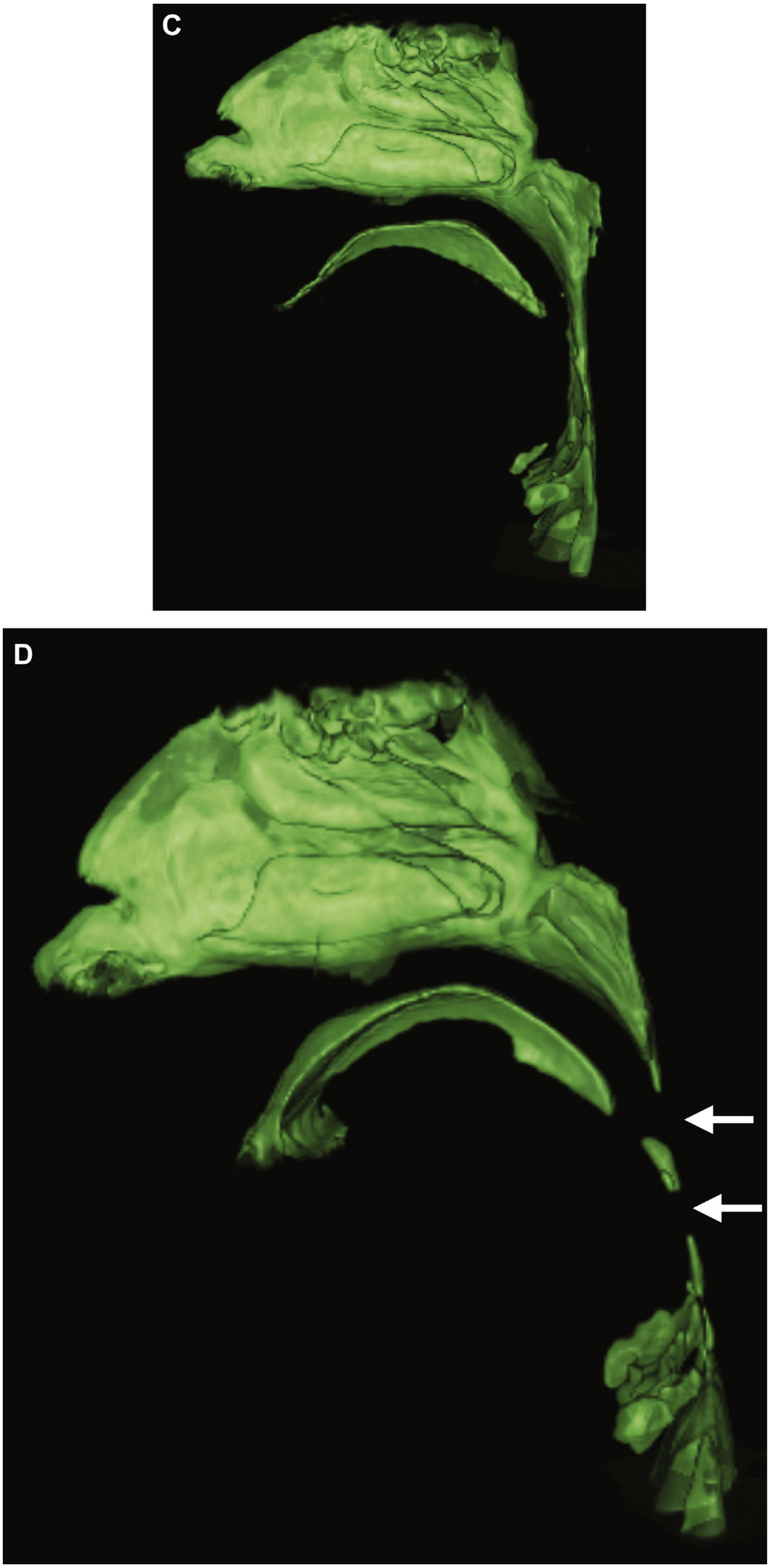

FIGURE 2 (cont'd). *C*, 3D image during the awake state; and *D*, 3D image during an apneic episode.

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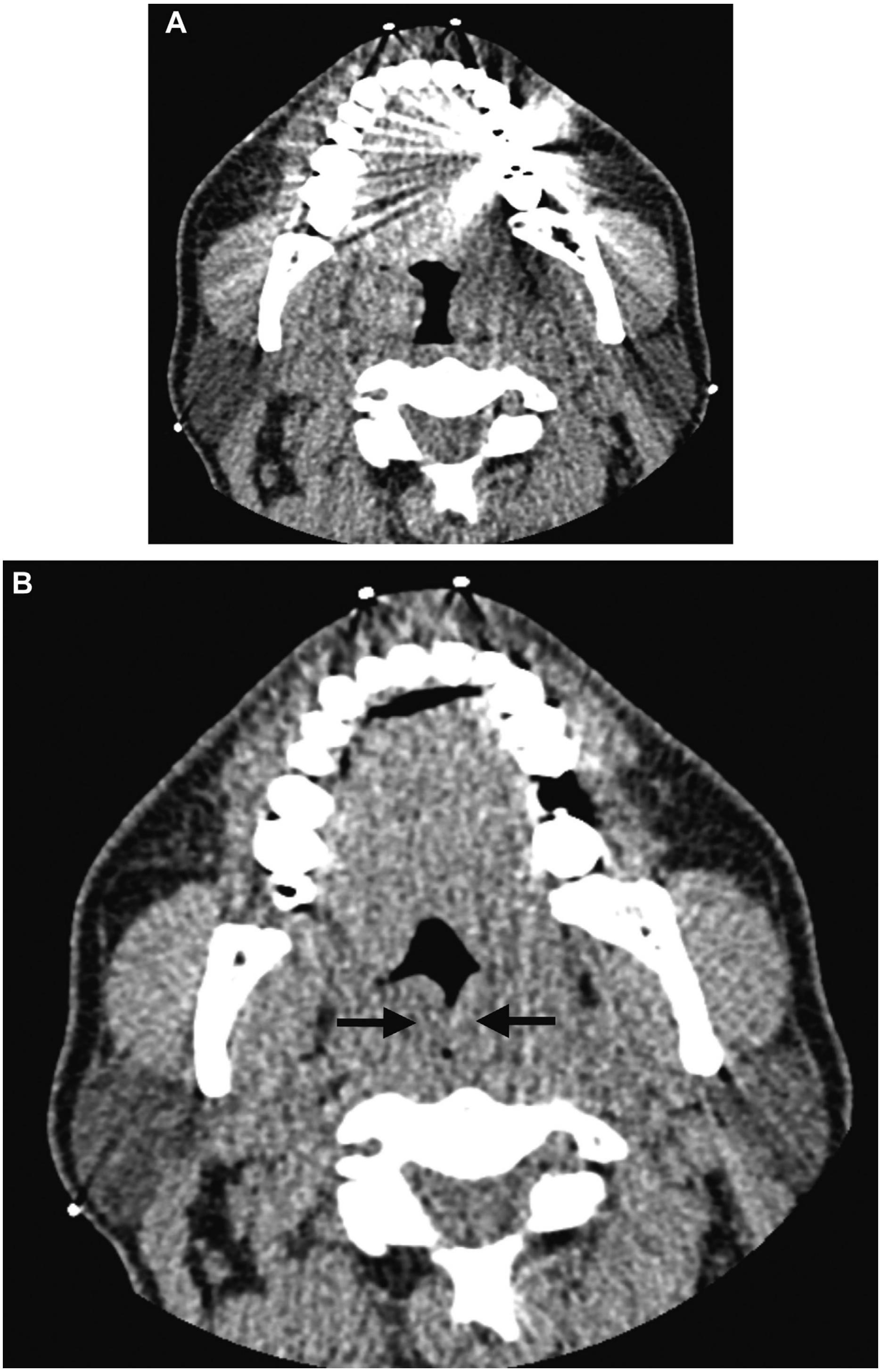

FIGURE 3. Complete obstruction related to enlarged palatine tonsils (*arrows*) presented as axial cross-sectional and 3-dimensional (3D) images in the same patient. *A*, Axial computed tomography (CT) scan during the awake state; *B*, axial CT scan during an apneic episode; **(Fig 3 continued on next page.)**

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different patients with partial single- or multilevel obstruction are presented in Figure 6.

The quantitative terms of RDI, BMI, NC, and WC were converted to qualitative values by constructing curves of diagnostic yield (ie, a receiver operating characteristic curve) to determine the optimal cutoff points for each variable to maximize its diagnostic yield. Comparisons of the level of obstruction (single-level and multilevel), degree of obstruction (partial and complete), and pattern of collapse (CCC and

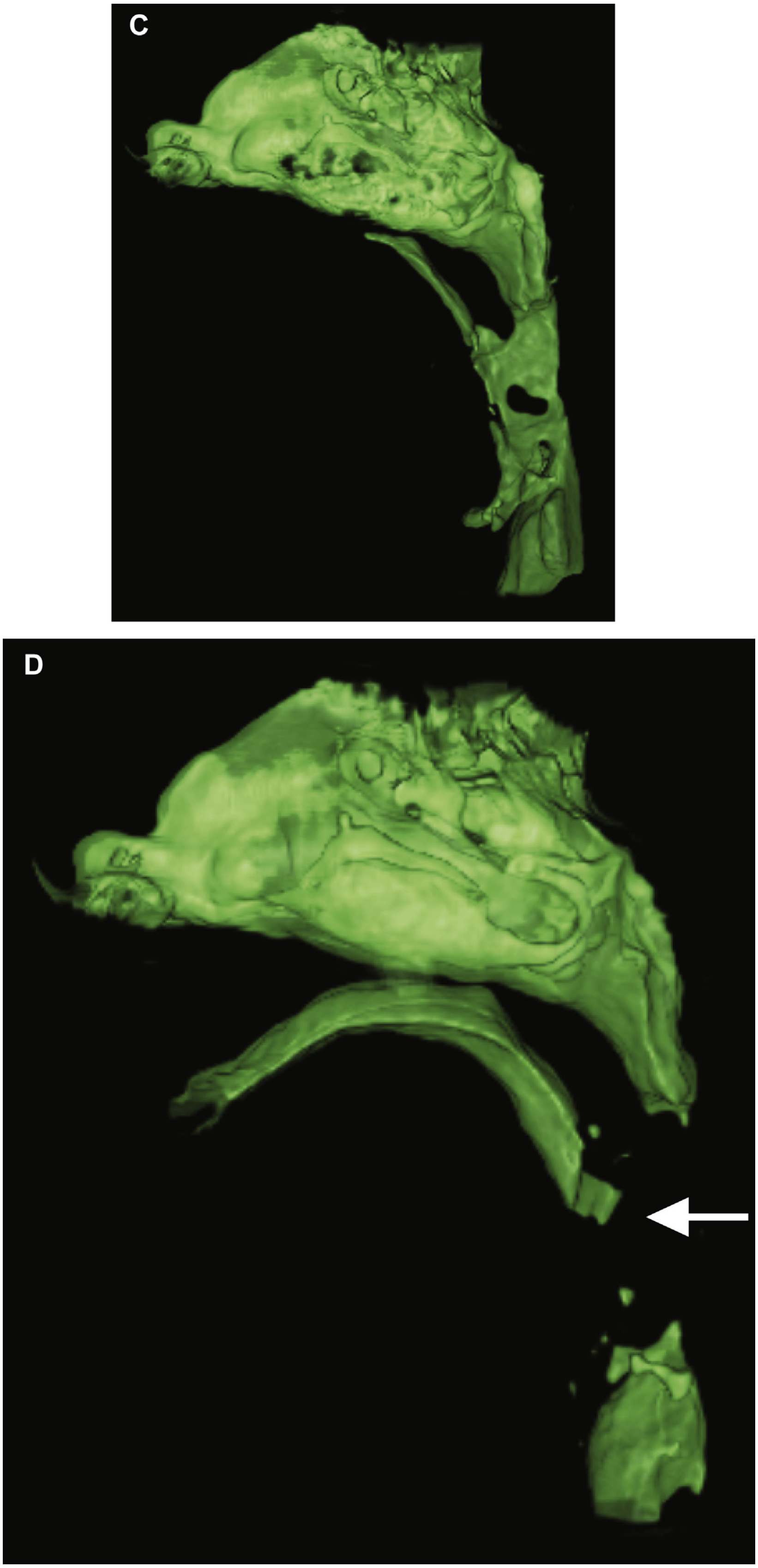

FIGURE 3 (cont'd). *C*, 3D image during the awake state; and *D*, 3D image during an apneic episode.

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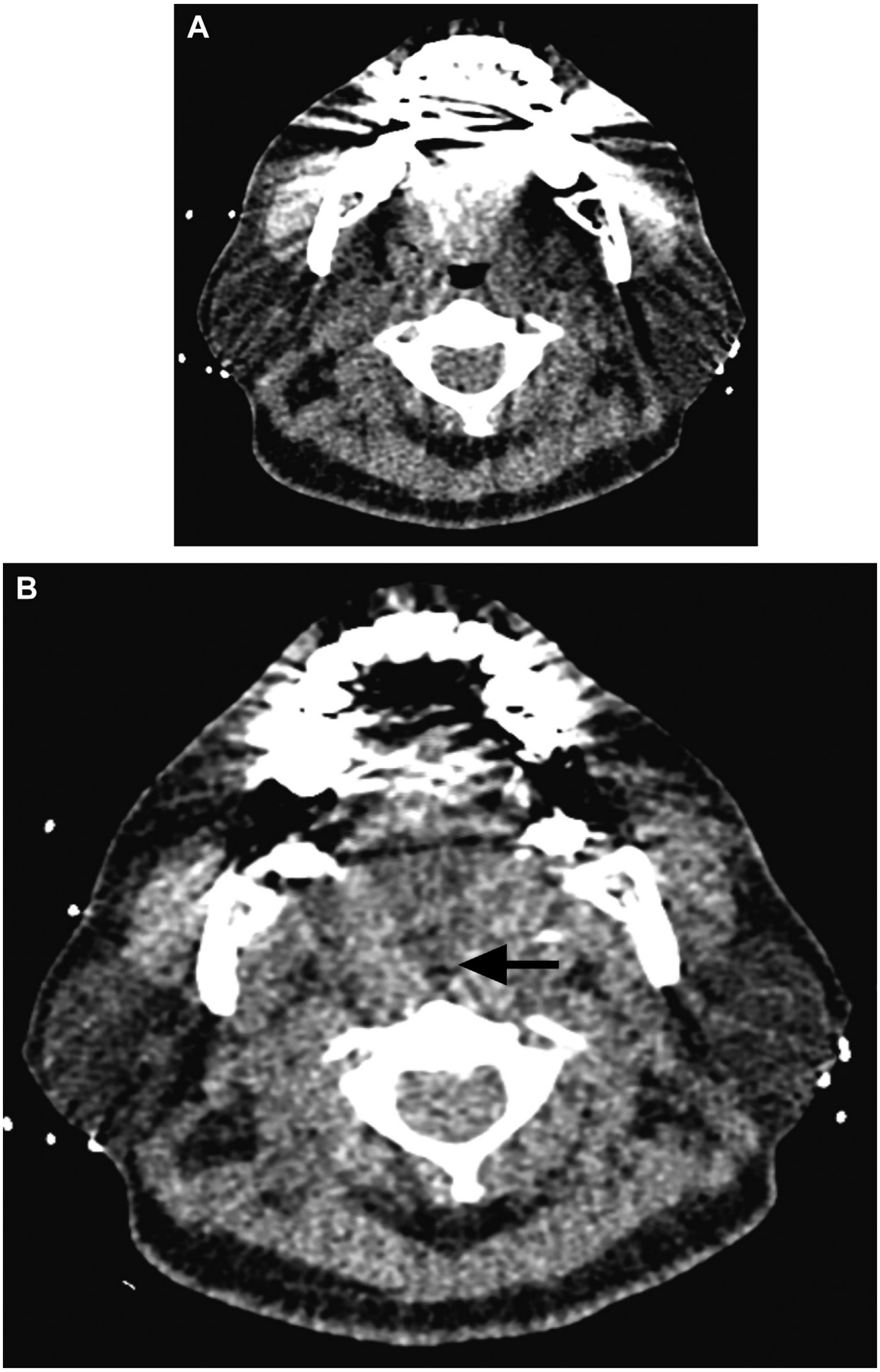

FIGURE 4. Multilevel complete concentric collapse in the retropalatal (RP) and retroglossal (RG) regions (*arrows*) presented as axial cross-sectional and 3-dimensional (3D) images in the same patient. *A*, Axial computed tomography (CT) scan at the RP region during the awake state; *B*, axial CT scan at the RP region during an apneic episode; **(Fig 4 continued on next page.)**

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other) among patients with lower and higher values of RDI (<30 and ≥30), BMI (<25 and ≥25 kg/m^2), NC (<36 and ≥36 cm), and WC (<88 and ≥88 cm) are presented in Tables 1 to 3. No variables were found to significantly distinguish between the presence of single-level and multilevel obstruction in the present study (Table 1). The presence of complete obstruction was significantly associated statistically with one variable, because the upper airway was completely collapsed more often in the patients with an RDI of ≥30 (P = .001; Table 2). The presence of CCC was observed more frequently in patients

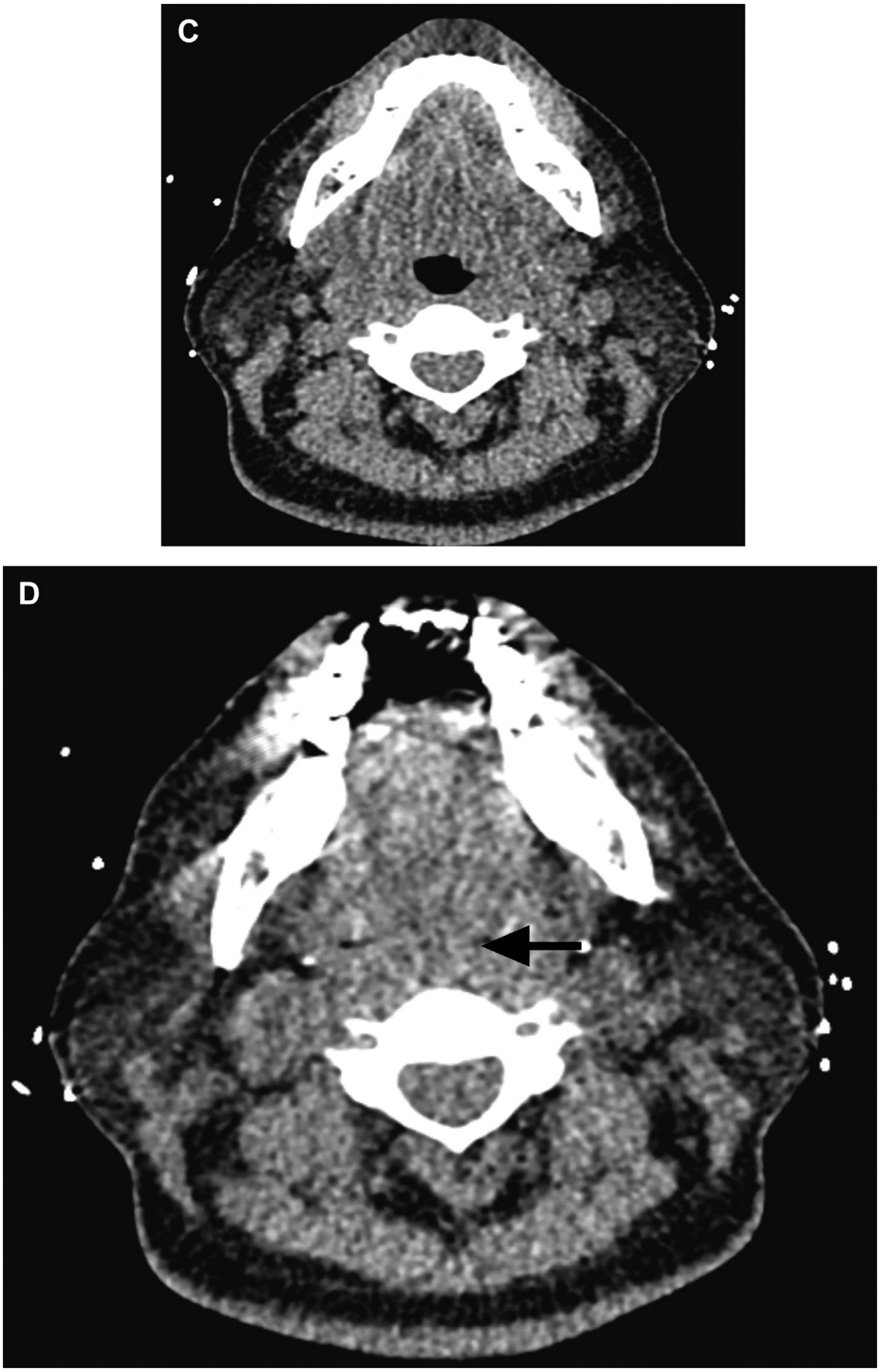

FIGURE 4 (cont'd). *C*, axial CT scan at the RG region during the awake state; *D*, axial CT scan at the RG region during an apneic episode; **(Fig 4 continued on next page.)**

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with a NC of ≥36 cm (*P* = .021) and RDI of ≥30 (*P* = .009; Table 3). A forward stepwise, multivariate, logistic regression analysis showed that an RDI of ≥30 (adjusted odds ratio [OR] 6.33, 95% confidence interval [CI] 1.55 to 25.90) was independently associated with the presence of complete obstruction (Table 2). Moreover, an RDI of ≥30 (adjusted OR 3.77, 95% CI 1.02 to 13.91) was independently associated with the presence of CCC (Table 3). No independent association between an RDI of ≥30 and multilevel obstruction was observed in the present study.

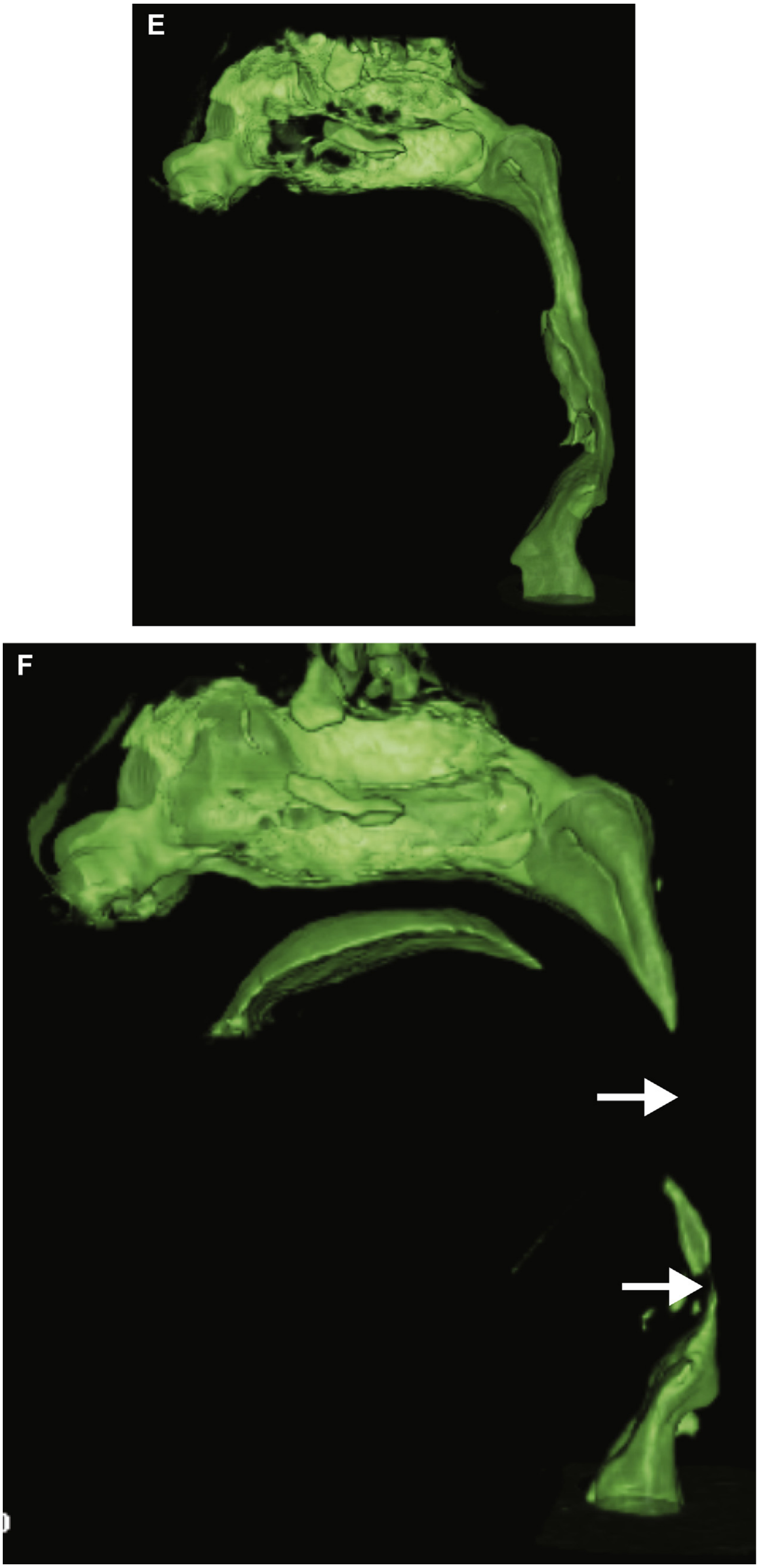

FIGURE 4 (cont'd). *E*, 3D image during the awake state; and *F*, 3D image during an apneic episode.

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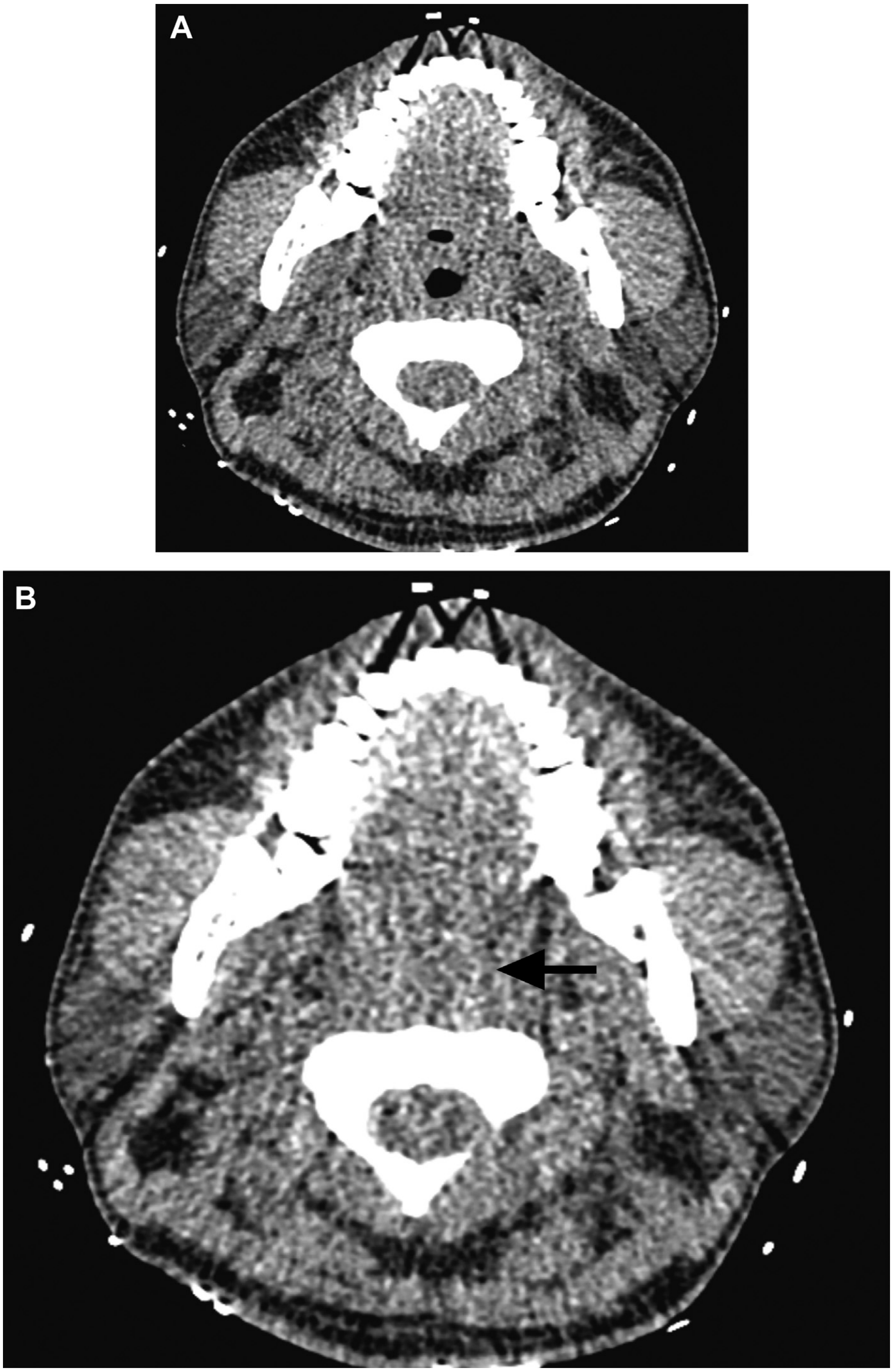

FIGURE 5. Single-level complete concentric collapse in the retropalatal region (*arrows*) presented as axial cross-sectional and 3-dimensional (3D) images in the same patient. *A*, Axial computed tomography (CT) scan during the awake state; *B*, axial CT scan during an apneic episode; **(Fig 5 continued on next page.)**

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Discussion

The purpose of the present study was to assess the CT findings (ie, level, degree, and pattern of upper airway obstruction) of patients with OSA during apneic episodes. We hypothesized that CT combined with portable PSG might reveal more relevant upper airway pathologic findings during these apneic episodes than during the awake state. This approach could avoid resource-intensive overnight stays and deliver more precise results on the location of the obstructions. The specific aim of the present study was to identify the associations between the RDI, BMI,

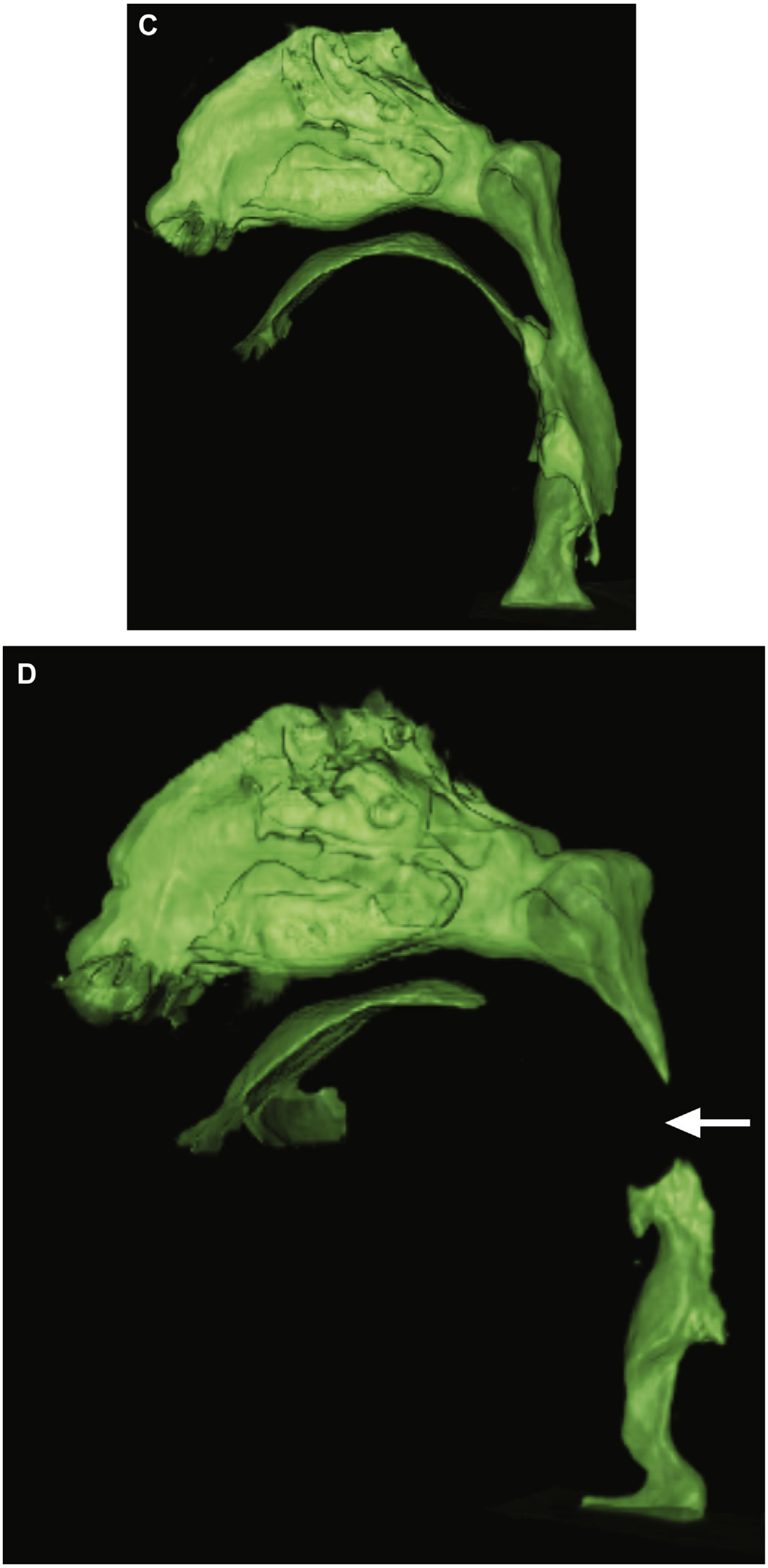

FIGURE 5 (cont'd). *C*, 3D image during the awake state; and *D*, 3D image during an apneic episode.

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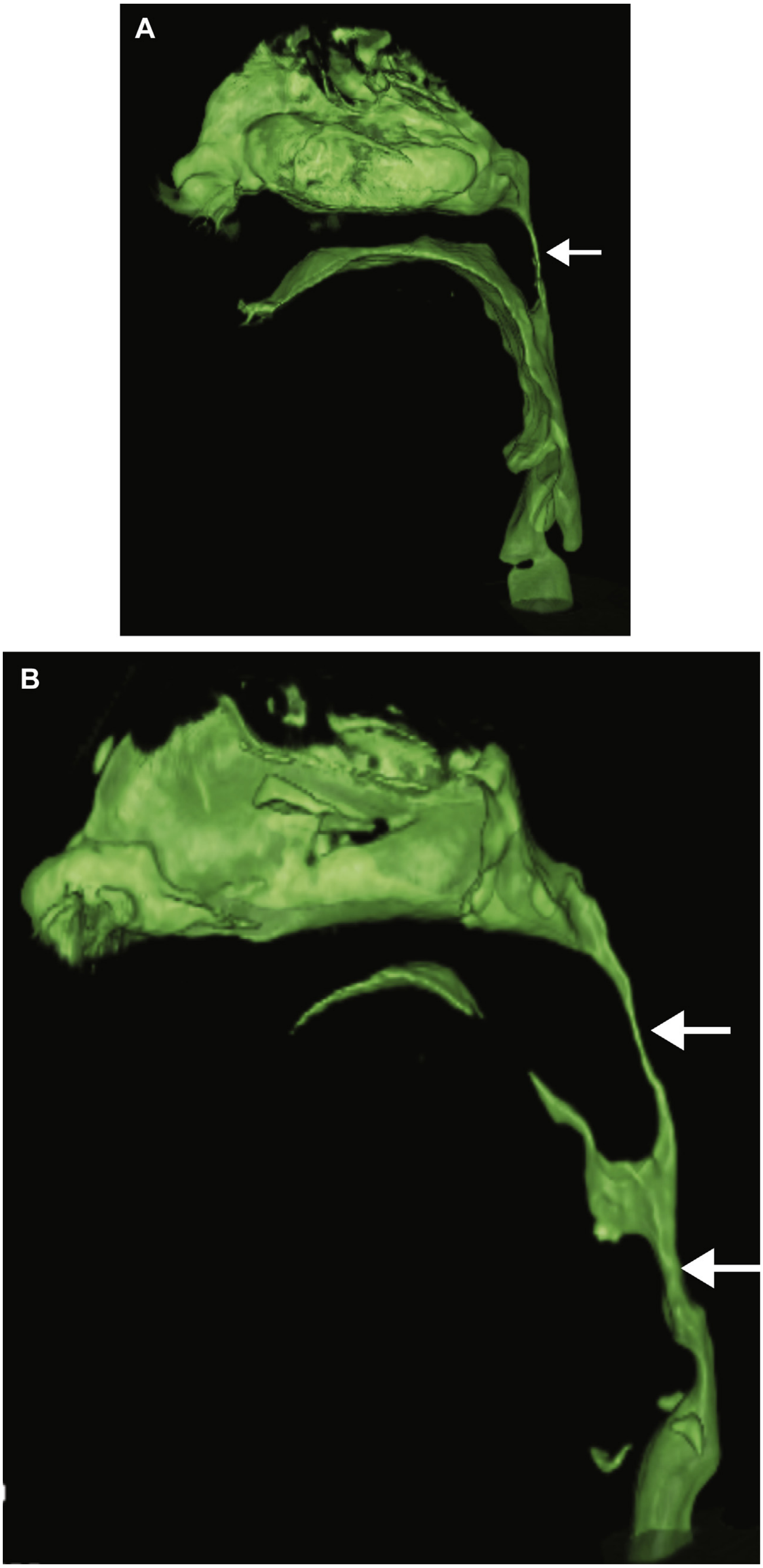

FIGURE 6. Partial obstructions scanned during apneic episodes *(arrows)* in different patients. *A*, Single-level partial obstruction; and *B*, multi-level partial obstruction.

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Table 1. UNIVARIATE AND MULTIVARIATE LOGISTIC REGRESSION ANALYSES FOR PREDICTING MULTILEVEL OBSTRUCTION

	Obstruction Level				
Variable	Multilevel	Single-Level	*P* Value	Crude OR (95% CI)	Adjusted OR (95% CI)
RDI			.969	0.98 (0.32-2.99)	NA
≥30	22 (68.8)	18 (69.2)			
<30*	10 (31.3)	8 (30.8)			
BMI (kg/m^2)			.826	1.14 (0.37-3.53)	NA
≥25	23 (71.9)	18 (69.2)			
<25*	9 (28.1)	8 (30.8)			
NC (cm)			.408	0.57 (0.15-2.17)	NA
≥36	24 (75.0)	21 (84.0)			
<36*	8 (25.0)	4 (16.0)			
WC (cm)			.339	0.55 (0.16-1.89)	NA
≥88	22 (68.8)	20 (80.0)			
<88*	10 (31.3)	5 (20.0)			

Data presented as n (%).

Abbreviations: BMI, body mass index; CI, confidence interval; NA, not applicable; NC, neck circumference; OR, odds ratio; RDI, respiratory disturbance index; WC, waist circumference.

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NC, and WC (predictors) and the CT findings (outcomes).

The most common level of upper airway obstruction was the uvulopalatal complex region, followed by the tongue base area. Multilevel obstruction was more frequently observed during an apneic episode (55.2%) than in the awake state (14.7%). Complete obstruction was seen more often in patients with a high RDI. CCC was frequently observed during apneic episodes. We found that CT could demonstrate the presence of CCC in patients during sleep apnea and that this was significantly associated with severe OSA (RDI of ≥30).

Previous studies investigating OSA using DISE[21,31] commonly found upper airway obstruction in the uvulopalatal complex region. Several studies,[21,31,32]

Table 2. UNIVARIATE AND MULTIVARIATE LOGISTIC REGRESSION MODELS FOR PREDICTING COMPLETE OBSTRUCTION

	Degree of Obstruction				
Variable	Complete	Partial	*P* Value	Crude OR (95% CI)	Adjusted OR (95% CI)
RDI			.001	8.75 (2.34-32.76)	6.33 (1.55-25.90)
≥30	35 (81.4)	5 (33.3)			
<30*	8 (18.6)	10 (66.7)			
BMI (kg/m^2)			.794	0.84 (0.23-3.13)	NA
≥25	30 (69.8)	11 (73.3)			
<25*	13 (30.2)	4 (26.7)			
NC (cm)			.174	2.50 (0.65-9.60)	NA
≥36	35 (83.3)	10 (66.7)			
<36*	7 (16.7)	5 (33.3)			
WC (cm)			.472	1.60 (0.44-5.80)	NA
≥88	32 (76.2)	10 (66.7)			
<88*	10 (23.8)	5 (33.3)			

Data presented as n (%).

Abbreviations: BMI, body mass index; CI, confidence interval; NA, not applicable; NC, neck circumference; OR, odds ratio; RDI, respiratory disturbance index; WC, waist circumference.

* Reference.

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Table 3. UNIVARIATE AND MULTIVARIATE LOGISTIC REGRESSION MODELS FOR PREDICTING COMPLETE CONCENTRIC COLLAPSE

	Pattern of Obstruction				
Variable	CCC	Other	*P* Value	Crude OR (95% CI)	Adjusted OR (95% CI)
RDI			.009	4.83 (1.43-16.34)	3.77 (1.02-13.91)
≥30	26 (83.9)	14 (51.9)			
<30*	5 (16.1)	13 (48.1)			
BMI (kg/m^2)			.074	2.87 (0.88-9.29)	NA
≥25	25 (80.6)	16 (59.3)			
<25*	6 (19.4)	11 (40.7)			
NC (cm)			.021	4.94 (1.17-20.83)	NA
≥36	28 (90.3)	17 (65.4)			
<36*	3 (9.7)	9 (34.6)			
WC (cm)			.057	3.25 (0.94-11.24)	NA
≥88	26 (83.9)	16 (61.5)			
<88*	5 (16.1)	10 (38.5)			

Data presented as n (%).

Abbreviations: BMI, body mass index; CI, confidence interval; NA, not applicable; NC, neck circumference; OR, odds ratio; RDI, respiratory disturbance index; WC, waist circumference.

* Reference.

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which had used DISE to assess the upper airway of patients, reported a significant positive association between the occurrence of multilevel collapse and the severity of OSA. However, higher RDI values were not associated with the presence of multilevel obstruction in our study. This discrepancy might have resulted from differences in data acquisition between the CT and DISE modalities. The super-fast, volumetric CT scanning performed in our study demonstrated multilevel obstruction within a single scan. In contrast, the DISE investigations of different levels were not simultaneous, because they used an endoscope inserted through the upper airway during each apneic episode. A multilevel approach to the surgical treatment of OSA (eg, uvulopalatopharyngoplasty with surgery on the tongue, radiofrequency ablation, midline glossectomy, tongue advancement, or tongue suspension) is required when upper airway collapse occurs at several sites.[33] CT scanning during apnea could support the development of an adequate multilevel surgical plan. Ravesloot and de Vries[31] reported that complete obstruction is associated with severe OSA, which our findings confirmed. Complete collapse can be more difficult than partial collapse to correct with surgery and, similarly, could limit the success of other non-CPAP therapies such as oral appliance use.[21] Hence, demonstrating complete collapse of the upper airway with CT could help clinicians identify the presence of severe OSA. Previous studies found that the absence of palatal CCC during DISE can predict for the therapeutic success with an implanted UAS.[13,34] Visualizing CCC using CT can assist surgeons in predicting severe OSA and the success of UAS implantation therapy, which is a good technique for treatment of AP collapse.[34] Nasal obstruction causes increased nasal resistance to air flow, which influences the patient's initial acceptance of CPAP as a treatment of OSA.[35,36] To increase patient acceptance, nasal surgery in patients with nasal obstruction should be performed before CPAP treatment.[37] In our study, we scanned the upper airway from the upper wall of the nasal cavity to the hyoid bone, a total length of ~16 cm. We found that 48.3% of patients with OSA had some nasal obstruction resulting from a deviated nasal septum and/or turbinate hypertrophy. Therefore, a single CT scan can demonstrate anatomic deformities from the nasal cavity to the hypopharynx and thus assist surgeons in the selection of patients for nasal surgical procedures (eg, septoplasty, nasal valve surgery, or turbinate reduction) before initiating CPAP.[1]

Low-dose volumetric CT provides upper airway images that augment the physiologic data recorded by portable PSG. Super-fast volumetric scanning is a noninvasive technique (contrast medium injection and endoscope insertion not required) that will reveal multilevel upper airway collapse with only a single axial scan (16-cm-wide coverage with 0.35 second per rotation). This reduces the risk of table movement (patients can maintain their sleep phase) and minimizes patients' radiation exposure dose. CT images can be reconstructed as 3D geometric models, which can be used for advanced computational fluid dynamic analyses to *1)* evaluate the airflow characteristics inside the upper airway of patients with OSA[38-41]; *2)* assess the outcomes of different treatment approaches (eg, MMA surgery,[19,42,43] oral appliance,[18] and mandibular advancement devices[44]); and *3)* plan upper airway surgery.[45] For CT scanning, using both supine and nonsupine positions should be considered,[46] because patient position will affect the patterns of upper airway collapse. However, the present study assessed airway changes with the patients only in the supine position, which is generally the most symptomatic for patients with OSA. The studies were performed during the early night, allowing us to observe the effects of airway obstruction in patients only during non–rapid eye movement (REM)–related events, similar to the timing of other OSA image-based diagnostic modalities (MRI and DISE). Only full-night PSG can comprehensively perform REM sleep analysis. Despite this, the proposed combination of CT and portable PSG demonstrated abnormalities of upper airway morphology that are likely related to OSA. The efficacy of combined CT and portable PSG for assisting clinicians for OSA management decisions should be studied in future research.

Conclusion

CT scanning during apneic episodes revealed multilevel obstruction better than did scanning with the patients awake. High RDI values were independently associated with complete obstruction and CCC of the upper airway during sleep apnea. Associations between CT upper airway measures (eg, length, cross-sectional area, and upper airway volume) and RDI will be examined further in future studies.

Acknowledgments

We thank the Section for Clinical Epidemiology and Biostatistics, Faculty of Medicine Ramathibodi Hospital, Mahidol University for performing the statistical analyses.

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