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Investigation of sequential properties of snoring episodes for obstructive sleep apnoea identification

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Abstract

In this paper, 'snore regularity' is studied in terms of the variations of snoring sound episode durations, separations and average powers in simple snorers and in obstructive sleep apnoea (OSA) patients. The goal was to explore the possibility of distinguishing among simple snorers and OSA patients using only sleep sound recordings of individuals and to ultimately eliminate the need for spending a whole night in the clinic for polysomnographic recording. Sequences that contain snoring episode durations (SED), snoring episode separations (SES) and average snoring episode powers (SEP) were constructed from snoring sound recordings of 30 individuals (18 simple snorers and 12 OSA patients) who were also under polysomnographic recording in Gülhane Military Medical Academy Sleep Studies Laboratory (GMMA-SSL), Ankara, Turkey. Snore regularity is quantified in terms of mean, standard deviation and coefficient of variation values for the SED, SES and SEP sequences. In all three of these sequences, OSA patients' data displayed a higher variation than those of simple snorers. To exclude the effects of slow variations in the base-line of these sequences, new sequences that contain the coefficient of variation of the sample values in a 'short' signal frame, i.e., short time coefficient of variation (STCV) sequences, were defined. The mean, the standard deviation and the coefficient of variation values calculated from the STCV sequences displayed a stronger potential to distinguish among simple snorers and OSA patients than those obtained from the SED, SES and SEP sequences themselves. Spider charts were used to jointly visualize the three parameters, i.e., the mean, the standard deviation and the coefficient of variation values of the SED, SES and SEP sequences, and the corresponding STCV sequences as two-dimensional plots. Our observations showed that the statistical parameters obtained from the

SED and SES sequences, and the corresponding STCV sequences, possessed a strong potential to distinguish among simple snorers and OSA patients, both marginally, i.e., when the parameters are examined individually, and jointly. The parameters obtained from the SEP sequences and the corresponding STCV sequences, on the other hand, did not have a strong discrimination capability. However, the joint behaviour of these parameters showed some potential to distinguish among simple snorers and OSA patients.

Keywords: snoring, sound analysis, detection, classification, obstructive sleep apnoea

1. Introduction

Snoring is caused by a narrowing at some location of the human upper airway due to the collapse of relaxed tissues during sleep. When air flow constriction yields sufficiently high pressure gradient along the narrowing, vibration of the tissues may be triggered and snoring sounds are produced accordingly. The sites of snoring were classified as hypo-pharyngeal, epiglottic, tongue base and palatal (Hill *et al* 1999). On the other hand, Dalmasso and Prota (1996) defined three snoring patterns as nasal, oral and oronasal after their investigations on simulated snores. About 50% of the adult population suffer from snoring (Lugaresi *et al* 1980, Norton and Dunn 1985). Snoring is disturbing, unpleasant and degrades the sleep quality of the bed partner. Wilson *et al* (1999) pointed to the connection of snoring with the development of diseases with high morbidity and mortality such as ischaemic brain infarction, systemic arterial hypertension, coronary artery disease and sleep disturbance. Snoring has been a point of significant concern in clinical medicine recently. The increase of the types of commercial devices and apparatus against snoring is also noteworthy. Diagnosis of snoring, identification of the snoring source site, treatment method and evaluation of treatment success are the major issues in the field.

The relationship between snoring and obstructive sleep apnoea (OSA) syndrome has been considered in a number of studies in recent years (Sola-Soler *et al* 2002, 2003, Abeyratne *et al* 2005, Lee *et al* 2000, Fiz *et al* 1996, Dalmasso and Prota 1996, Beck *et al* 1995, McCombe *et al* 1995).

In OSA syndrome, air flow pauses occur during sleep for ∼10 s or more because of a blocking tissue along the airway. It is usually associated with loud heavy snoring. The individual suffers reduced oxygen saturation and frequent awakenings. OSA threatens human health; excessive sleepiness during daytime (hypersomnolence), which is the basic diagnostic criterion for OSA, reduction in cognitive function, cardiovascular diseases, stroke, decreased quality of life and fatigue are commonly observed among OSA patients (Beck *et al* 1995, Abeyratne *et al* 2005, Liu *et al* 2007). In a study conducted by Young (1993), it was estimated that 9% of the women and 24% of the men in the US population of 30–60 years have more than five apnoeas or hypopnoeas per hour of sleep. A fundamental clinical practice to examine patients' sleep behaviour is to produce a whole night polysomnography record, which requires the individual to spend a full night in a medical facility. Nowadays, ambulatory devices which can be used at home are also emerging. However, such devices have at least one sensor connected to the body. This makes the devices difficult to use by untrained persons, and hard to use on children. Recent research focuses on the investigation of sleep sound recordings to identify certain sleep disorders. Sleep sounds can conveniently be collected in one's own sleeping environment (Abeyratne *et al* 2001, 2005, Fiz *et al* 1996, Sola-Soler 2002, Lee *et al* 2000, Wakwella *et al* 2004, Van Brunt *et al* 1997, Duckitt *et al* 2006, Cavusoglu *et al* 2007, Agrawal *et al* 2002, Saunders *et al* 2004). Jane *et al* (2003) stated that information about breathing abnormalities, OSA or other pathologies, such as upper airway resistance syndrome can be obtained by examining sleep sounds. Snoring sounds have been investigated for different purposes. Identification of the type of snoring as palatal or nonpalatal (Osborne *et al* 1999 and Hill *et al* 1999, 2000) for surgical planning, distinguishing among simple snoring and heavy snoring accompanied by OSA (Hara *et al* 2006, Dalmasso and Prota 1996, Sola-Soler *et al* 2003, Fiz *et al* 1996, Abeyratne *et al* 2005, McCombe *et al* 1995), prediction of the outcome of surgical treatment (Jones *et al* 2005, 2006a, 2006b, 2006c, Brietzke and Mair 2006), comparison of natural snores and snores during propofol sedation (Jones *et al* 2006c) are some of the examples.

A number of attributes are proposed for snore sound characterization in fields other than OSA/non-OSA classification. According to the findings of Hill *et al* (1999) and Osborne *et al* (1999), the average crest factor value can be used for distinguishing among palatal and nonpalatal snoring. In their work, they define the crest factor as the ratio of the 99th centile of the peak values to the rms value of a snoring epoch of ~ 200 ms. The average of epoch crest factors over the whole snoring episodes in an individual's recording was proposed as a discriminating quantity. The evaluation of the success of surgical treatment is another topic of major concern. For example, the preoperative and postoperative values of average snore duration, average snore loudness, periodicity of snore waveforms and relative energy for each of four frequency subbands were compared (Jones *et al* 2005, 2006a, 2006b, 2006c). The same parameter set was also used to compare natural snores to snores during steady-state propofol sedation (Jones *et al* 2006c). The study showed that the two types of snores differ considerably.

There are various works on the diagnosis of OSA via analysing snore sounds (Sola-Soler *et al* 2002, 2003, Abeyratne *et al* 2005, Lee *et al* 2000, Fiz *et al* 1996, Dalmasso and Prota 1996, Beck *et al* 1995). McCombe *et al* (1995) introduced the Hawke index (HI) as a criterion for screening OSA. The HI is devised as a measure of high frequency content. High high-frequency content has been frequently observed with OSA patients in their experiments. Sola-Soler *et al* (2003) studied the contrasts between snores of OSA patients and simple snorers by investigating the spectral envelopes of snore waveforms. Higher standard deviation of formant frequencies in snoring episodes was consistently observed in OSA snores even though the spectral envelopes did not show a significant deviation among OSA patients and simple snorers. It is also remarkable that formant frequency variability in OSA patients' snores exists in their nonpostapnoeic snores. Hence, this could relinquish the need for identification of postapnoeic snores in one's sleep sound recording for diagnosis purposes. Abeyratne *et al* (2005) proposed the measure 'intra-snore-pitch-jump' to diagnose OSA. Discontinuities in pitch as sudden changes among roughly discrete levels in a snoring episode are frequently observed in OSA patients and can be useful for OSA diagnosis. Fiz *et al* (1996) studied the spectral patterns of snore sounds from simple snorers and OSA patients and reported that all seven simple snorers' snores and two of ten OSA patients' snores in their database were dominated by a harmonic spectral content, whereas the rest of OSA patients' snores had a narrow low frequency content without distinctive harmonic components. Furthermore, they indicated that the peak frequency in most of the OSA patients is lower compared to that of simple snorers. Hara *et al* (2006) investigated the differences between the snoring sounds of simple snorers and OSA patients in terms of peak frequency (PF, the location of spectral peak), soft phonation index (SPI, the ratio of harmonic energy in the 70–1600 Hz band to that in the 1600–4500 Hz range), noise-to-harmonics ratio (NHR, the ratio of inharmonic energy in the 1500–4500 Hz band to harmonic energy in the 1600–4500 Hz band) and power ratio (PR, the ratio of spectral power below 800 Hz to that above 800 Hz). The average scores of all these parameters show significant differences over the two groups, simple snorers and OSA patients. In particular, PF, SPI and PR turned out to be much more different compared to NHR. They found higher peak frequency values for OSA patients in contrast to the findings of Fiz *et al* (1996).

The studies in the literature are dominated by the investigation of spectral properties of intra-episode signals, i.e. snoring sound waveforms. Snoring is a quasiperiodic sequence of snoring episodes. Such sequences can also be perceived in terms of qualities such as their episode periodicity variation, episode duration variation and episode power variation. The viewpoint can also be stated as an investigation of inter-episode associations instead of intra-episode properties. Examination of snoring episode sequences with such a perspective has not been worked out previously. The motivation of this study is to explore the distinctions among snoring sequences of simple snorers and OSA patients by following such an approach. The findings could contribute to the diagnosis of OSA by analysing sleep sounds recorded at home. Snoring episode sound sequences of OSA patients and simple snorers were investigated in terms of episode durations, episode separations and episode average powers. Our observations indicate considerably higher variability of sequential properties of OSA patients' snores. The higher tendency in OSA patients towards airway blocking may be a cause of the deregulation of the sequential properties. The higher tendency may stem from, for example, looser or bigger/longer tissue structures. Breathing nonuniformity may be accompanied by nonuniform oxygen demand and nonuniformity of breathing motions. The spatial and temporal variation of the upper airway cross section has to be different; in particular, short-duration blockings, semi-blockings and consequent pressure build-ups, and possibly the related stimuli to the breathing mechanism of the central nervous system after sensing the chemical variations are expected to contribute to the observed differences between the snoring characteristics of OSA patients and simple snorers. Our observations led us to introduce the concept of snore regularity. It is quantified specifically according to the characteristics of the sequences of interest. The sequential properties of snoring episode durations, separations and powers form an aspect which has not been investigated previously. A fundamental element of the motivation of this study is to study to what extent these sequential properties of snoring episodes may contribute to distinguish among OSA patients and simple snorers.

The sleep sound data in this study were collected from 30 individuals while they were also under polysomnographic recording in Gülhane Military Medical Academy Sleep Studies Laboratory (GMMA-SSL), Ankara, Turkey. Among the 30 individuals, 12 were diagnosed to have OSA and the remaining 18 are simple snorers. The investigation of sequential properties of snoring episodes requires the identification of snoring intervals in a given sleeping room sound recording (Abeyratne *et al* 2005, Duckitt *et al* 2006, Cavusoglu *et al* 2007). The analysis in this study is based on the method of Cavusoglu *et al* (2007). The recording setup and snoring database are explained in section 2. Typical characteristics of episode durations, separations and average powers are exposed in section 3 and based on the observations presented in this section, the snore regularity concept and related quantities are introduced in section 3.4. In particular, the short-time coefficient of variation is introduced and observed to be a candidate to enhance the discrimination capability among simple snorers and OSA patients. The appearance of these quantities over simple snorers and OSA patients is presented in section 4. Conclusions and discussion are given in section 5.

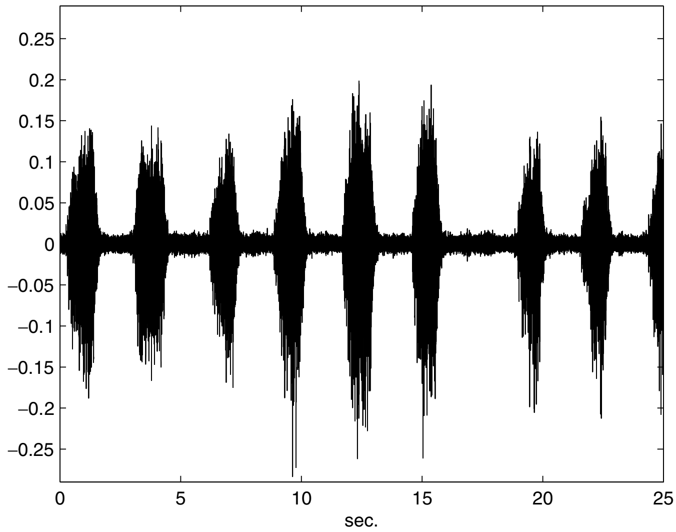

Figure 1. 25 s long snoring signal.

2. Materials and methods

2.1. Recording setup

A Sennhiser ME 64 condenser microphone with a 40–20000 Hz ± 2.5 dB frequency response was used for recording sounds. The microphone has a cardioid pattern which helps to suppress some of the echoes from the environment. It was placed 15 cm over the patient's head during sleep. The signal was fed via a BNC cable to the Edirol UA-1000 model multi-channel data acquisition system connected to a personal computer via universal serial bus. The computer was placed outside the sleeping room to avoid its noise in the recording. The acquired signal was digitized at a sampling frequency of 16 KHz with 16-bit resolution. The data were stored in the computer together with the patient information. Figure 1 shows a 25 s long sleep sound recording including some snoring episodes.

2.2. Snoring database

The database contains whole night sound recordings of 30 individuals taken in the Sleep Studies Laboratory of Gülhane Military Medical Academy, Ankara. These individuals were also under polysomnographic recording during their whole night sleep in order to determine their apnoea/hypopnoea indices (AHI). Among the 30 individuals, 18 were simple snorers and 12 were diagnosed with OSA syndrome. The average values and ranges of the ages, AHIs, body mass indices (BMI) of these individuals are given in table 1. The average number of snoring episodes and their standard deviations are 2387.55 ± 331.80 and 3403.25 ± 394.70 for simple snorers and OSA patients, respectively.

3. Distinctive properties of snoring episode sequences: durations, separations, average powers and regularity

In this section, some distinctive properties of snoring episode sequences are described and typical examples are given by using a pair of 1000 episode sequences of a simple snorer and an

Table 1. Number of individuals, their genders, averages of their ages, AHIs and BMIs in OSA patients and simple snorers. The values inside the parenthesis are the ranges for age, AHI and BMI.

Patient Info	OSA patients	Simple snorers
Number of patients	12	18
Age	53.25 (36–64)	46.94 (36–58)
Gender	12 males, no females	16 males, 2 females
AHI	39.21 (10.31–69.49)	4.28 (1.03–5.61)
BMI	32.76 (25.08–39.73)	27.66 (21.46–34.01)

Table 2. Average, maximum and coefficient of variation values of SED sequences of a simple snorer and an OSA Patient.

SED parameters	Simple snorer	OSA patient
Average SED (s)	0.77	0.72
Maximum SED (s)	2.15	3.35
Coefficient of variation of SED	0.35	0.57

OSA patient throughout the section. The OSA patient falls within the moderate-OSA category with an AHI of 27.86. (For an explanation of severity grading of OSA, refer to section 4.1.4.)

3.1. Snoring episode durations

The sequences of snoring episode durations (SED) of simple snorers and OSA patients were investigated. Typical examples of these sequences are plotted in figure 2 for a simple snorer and an OSA patient on the same scale. A fundamental distinction is that the short-term variation of SED is much larger for the OSA patient compared to that of the simple snorer. In general, large duration swings from episode to episode are much rarer for the simple snorer. On the other hand, the longest SED and the average value of SED of the OSA patient are also larger than those of the simple snorer. The average, maximum and coefficient of variation values of SEDs of the simple snorer and the OSA patient are given in table 2.

The distributions of these sequences are shown by the normalized histograms in figure 3. As expected from figure 2, a SED sequence exhibits a relatively concentrated distribution for the simple snorer compared to that of the OSA patient. Although the two distributions greatly agree in their region of supports, the coefficient of variations (the ratio of standard deviation to the mean) of SED for the simple snorer and the OSA patient (0.35 and 0.57, respectively) differ by a factor of approximately 1.6.

Some sudden changes in episode durations are observed for the simple snorer duration sequence. Some of these changes are normal as our experience shows that it is possible to observe, for example, three consecutive snoring episodes with almost doubled durations one after the other. On the other hand, duration changes are also observed due to the head, body or mouth movements during sleep. As will be seen in the following sections, sudden duration changes are rarer compared to those in separation and power sequences.

3.2. Snoring episode separations

The sequences of durations between snoring episodes (snoring episode separations, SES) were also investigated for distinction among simple snorers and OSA patients. An individual does

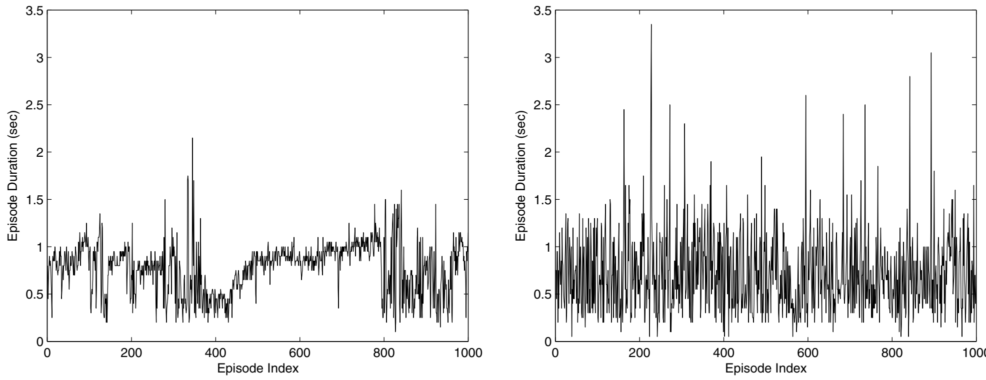

Figure 2. Sequences of snoring episode durations (left) for a simple snorer and (right) for an OSA patient.

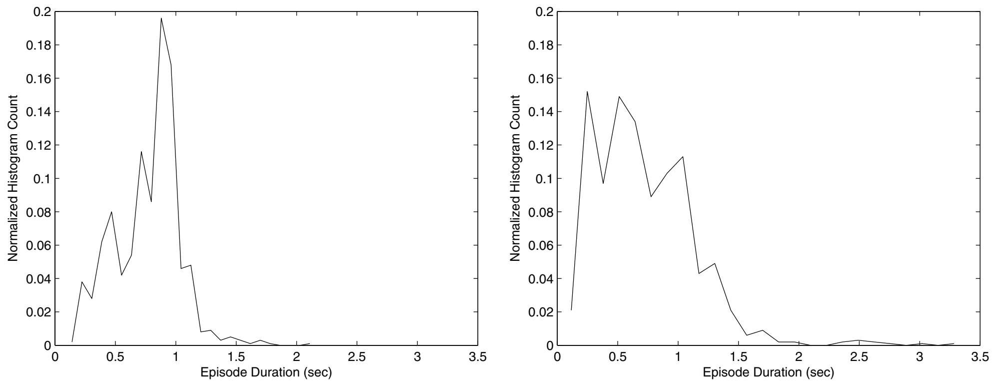

Figure 3. Normalized histograms of snoring episode durations (left) for a simple snorer and (right) for an OSA patient.

not necessarily stay in snoring state all through his/her sleep. It is possible for a subject to leave the snoring state for a while and then go into the snoring state again. In investigating SES, we are interested in those separations between consecutive snoring episodes in the same snoring state. In other words, we are not interested in separations between snoring states. Unfortunately, a criterion to automatically identify the boundaries of snoring states does not exist and we have not aimed to find one. Instead, we have considered the separations less than 10 s. The choice of 10 s is based on the accepted convention that an air flow cessation that lasts more than 10 s is considered as apnoea (Jureyda *et al* 2004). Furthermore, 10 s separation between two snoring episodes is short enough to consider the two episodes as they are taking place in the same snoring state. Typical examples of SES sequences for a simple snorer and an OSA patient are plotted in figure 4. The arguments about the distinction between the two SES sequences would be partly similar to those for the distinction among the two SED sequences in figure 2. The short-term variation of OSA-SES is much more higher compared to that of simple snorer-SES. Peaks close to the maximum are observed very frequently on the OSA-SES sequence which is not that much apparent for the OSA-SED sequence. However, the maximum values and the average values of the two SES sequences are not significantly

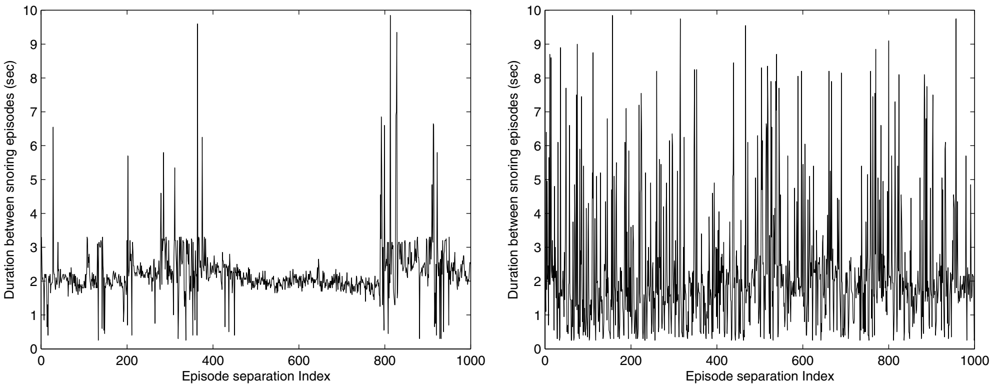

Figure 4. Typical examples of episode separation sequences (left) for a simple snorer and (right) for an OSA patient.

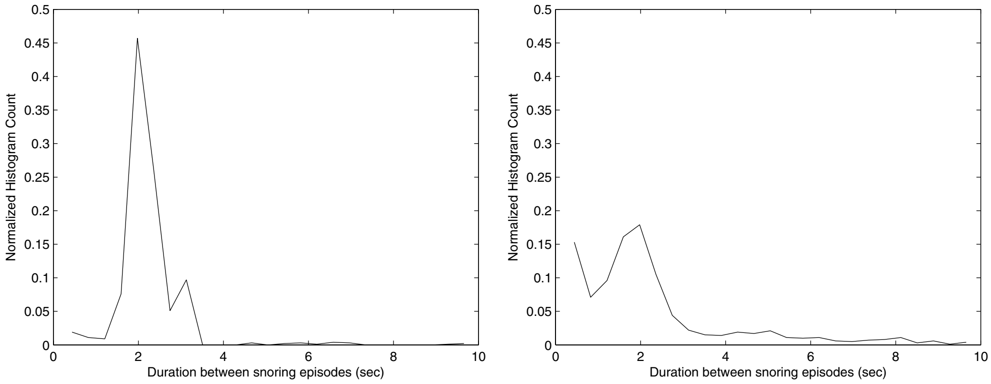

Figure 5. Normalized histograms of separations (left) for a simple snorer and (right) for an OSA patient.

different as it is for the SED sequences. The average, maximum and coefficient of variation values of SESs of the simple snorer and the OSA patient are given in table 3.

The SES distributions for the simple snorer and the OSA patient are shown by the normalized histogram plots in figure 5. They differ mainly in two aspects: first, simple snorer-SES is highly concentrated around its average value (approximately 2.3 s), whereas OSA-SES has a significant content all over the values up to approximately 2.5 s; second, the OSA-SES histogram has a heavy tail towards the maximum value, which is a consequence of the frequent occurrence of larger and, in particular, near-maximum values. The coefficient of variation values of the SES sequences in figure 4 differ by a factor of approximately 2.3.

In figure 4, the episode separation sequence of the simple snorer exhibits some sudden changes. There are around 12 significant isolated peaks among 1000 episodes. Some snoring episodes have quite low sound levels or the sound is more like loud breathing instead of snoring. In both cases the detection algorithm may decide the episode as a nonsnore episode. In such a case the measured duration between snoring episodes increases. On the other hand, there are 25–30 dips in figure 4. It is an interesting observation that during some intakes the individual produces two snoring bursts with short separations. There are also loud breathing

Table 3. Average, maximum and coefficient of variation values of SES sequences of a simple snorer and an OSA patient.

SES parameters	Simple snorer	OSA patient
Average SES (s)	2.25	2.25
Maximum SES (s)	9.85	9.85
Coefficient of variation of SES	0.36	0.82

Table 4. Average, maximum and coefficient of variation values of SEP sequences of a simple snorer and an OSA patient.

SEP parameters	Simple snorer	OSA patient
Average SEP ($\times 10^{-4}$)	8.7	10.5
Maximum SEP ($\times 10^{-3}$)	5.6	8.7
Coefficient of variation of SEP	0.78	1.03

sounds, close to a snoring episode, that are misclassified as snoring. Another reason for sudden changes is the change in the breathing organization of the individual during and after his/her head/body movement. Sometimes the individual also moves his/her chin and tongue.

3.3. Average powers of snoring episodes

Snoring episode durations and separations are not the only distinctions indicated by the waveforms of sleep sound recordings of simple snorers and OSA patients. It is observed that the variation of snoring intensity has different patterns for these two classes of individuals. The average power of a snoring episode (snoring episode power, SEP) is defined as

$$\mathrm{SEP} = \frac{1}{M}\sum_{k=1}^{M} s_k^2 \tag{1}$$

where M is the number of samples in the episode. The SEP sequences of a simple snorer and an OSA patient are shown in figure 6. The two sequences contrast in a manner similar to that of SED sequences. The significantly larger short-term variation of the OSA-SEP and also differences in their average and maximum values are the prominent indications. The average, maximum and coefficient of variation values of SEPs of the simple snorer and the OSA patient are given in table 4.

The distributions of SEP sequences are shown by the normalized histograms in figure 7. The two histograms mainly deviate in their behaviour over smaller SEP values and also by the heavier tail in the case of the OSA patient. The coefficient of variations of SEP sequences for the simple snorer and the OSA patient (0.78 and 1.03, respectively) differ by a factor of approximately 1.3.

Sudden changes in the episode powers of the simple snorer are observed in figure 6. Some of the power peaks appear as a final (or intermediate) element of a local snoring episode sequence displaying gradual increase (or gradual increase and decrease) in their powers. The number of isolated (peak) power values is quite small (less than 10 in figure 6). Roughly, half of them are true snores and the others are due to misclassified events.

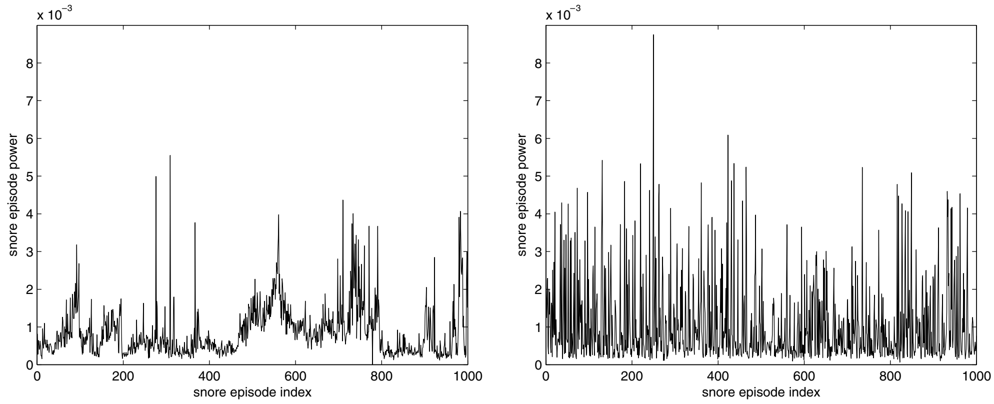

Figure 6. Average power sequences of snoring episodes taken from (left) a simple snorer and (right) an OSA patient.

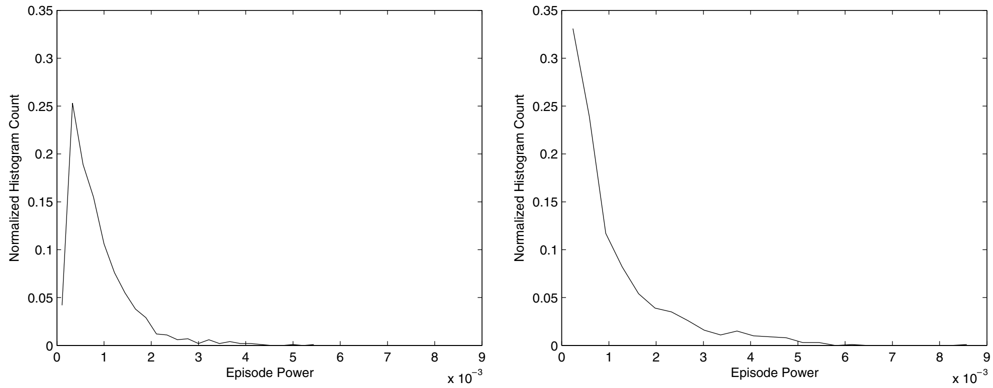

Figure 7. Normalized histograms of average powers of snoring episodes (left) for a simple snorer and (right) for an OSA patient.

3.4. Snore regularity

The motivation for defining such a concept arises after the observations of the behaviours of the SED, SES and SEP sequences of simple snorers and OSA patients. Snore regularity can be conceived as a measure of similarity (or diversity) of snoring episodes of an individual in terms of one or more characteristic features (i.e., intensity, duration, separation, etc). Loosely stating, whenever the sample values in a sequence are closer to each other compared to those of another sequence, the former sequence is said to be more regular. Higher bounds of short time variation are obvious for the SED, SES and SEP sequences of the OSA patient compared to those of the simple snorer in figures 2, 4 and 6. Furthermore, large variations govern almost whole OSA patient's sequence whereas they are occasionally observed in the case of the simple snorer. On the other hand, the baselines of the simple snorer's sequences have some variation. This is considered as a slow variation of an otherwise more 'regular' sequence. Then, according to our definition of regularity, an OSA patient's sequences are said to be more irregular than those of a simple snorer. A number of different mathematical representations

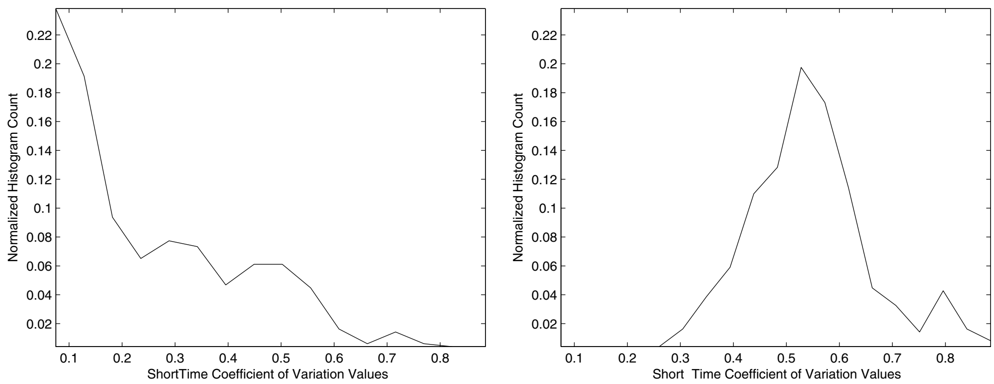

Figure 8. Normalized histograms of STCV of snoring episode durations: (left) a simple snorer; (right) an OSA patient.

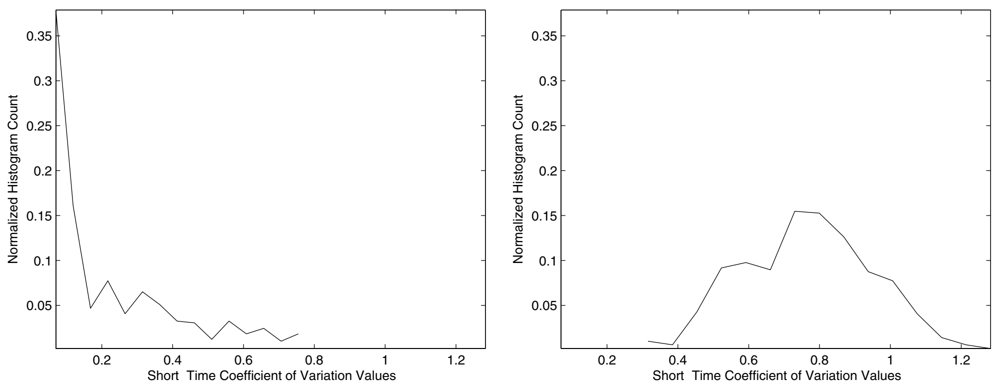

Figure 9. Normalized histograms of STCV of snoring episode separations: (left) a simple snorer; (right) an OSA patient.

have been worked out to quantify regularity. Indeed, the coefficient of variation can simply be taken as a measure of regularity of SED, SES and SEP sequences. The SED, SES and SEP sequences of the simple snorer and the OSA patient differ by factors of 1.6, 2.3 and 1.3, respectively. However, we have found it more useful to exclude the effect of long-term variation of short-term average values in the representation of regularity. The short-term coefficient of variation (STCV) is defined as the coefficient of variation of the sample values in a 'short' signal frame of N samples. It has been observed that the distribution of STCV values is a strong candidate to distinguish among simple snorers and OSA patients. The normalized histograms of STCV distributions of the simple snorer and the OSA patient for SED, SES and SEP sequences are shown in figures 8, 9 and 10, respectively. STCV values are calculated at every two samples with $N = 20$ samples.

Examining figures 8, 9 and 10 one can observe that the distributions of STCV values of SED, SES and SEP sequences depart significantly in their mean values and bear significant separation in their bases of major mass. Furthermore, the coefficient of variations of STCV values of SED, SES and SEP sequences of the simple snorer and the OSA patient differ by factors of 3.3, 3.6 and 2.8, respectively, as indicated in tables 5–7. These are

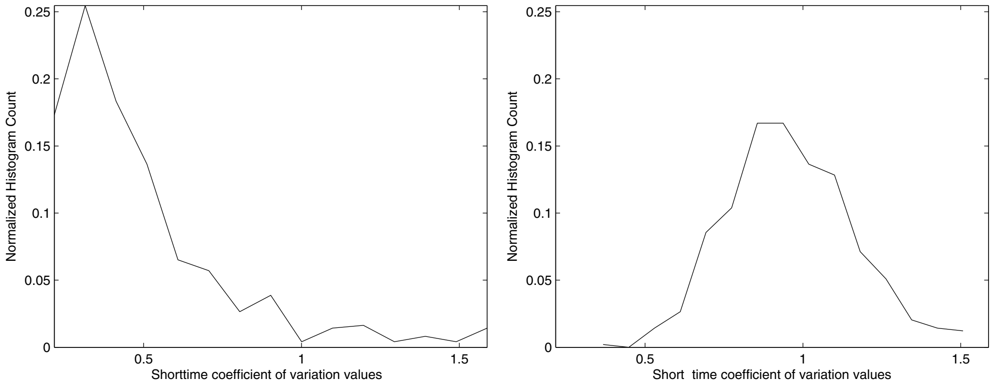

Figure 10. Normalized histograms of STCV of snoring episode powers: (left) a simple snorer; (right) an OSA patient.

Table 5. Variances, averages and coefficient of variations of STCV of snoring episode durations for a simple snorer and an OSA patient. The last line contains the ratios of the simple snorer (SS) value to that of the OSA value.

	Variance	Average	Coefficient of variation
SS	0.0321	0.2565	0.6988
OSA	0.0137	0.5445	0.2149
ratio (SS/OSA)	2.3472	0.4712	3.2517

Table 6. Variances, averages and coefficient of variations of STCV of snoring episode separations for a simple snorer and an OSA patient. The last line contains the ratios of the simple snorer value to that of the OSA value.

	Variance	Average	Coefficient of variation
SS	0.0347	0.2210	0.8426
OSA	0.0329	0.7650	0.2371
ratio (SS/OSA)	1.0543	0.2889	3.5538

Table 7. Variances, averages and coefficient of variations of STCV of snoring episode powers for a simple snorer and an OSA patient. The last line contains the ratios of the simple snorer value to that of the OSA value.

	Variance	Average	Coefficient of variation
SS	0.0790	0.4836	0.5812
OSA	0.0391	0.9574	0.2066
ratio (SS/OSA)	2.0188	0.5051	2.8129

significantly 'enhanced' figures compared to the factors of 1.6, 2.3 and 1.3, for the coefficient of variations of SED, SES and SEP sequences themselves, and quite promising indications for the discriminative capability of STCV distributions.

Table 8. The average of means, standard deviations (SD) and coefficient of variations (CV) of sequences obtained for simple snorers and OSA patients. Here the mean, SD and CV columns with the title 'From the sequences' refer to parameters obtained from the SED, SES and SEP sequences themselves, and those with the title 'From the STCV sequences' refer to parameters obtained from the short time coefficient of variation sequences of SED, SEP and SEP sequences.

		From the sequences			From the STVC sequences		
		Mean	SD	CV	Mean	SD	CV
SED	SS	1.01	0.20	0.20	0.30	0.23	0.79
	OSA	0.86	0.42	0.49	0.45	0.09	0.21
SES	SS	2.62	0.67	0.26	0.33	0.22	0.65
	OSA	2.26	1.58	0.70	0.65	0.15	0.22
SEP	SS	0.98×10^{-3}	5.47×10^{-4}	5.72×10^{-1}	0.47	0.18	0.4
	OSA	1.58×10^{-3}	1.14×10^{-3}	7.42×10^{-1}	0.65	0.15	0.23

4. Comparison of snoring characteristics for simple snorers and OSA patients

In this section, the following information are presented for all simple snorers and OSA patients in our database:

(1) the mean, standard deviation (SD) and coefficient of variation (CV) of the duration, separation and average power sequences;
(2) the mean, SD and CV of the STCV sequences of duration, separation and average power sequences.

The presentation involves spider charts, two-dimensional joint distributions of mean and standard deviation values, and tabulated data. A spider chart, also known as a radar chart or star chart, is a way of joint visualization of three or more variables as a two-dimensional plot. The relative position and angle of the axes is uninformative. Spider charts provide a two-dimensional pattern by which the variables can be compared to each other. The patterns make it easier to remember and compare the parameters of different sets. In the following, spider charts have three axes: mean, SD and CV. Separate spider charts are plotted for simple snorers and OSA patients. Each spider chart displays all the information for the particular group, i.e. simple snorers or OSA patients. Every pair of spider charts, i.e. for simple snorers and OSA patients, is identically scaled so that the patterns of the simple snorers and OSA patients can be compared. Student's *t*-test was also applied to test whether the parameters obtained from the simple snorers and the OSA patients differ significantly. Two-dimensional joint distributions of mean and SD values shown in figure 17 provide an alternative way to compare sequences obtained from simple snorers and OSA patients. The average values of the three parameters (i.e. mean, SD and CV) are calculated for simple snorers and OSA patients and displayed in table 8. In this table, the mean, SD and CV columns corresponding to 'From the sequences' and 'From the STCV sequences' refer to parameters calculated from the snoring episode duration (SED), separation (SES) and average powers (SEP) themselves and parameters calculated from the short time coefficient of variation sequences of SED, SES and SEP sequences, respectively.

4.1. Duration, separation and average power sequences

4.1.1. Duration sequences. Spider charts of duration sequences are given in figure 11 for simple snorers and OSA patients. The average values of these three parameters in each

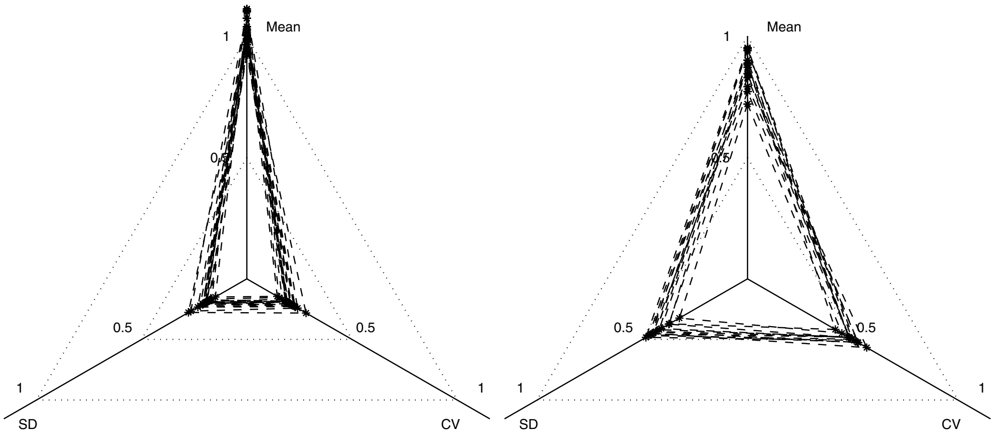

Figure 11. Spider charts for SED sequences: (left) simple snorers; (right) OSA patients.

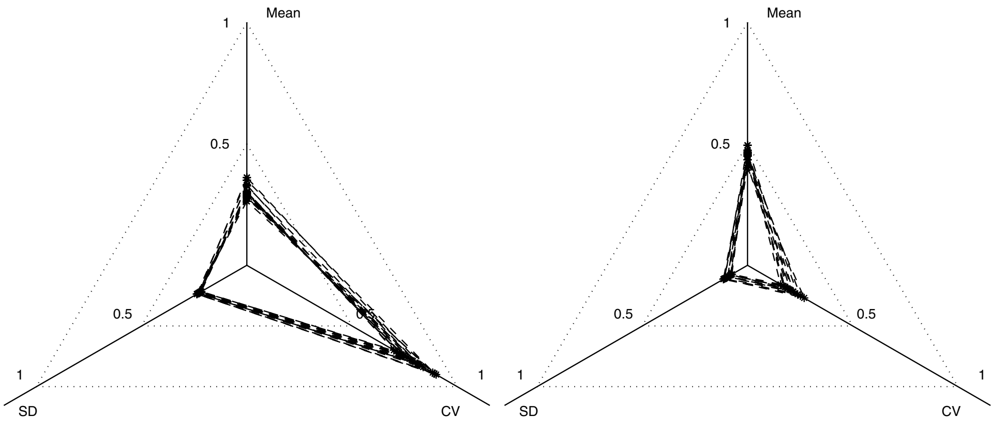

Figure 12. Spider charts for STCV sequences of episode durations: (left) simple snorers; (right) OSA patients.

group are given in table 8. It is seen from the spider charts that SD and CV values deviate significantly among simple snorers and OSA patients (Student's *t*-test indicates that the means of two groups are statistically different from each other at a significance level of $p < 0.01$). The deviation among the mean values of the two groups is not so apparent visually; however, the Student's *t*-test indicates that their means are statistically different from each other at a significance level of $p < 0.01$. This is also observed in the average values in table 8. The difference in the triangular patterns indicates the possibility of classifying simple snorers and OSA patients using three-dimensional feature vectors containing the mean, SD and CV values of duration sequences.

Spider charts of STCV sequences of snoring episode durations are given in figure 12 for simple snorers and OSA patients. The average values in each group are given in table 8. The spider charts and the average values show that all three parameters deviate significantly ($p < 0.01$ for all three parameters), which can be an indication of better discrimination capability among simple snorers and OSA patients.

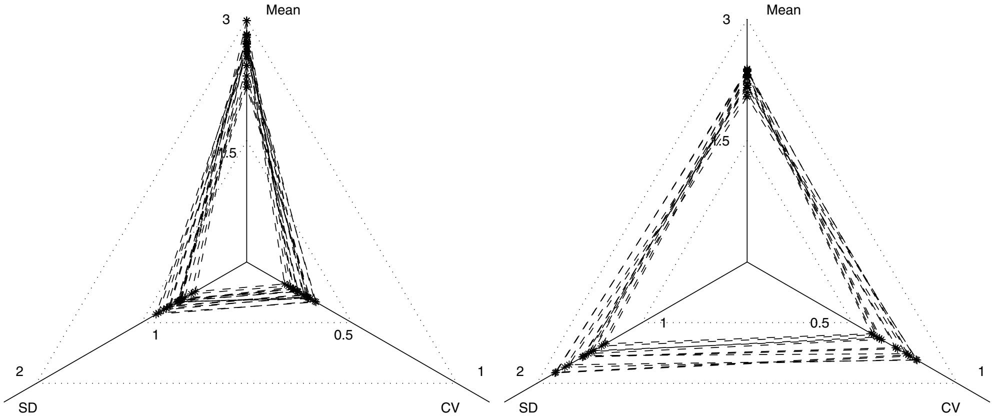

Figure 13. Spider charts for SES sequences: (left) simple snorers; (right) OSA patients.

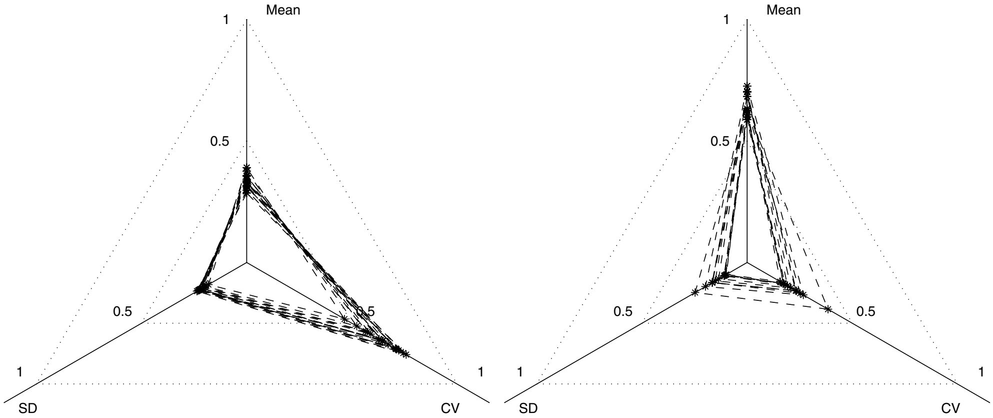

Figure 14. Spider charts for STCV sequences of episode separations: (left) simple snorers; (right) OSA patients.

4.1.2. Separation sequences. Spider charts of separation sequences are given in figure 13 for simple snorers and OSA patients. The average values are given in table 8. It is seen from the spider charts that, similar to the case with duration sequences, SD and CV values deviate significantly among simple snorers and OSA patients ($p < 0.01$) while the mean values of the two groups overlap. However, similar to the case with the SED sequences, Student's t-test indicated that the mean values are also different for each group ($p < 0.01$). The triangular patterns of simple snorers and OSA patients differ significantly indicating that separation sequences could also be used for classifying simple snorers and OSA patients.

Spider charts of STCV sequences of snoring episode separations are given in figure 14 for simple snorers and OSA patients. The average values are given in table 8. The spider charts and the average values show that although SD values overlap, the difference in the triangular patterns still indicate a good classification ability among simple snorers and OSA patients ($p < 0.01$ for all three parameters).

4.1.3. Average power sequences. Spider charts of average power sequences are given in figure 15 for simple snorers and OSA patients. The average values are given in table 8. It is

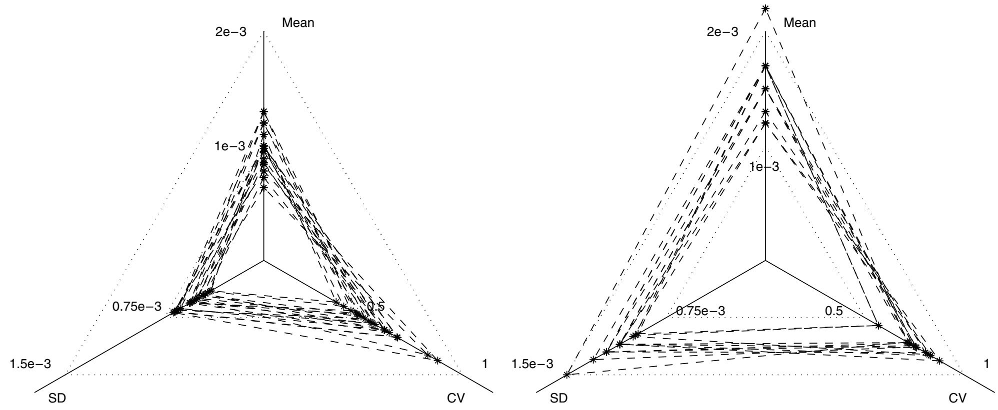

Figure 15. Spider charts for SEP sequences: (left) simple snorers; (right) OSA patients.

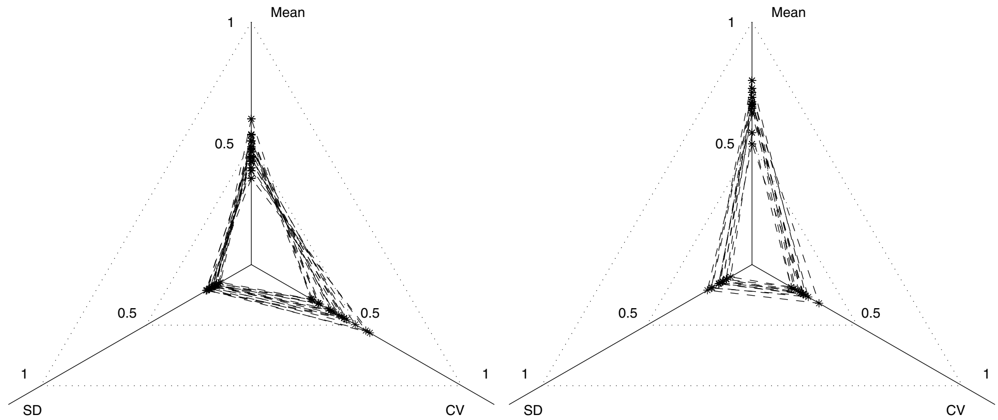

Figure 16. Spider charts for STCV sequences of average episode powers: (left) simple snorers; (right) OSA patients.

seen from the spider charts that SD values deviate significantly, mean values overlap slightly and CV values overlap significantly among simple snorers and OSA patients. Nevertheless, when these parameters are compared using Student's *t*-test, they were found to be different ($p < 0.01$) for the simple snorers and the OSA patients. The triangular patterns look different enough to consider an amount of classification capability of power sequences. However, this capability is obviously weaker than those of duration and separation sequences. The average values for simple snorers and OSA patients in table 8 are promisingly different; however, this is obscured by the high inter-patient variations of the mean, SD and CV values observed from the spider charts.

Spider charts of STCV sequences of average powers are given in figure 16 for simple snorers and OSA patients. The average values are given in table 8. Spider charts show that SD values severely overlap, mean and CV values partially overlap. Hence, these parameters do not have strong discrimination capability individually. However, their joint behaviour as revealed by the triangular patterns is reminiscent of some level of discrimination ability. The Student's *t*-test indicated that the mean, the SD and the CV values are different for the simple snorers and the OSA patients ($p < 0.01$).

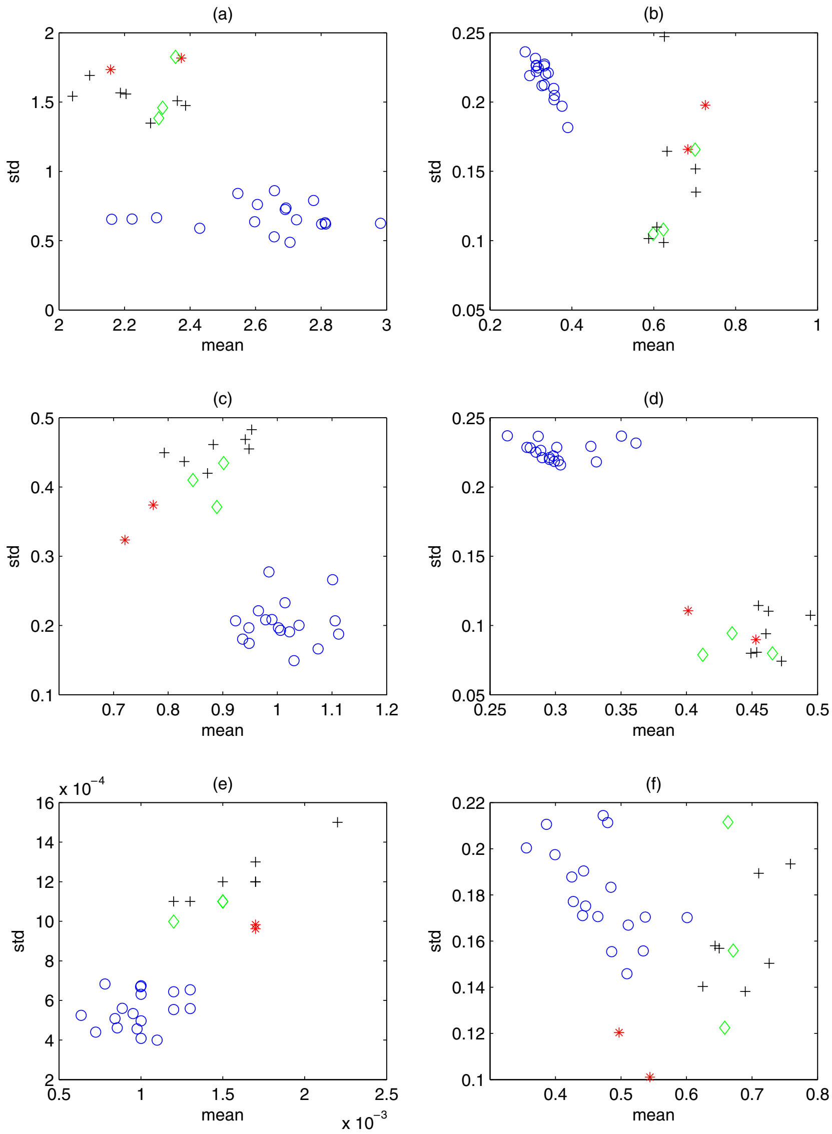

Figure 17. Joint distributions of mean and standard deviation values of (a) snoring episode separation sequences, (b) STCV sequences of the separation sequences, (c) snoring episode duration sequences, (d) STCV sequences of the duration sequences, (e) snoring episode power sequences and (f) STCV sequences of the power sequences. In these plots, (blue) circles correspond to AHI < 6, (red) stars correspond to $6 <$ AHI < 15, (green) diamonds correspond to $15 <$ AHI < 33 and (black) plus signs correspond to $33 <$ AHI.

(This figure is in colour only in the electronic version)

4.1.4. Effect of AHI (severity grading of OSA) on snoring episode sequences. We plot two-dimensional joint distributions of mean and SD values in figure 17. In this figure, (a) corresponds to snoring episode separation sequences, (b) corresponds to STCV sequences of the separation sequences, (c) corresponds to snoring episode duration sequences, (d) corresponds to STCV sequences of the duration sequences, (e) corresponds to snoring episode power sequences and finally (f) corresponds to STCV sequences of the power sequences. In order to study the effects of severity of apnoea on the mean and the SD value distributions, we divided the patients into four groups according to their AHI levels. The American Academy of Sleep Medicine Task force (1999) defines sleep apnoea to be normal when $0 < \text{AHI} < 5$, mild when $5 < \text{AHI} < 15$, moderate when $15 < \text{AHI} < 30$ and severe when $30 < \text{AHI}$. We slightly modified these levels to include close AHI levels in the same group. In figure 17, we have the normal group (simple snorers) with $0 < \text{AHI} < 6$ ((blue) circles), mild-OSA group with $6 < \text{AHI} < 15$ ((red) stars), moderate-OSA group with $15 < \text{AHI} < 33$ ((green) diamonds) and severe-OSA group with $33 < \text{AHI}$ ((black) plus signs). These plots show that the mean and the SD values are distributed differently in simple snorers (normal group) and the OSA patients, hence both the snoring episode duration, separation and power sequences themselves, and the corresponding STCV sequences, appear to be useful for simple snorer–OSA patient discrimination. However the number of OSA patients in each group was not sufficient to demonstrate whether the mild, the moderate and the severe OSA groups show noticeable differences among themselves in terms of the mean and the SD value distributions.

5. Discussion and conclusions

In this paper, we investigated variations in snoring sound episode durations, separations and average powers in simple snorers and in OSA patients. Snoring sound recordings of 30 individuals, who were also under polysomnographic recording in Gülhane Military Medical Academy Sleep Studies Laboratory (GMMA-SSL), Ankara, Turkey, were included in the study. Sound activities in a recording were first classified as snore or nonsnore according to their subband energy distributions (Cavusoglu *et al* 2007). After this classification, sequences that contain snoring episode durations (SED), snoring episode separations (SES) and average snoring episode powers (SEP) were obtained. To study variations in these sequences, we proposed using ‘snore regularity,’ which can be defined as a measure of similarity or diversity of snoring episodes. To quantify snore regularity, we obtained mean, standard deviation and coefficient of variation values from SED, SES and SEP sequences. Our observations indicated that the sequential properties of OSA patients’ snores had considerably higher variability than those of simple snorers. However, the long-term variation of short-term average values had a negative effect in the representation of regularity. To overcome this shortcoming, a new parameter called the ‘short-term coefficient of variation (STCV),’ which is the coefficient of variation of the sample values in a ‘short’ signal frame, was defined. Sequences of STCV were then obtained from the SED, SES and SEP sequences. The mean, the standard deviation and the coefficient of variation values calculated from the STCV sequences turned out to be stronger candidates to distinguish among simple snorers and OSA patients.

We displayed our results in tabulated form, as spider charts and as two-dimensional joint distributions of the mean and the SD values. The spider charts displayed the joint behaviour of three parameters, i.e. the mean, the standard deviation and the coefficient of variation of SED, SES and SEP sequences, and the corresponding STCV sequences. The joint behaviours represented by the triangular patterns posed by the spider charts are important in distinguishing among simple snorers and OSA patients because any difference related to the orientation and/or size of the triangular patterns produced by simple snorer and OSA patient data indicates a displacement of the accumulation regions in the three-dimensional space of the respective data. Our observations and Student’s *t*-test applied to the mean, the SD and the CV values showed that the statistical parameters obtained from the SED and SES sequences, and the corresponding STCV sequences, possessed a strong potential to distinguish among simple snorers and OSA patients, both marginally, i.e. when the parameters are examined individually, and jointly. The parameters obtained from the SEP sequences and the corresponding STCV sequences, on the other hand, did not have as strong a discrimination capability. However, the joint behaviour of these parameters showed some potential to distinguish among simple snorers and OSA patients, and Student's *t*-test also indicated that they differ in simple snorers and the OSA patients.

We also studied whether the sequential properties defined in this paper would show any differences among OSA patients of different severity levels in terms of AHI values (mild, moderate and severe). However, this study was inconclusive with the few number of OSA patient recordings available in this study. A larger group of patient recordings is required to further investigate this problem.

The work presented here showed the possibility of distinguishing among simple snorers and OSA patients using only sleep sound recordings of individuals. The elimination of the need for spending a night in the clinic for polysomnographic recording is one of the main goals of current research. The findings of this study can be considered valuable since sleep sound recordings can be obtained in one's own sleeping environment.

Possible future work includes a comparison of the sequential properties of

- snoring episodes before and after surgical treatment to evaluate the treatment effectiveness,
- palatal and nonpalatal snores to identify the physiological sources.

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