OSAHS

Sound frequency spectra of snore in relation to the site of obstruction among snorers

Tipi di tracciato spettrografico nel russamento in relazione al sito ostruttivo

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SUMMARY

Objective. This study aimed to describe the sound frequency of snoring in relation to the site of upper airway vibration among snorers.

Methods. 383 snores from 40 participants who complained of snoring were digitally recorded during natural and induced sleep using a level III polysomnography monitor with a built-in microphone. During drug-induced sleep endoscopy (DISE), the real-time site of upper airway obstruction was assessed, and the sound frequency of snoring was recorded synchronously.

Results. The mean peak of snoring frequency for unilevel palatal, oropharynx and epiglottis obstruction were 522.5, 482.4 and 300.0 Hz, respectively. Most participants showed multilevel obstruction at the palate and oropharynx, in which the mean for bi-peak snoring frequency were 402.90 Hz and 1086.96 Hz, respectively. Severity of OSA was significantly associated with multilevel obstruction.

Conclusions. There was a significant association between the snoring sound frequency and site of unilevel obstruction. Palatal or oropharyngeal obstruction produced sound at mid-frequency range, while the epiglottis produced a low frequency range. Multilevel obstruction documented a bi-peak snoring frequency.

KEY WORDS: drug-induced sleep endoscopy, obstructive sleep apnoea, frequency analysis, snoring

RIASSUNTO

Obiettivo. *Questo studio mira a descrivere la frequenza del suono del russamento in relazione al sito di ostruzione delle vie aeree superiori.*

Metodi. *È stata ottenuta la registrazione di 383 russamenti da 40 partecipanti affetti da russamento cronico. Il russamento è stato registrato digitalmente durante il sonno naturale e indotto, utilizzando un monitor per polisonnografia di livello III con microfono incorporato. Durante la sleep endoscopy a sonno indotto farmacologicamente (DISE), è stato valutato il sito, in tempo reale, dell'ostruzione delle vie aeree superiori, registrando contestualmente la frequenza del russamento.*

Risultati. *Il picco medio della frequenza del russamento per l'ostruzione ad un singolo livello, palatale, orofaringeo o epiglottico, era rispettivamente di 522,5, 482,4 e 300,0 Hz. La maggior parte dei partecipanti ha mostrato un'ostruzione a più livelli (palato e orofaringe), in cui la media per la frequenza del russamento a due picchi era rispettivamente di 402,90 Hz e 1086,96 Hz. La gravità dell'OSA era significativamente associata all'ostruzione multilivello.*

Conclusioni. *È risultata un'associazione significativa tra la frequenza del suono del russamento e il sito di ostruzione ad un singolo livello. L'ostruzione palatale o orofaringea produceva un suono a una gamma di frequenze medie, mentre l'epiglottide produceva una gamma di basse frequenze. L'ostruzione multilivello ha documentato una frequenza di russamento bi-picco.*

PAROLE CHIAVE: *sleep endoscopy, apnea ostruttiva del sonno, analisi della frequenza, russamento*

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Conflict of interest
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Introduction

Snoring is a social nuisance to bed partners and everyone who hears this unpleasant sound. Produced while sleeping, snoring is due to upper airway narrowing and increased resistance to airflow, which results from the following mechanisms: 1) lax pharyngeal muscles with reduced tone; 2) reduced airflow in the nose; and 3) crowded airway due to enlarged tonsils or tumours [1]. The craniofacial profile of Asians has been shown to cause more severe snoring than that of Caucasians [2,3].

The clinical significance of snoring is when the snorer falls into the category of obstructive sleep apnoea (OSA). These snorers are at an increased risk of hypertension, stroke, myocardial infarction and sudden death [1,4-7].

The current standard for clinical practice is to confirm diagnosis of OSA with in-laboratory polysomnography (PSG). However, this is relatively expensive and technically complex. Therefore, level III PSG monitors have been used as an alternative diagnostic test for OSA. These utilise biosensors to monitor airflow, respiratory effort, blood oxygenation, cardiac activity and sleep/wake activity [4].

Identifying the site of obstruction and pattern of upper airway changes during sleep is pertinent in the management of OSA. The awake state findings of the Müller manoeuvre may differ quite significantly from the sleep-breathing situation [5]. Conversely, drug-induced sleep endoscopy (DISE) provides a good objective assessment of the site of obstruction in the sleep state. It helps in tailoring therapy on an individual basis, leading to a higher rates of surgical success [6]. Therefore, it would be particularly useful if a level III PSG monitor could provide clinicians with information on the site of obstruction in snorers.

The site and mechanism of upper airway obstruction and vibration among Caucasian and East Asian populations have been found to produce snoring sounds with specific acoustic characteristics. Palatal snoring has been found to have a lower centre frequency than tongue base snoring, although the actual frequencies reported varied substantially [7-9]. However, none of these studies has used a level III PSG monitor with a built-in microphone, which can carry out an acoustic analysis concurrently. Furthermore, no study has investigated snoring sound frequency in Southeast Asian countries, which comprise multi-ethnic Asian populations.

Therefore, the present study aimed to describe the acoustic characteristics of snores using NOX-T3 (a level III PSG monitor with a built-in microphone) among participants of various local Asian ethnicities. The study also investigated the acoustic characteristics of uni- and multilevel upper airway obstruction involving the palate, oropharynx, base of tongue and epiglottis and assessed their relationship with the severity of apnoea-hypopnoea index (AHI).

Materials and methods

Study design and patient recruitment

A cross-sectional study was conducted over 15 months on 40 patients above the age of 18 years who attended the otorhinolaryngology (ORL) clinic in the Universiti Kebangsaan Malaysia Medical Centre (UKMMC) with complaints of snoring with or without daytime somnolence. Informed consent was obtained from all participants before enrolment in the study. The study protocol was approved by the ethics and research committee of UKMMC (FF–2016–326), which adheres to the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Patients were excluded from this study if they had undergone previous treatments for sleep apnoea with continuous positive airway pressure, corrective upper airway surgery, or a mandibular advancement device. Patients with significant signs and symptoms of nasal obstruction amenable to medical therapy or nasal surgery; those with a known underlying decompensated cardiorespiratory disease or a neurological or psychiatric disease that could account for sleepiness; and those with other known sleep disorders, such as narcolepsy or restless leg syndrome, were also excluded from this study.

Other exclusion criteria included patients who were known to be on medication, such as stimulants, hypnotics, benzodiazepines, antidepressants, or had a history of excessive alcohol consumption; those with a body mass index (BMI) of more than 35; those with an American Society of Anaesthesiologists score of 3 or more; and those who are allergic to propofol.

The patients were seen in the clinic for a comprehensive sleep evaluation, which included history taking, physical examination (nasal septum, inferior turbinates, tonsil size, Friedman tongue position and type of jaw malocclusion) and answering the Epworth Sleepiness Scale. Awake flexible nasopharyngolaryngoscopy was conducted and video-recorded for all participants. Participants were then scheduled for a level III PSG monitoring at night and DISE on the next day.

Study instruments

A. Polysomnography

All participants were subjected to a level III PSG monitoring using the NOX–T3 (Nox Medical, Iceland) device, which is a type 3 monitor with a position sensor, pressure transducer, pulse oximeter and audio recording from a built-in microphone. It can analyse the acoustic characteristics of snores. The microphone on the T3 device has a sampling frequency of 8 kHz. It was checked against calibrated industrial sound level metres with a frequency sweep measured in a specially set up insulated sound box with a speaker. The participants were not allowed to consume caffeine or alcohol on the night and day of testing. The NOX- T3 device was adjusted to their chest using a belt placed 10 cm from the lower lip. Oxygen saturation and heart rate were recorded using a pulse oximeter. The snore events were scored automatically by the Noxturnal version 5.1 software algorithm (Nox Medical). The mean of the snoring frequency during the supine position was selected randomly. The frequency and severity of obstructive events were reported as AHI. Automatic scoring was used to obtain the parameters from the level III PSG monitor. OSA severity was defined as mild for AHI ≥ 5 and < 15, moderate for AHI ≥ 15 and ≤ 30 and severe for AHI > 30 [10].

B. Drug-induced sleep endoscopy

Participants underwent DISE the following morning. The procedure was conducted at the General Operating Theatre of UKMMC. Participants were placed in the supine position on the operating table. They received continuous oxygen (0.5 L/min) and underwent pulse oximetry, electrocardiography and blood pressure monitoring throughout the procedure. Unconscious sedation was achieved using intravenous propofol infusion. The propofol titration was done through the target control infusion algorithm in the machine, in which the patient's age, height, weight and gender were keyed in and titration started at 1.5 mcg/ml. Sedation was given by a qualified anaesthetist. Once a favourable level of sedation [bispectral index level (BIS) 50-70] was reached, flexible endoscopy was performed. If the BIS level went out of range, the scope was withdrawn until another steady state was achieved after adjusting the dose of propofol. The velum, oropharynx, tongue base and epiglottis were examined and continuously video-documented. Parallel to the visual recording, the NOX-T3 unit was adjusted to the participant's chest using a belt placed 10 cm from the lower lip. A minimum of 10 snores were captured from each patient. The observation from sleep endoscopy was recorded using the VOTE classification system [11], while the acoustic recordings were traced from the NOX-T3. The level of obstruction was evaluated alongside the frequency of snoring by incorporating the flexible endoscopy video into the NOX-T3 recording (Fig. 1). The beginning of the video recording was captured by NOX-T3 through a verbal cue given by the endoscopist.

C. Snoring frequency analysis

The snoring sounds were analysed by fast Fourier transformation (FFT) available in the NOX- T3 device. Peak frequency, which is the sound frequency of the highest magnitude in an analysed snoring sample, was used for data analysis. The upper limit for the range of frequencies in which sound occurs was fixed at 2,000 Hz, as most snoring sounds are produced at frequencies below 2,000 Hz. The spectra produced were grouped into three different bands, namely B1 (low-frequency, 40-300 Hz), B2 (mid-frequency, 301-850 Hz) and B3 (high-frequency, 851-2,000 Hz), as proposed by Lee et al. [12,13]. The snoring samples during DISE were compared with the same participant's natural snore samples in the supine position for a valid statistical analysis. The selection of peak frequency was performed manually, and thus all non-snore sounds were excluded (e.g. coughing, groaning, high-pitch squeaks and duvet noise).

Statistical analysis

All data were computerised and analysed using Statistical Package for Social Sciences version 23.0 software. The spectrum of snoring frequency was documented as the mean and median. The comparison between the frequency of snoring and the origin of unilevel vibration was made using the Kruskal-Wallis test. The chi-square test of independence was used to analyse the association between: 1) the uni- or multilevel site of obstruction and severity of OSA (normal or mild, moderate or severe OSA) and 2) the snoring acoustic frequency spectra (B1, B2 and B3) and the site of unilevel obstruction. The Wilcoxon signed-rank test was used to compare the difference in the mean frequency of snoring acoustic between natural and induced sleep.

Results

Patient demographics

A total of 383 snores were collected from 40 patients (28 males and 12 females) who were included in the study. The mean age was 39 years (standard deviation (SD): 10.7; minimum: 23; maximum: 65). The mean BMI was 28.4 (SD: 4.8; minimum: 16.4; maximum: 35). Among these, 7 were primary snorers, and 9, 9 and 15 had mild, moderate and severe OSA, respectively. A summary of the demographic data is presented in Table I.

Snoring acoustic frequency and pattern of upper airway obstruction

In the 40 participants, multilevel upper airway obstruction (62.5%) was more common than unilevel obstruction

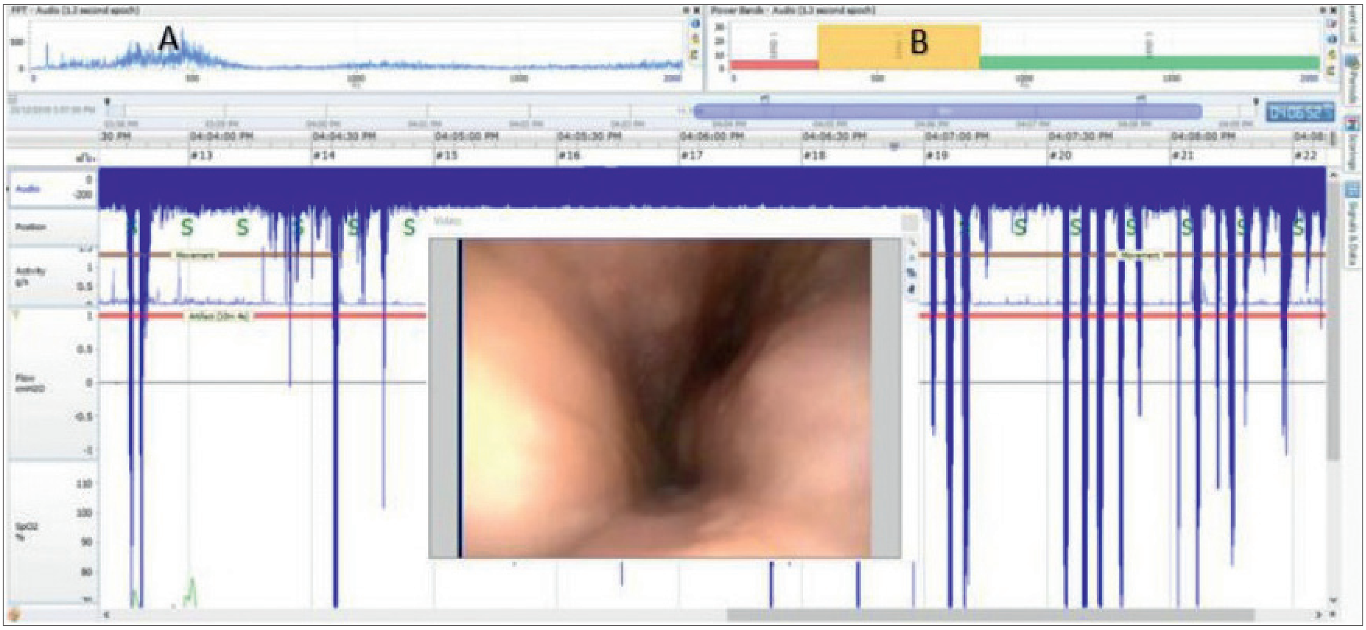

Figure 1. Oropharynx obstruction. Demonstration of drug-induced sleep endoscopy and concurrent recording of snoring of a 50-year-old Indian man who had severe OSA (AHI = 53 events/hour) and a unilevel obstruction in the oropharynx. (A) FFT shows the peak frequency at 450 Hz. (B) The power spectra of the snore are in the mid-frequency band (B2: 301-850 Hz).

Table I. Summary of the demographic data of the study participants.

Characteristics	Number (total 40)	Percentage (%)
Ethnicity		
Malay	27	70.0
Chinese	10	25.0
Indian	3	5.0
Gender		
Male	28	70.0
Female	12	30.0
Body Mass Index (BMI)		
Underweight (< 18.5)	1	2.5
Normal (18.5-24.9)	7	17.5
Overweight (25-29.9)	14	35.0
Obese (30-34.9)	14	35.0
Extremely obese (35)	4	10.0
Apnoea-Hypopnea Index (AHI)		
None/Minimal (< 5 per hour)	7	17.5
Mild (5-14.9 per hour)	9	22.5
Moderate (15-29.9 per hour)	9	22.5
Severe (≥ 30 per hour)	15	37.5

(37.5%). For the unilevel obstruction, 3, 9 and 3 participants had palatal, oropharynx or epiglottis obstruction, respectively. None of the patients had tongue base collapse alone. The most common combination for multilevel obstruction was 'palate and oropharynx' (21 patients), followed by 'palate and tongue base' and 'palate and epiglottis' with 2 participants each (Tab. II).

Table II. Summary of the level and site of obstruction contributing to snoring.

Description	Number (n = 40)	Percentage (%)
Level of obstruction		
Unilevel	15	37.5
Multilevel	25	62.5
Site of obstruction		
Epiglottis only	3	7.5
Oropharynx only	9	22.5
Palate only	3	7.5
Palate and epiglottis	2	5.0
Palate and oropharynx	21	52.5
Palate and tongue base	2	5.0

In the analysis of the data of 383 snoring samples, uni-peak and bi-peak frequencies were detected in unilevel and multilevel obstruction, as shown in Figures 1 and 2, respectively. For the unilevel obstruction, the ranges of the uni-peak sound frequency obtained for each site of obstruction were as follows: palate (lowest: 200 Hz, highest: 1300 Hz), oropharynx (lowest: 150 Hz, highest: 750 Hz) and epiglottis (lowest: 100 Hz, highest: 600 Hz). The bi-peak frequency of snoring acoustic was identified in the participants with

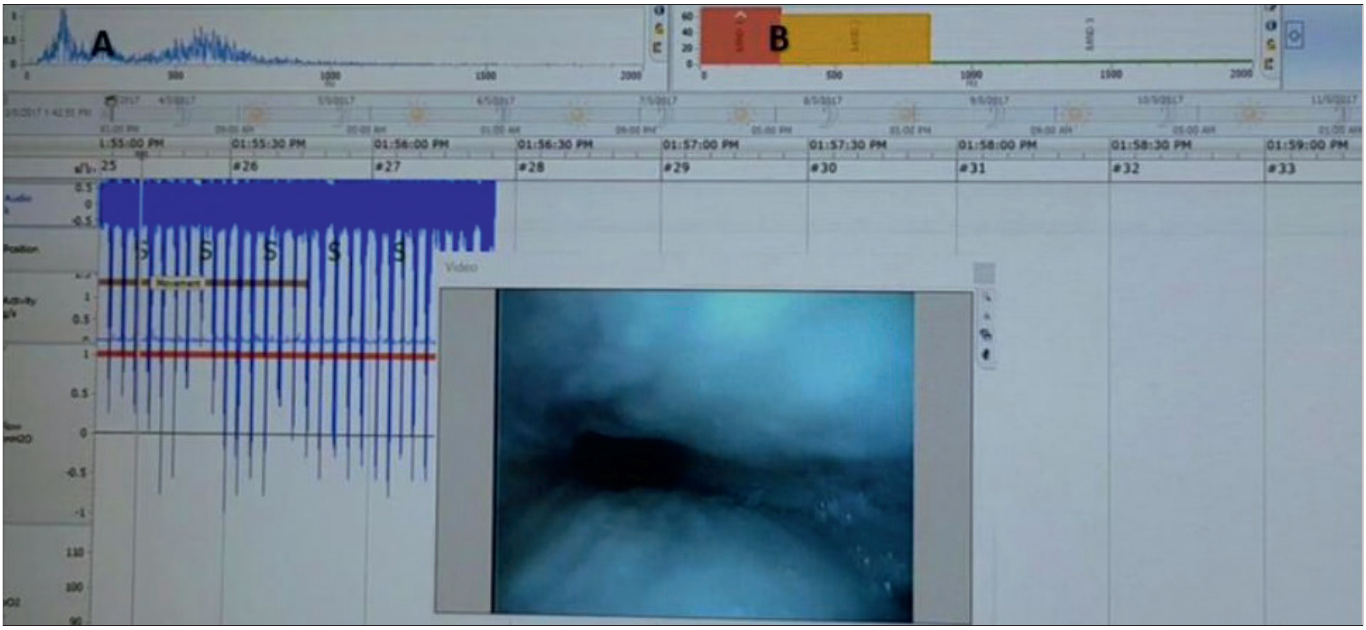

Figure 2. Multilevel obstruction. Demonstration of drug-induced sleep endoscopy and concurrent recording of snoring of a 31-year-old Malay man who had moderate OSA (AHI = 17 events/hour) and a multilevel obstruction in the palate and oropharynx. (A) FFT shows the bi-peak frequency at 150 Hz and 600 Hz. (B) The power spectra of the snore are in the low- and mid-frequency bands (B1: 40-300 Hz; B2: 301-850 Hz).

Table III. Frequency of snore in relation to the site of obstruction.

Level of obstruction	Site of occurrence	n	Frequency (Hz)		X^2	p-value
			Median	IQR		
Unilevel	Epiglottis only	26	300.00	100.0-350.0	18.929	< 0.001
	Oropharynx only	91	500.00	350.0-650.0		
	Palate only	20	450.00	200.0-537.5		

P-value is based on the Kruskal-Wallis test.

multilevel obstruction. For the bi-peak frequency, the means of the lower and upper peaks were 402.90 Hz and 1086.96 Hz for 'palate and oropharynx', 445.83 Hz and 833.33 Hz for 'palate and tongue base' and 668.75 Hz and 1275.00 Hz for 'palate and epiglottis', respectively.

Comparison between the frequency of snoring acoustics and the site of unilevel obstruction

The comparison of the median of the snoring acoustic frequency produced at the palate, oropharynx or epiglottis revealed a significant difference in snoring frequency between the different levels ($p < 0.0001$) (Tab. III).

Association between the snoring acoustic frequency bands and the site of unilevel obstruction

The relationship between the snoring acoustic frequency bands (B1, B2 and B3) and the origin of vibration revealed a significant association between the different bands and the site of unilevel obstruction, (X^2 (4, N = 125) = 32.611, $p < 0.0001$) (Tab. IV). The epiglottis was found to produce snores in the low-frequency band (B1), and the oropharynx and palate produced snores in the mid-frequency band (B2).

Association between the site of obstruction and the severity of OSA

The analysis between the site of obstruction (uni- and multilevel) and the severity of OSA (normal, mild, moderate or severe) showed a significant association between both variables (X^2 (3, N = 383) = 35.199, $p < 0.0001$). Multilevel obstruction was significantly associated with higher AHI, in which the participants with moderate and severe OSA were more likely to have multilevel obstruction (Tab. V).

Comparison of snoring acoustic frequency between natural and induced sleep

The comparison between the mean snoring acoustic fre-

Table IV. Association between snoring acoustic frequency bands and unilevel obstruction.

	Site of obstruction (unilevel)			Chi-Square (X^2)	p-value
	Epiglottis	Oropharynx	Palate		
Overall, n (%)					
B1 (40-300 Hz)	14 (36.8%)	17 (44.7%)	7 (18.4%)		
B2 (301-850 Hz)	12 (14.5%)	62 (74.7%)	9 (10.8%)	32.611	< 0.0001
B3 (851-2000 Hz)	0 (0.0%)	0 (0.0%)	4 (100.0%)		
Total	26 (20.8%)	79 (63.2%)	20 (16.0%)		

P-value is based on the chi-square test.

Table V. Association between the severity of OSA and the site of obstruction.

Site of obstruction	AHI (transform refer to cut-off point)				Total % (by row)	Chi-Square (X^2)	p-value
	None/Minimal (< 5 per hour)	Mild (5-14.9 per hour)	Moderate (15-29.9 per hour)	Severe (≥ 30 per hour)			
Unilevel	38 (27.7%)	44 (32.1%)	24 (17.5%)	31 (22.6%)	137 (100.0%)	35.199	< 0.0001
Multilevel	31 (12.6%)	41 (16.7%)	63 (25.6%)	111 (45.1%)	246 (100.0%)		

P-value is based on the chi-square test.

quency recorded during natural sleep at night and induced sleep during DISE showed no significant difference (p = 0.464).

Discussion

The main diagnostic challenge in patients with OSA is to determine the site of the upper airway obstruction during sleep. DISE has the advantage of identifying the collapse of the upper airway, which is not visible when awake, resulting in a better selection of a specific surgical procedure for patients. However, due to time and personnel constraints in many centres, DISE cannot be offered to all OSA patients. Thus, it is useful to know the pattern of upper airway obstruction among snorers as well as the frequency of snoring acoustic that they produce. This knowledge can enable doctors to use sound frequency analysis as an evaluation tool to ascertain the site of vibration or obstruction during sleep without the need for DISE. Patients can then receive therapy targeted to the identified level of upper airway obstruction, which may result in greater treatment success.

To the authors' knowledge, previous studies evaluating the acoustic characteristics of snores were conducted among Caucasian and East Asian populations. The present study is the first to involve participants of various ethnicities Malay: n = 27, Chinese: n = 10, Indian: n = 3). This study included habitual snorers and OSA patients of various severities, unlike other studies that recruited habitual snorers alone or those with mild to moderate OSA [7-9,14].

The key findings of the present study are as follows: 1) multilevel obstruction is more common than unilevel obstruction; 2) there is a significant difference in the mean of snore frequency at different levels of obstruction ($X^2 = 18.929$, $p \leq 0.001$); 3) snorers with a multilevel obstruction have higher AHI ($p \leq 0.0001$); and 4) a similar snoring acoustic frequency was recorded for both natural and induced sleep. Unlike earlier studies which found that palatal snore lies in the low-frequency band [7,8,14] the present study shows that the mean peak frequencies of palatal snore (522.50 Hz) and oropharyngeal snore (482.42 Hz) fell into the mid-frequency band of the power spectra, while epiglottal snore (300.0 Hz) fell into the low-frequency band. The authors attributed these findings to the difference in the craniofacial profile of the participants compared with that in previous studies.

Despite suffering from a similar degree of OSA severity, Asian patients are mostly less overweight than Caucasians, suggesting that OSA risk factors may be influenced by ethnicity [3]. Obese OSA patients have features of increased upper airway soft tissue structures, whereas non-obese patients have abnormal craniofacial structures that increase the risk of upper airway collapse during sleep. Li et al. reported that unlike in Caucasians, obesity is a less significant risk factor for OSA in Asian patients. Asians with OSA have features of a maxillomandibular protrusion, narrower cranial base angle, larger posterior airway space and more superiorly positioned hyoid bone compared with Caucasians [15]. In this study, more than half of the recruited patients were non-obese. A local study on craniofacial morphology among OSA patients revealed that differences exist in the craniofacial profile among patients of different ethnicities but with the same severity of disease. Among those with moderate to severe OSA, Malay patients had shorter maxillary and mandibular length, whereas Chinese patients were found to have a more caudally located hyoid bone [16]. The snoring acoustic is a result of the vibration of the upper airway structures, namely the palate, pharynx, tongue base and epiglottis. Therefore, the length of the soft palate, dimension of the pharyngeal airway, position of the hyoid bone and other cephalometric differences between Asians and Caucasians may translate into different findings of snoring acoustic frequency as depicted by the participants in the present study.

This study has several potential limitations. First, the level of sedation was not necessarily equal to sleep stages. Although an increasing depth of sleep was associated with a gradual decrease in BIS, many overlapping scores were found between different sleep stages [17]. Nonetheless, the monitoring of BIS to ensure that DISE was performed under the same level of BIS during each examination remains a recommended practice. In the present study, DISE was performed at the BIS level of 50-70, as earlier studies revealed that N3 and REM sleep stages correspond to this BIS level [17-19]. Second, obtaining a large sample of diverse ethnic groups with equal numbers of patients in each group over a short period was difficult. This limited the ability of this study to compare the snoring acoustic frequency between the different ethnicities. Third, although DISE should ideally be conducted in a sleep laboratory to eliminate background noise, it was not feasible to do this in the present study because the sleep laboratory was not equipped with personnel and facilities for resuscitation in case of an airway emergency. The authors were also unable to perform statistical analysis on the origin of the corresponding bi-peak sound frequency shown among snorers with multilevel obstruction. Further studies are required to analyse this. Lastly, the level III PSG monitor used in this study uses FFT for the analysis of snoring acoustic. Note that for non-stationary signals such as snoring sound, the locality in the frequency domains by the FFT is poor. Many methods, such as the wavelet transform, Hilbert-Huang transform and blind source separation, have been proposed to give a better acoustical analysis of snoring [20]. However, currently, there is no other level III PSG machine with a built-in microphone that uses a different method of acoustic analysis of snoring sound.

With respect to these limitations, this study asserts that the acoustical analysis of snoring is a non-invasive, convenient and promising method to identify the site of obstruction in OSA patients. To improve the outcome of this study, aside from a larger number of participants, inter-observer agreement should be assessed, and a better method of acoustical analysis should be applied. Nonetheless, the primary objective of this study, which is to determine the spectrum of snoring frequency in relation to the site of obstruction among snoring patients of a local multi-ethnic Asian population, was achieved.

Conclusions

This study demonstrated that a unilevel obstruction has a uni-peak frequency, whereas a multilevel obstruction has a bi-peak snoring acoustic frequency. The mean and range of the snoring acoustic frequency were documented, with the palatal and oropharyngeal snoring recording a mid-frequency band of the snoring acoustic spectrum. The multilevel site of obstruction was significantly associated with a higher severity of OSA.

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