An Investigation of Acoustical and Signal Processing Techniques for Classification, Diagnosis and Monitoring of Breathing Abnormalities in Sleep

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Abstract. Snoring is the often earliest symptom of Obstructive Sleep Apnoea (OSA) and other respiratory problems. A successful medical outcome depends on an accurate preoperative diagnosis of the anatomical reason for snoring. The perception of snoring is highly subjective; therefore, there is a need for an objective measurement of snoring for an accurate patient assessment and the evaluation of treatment effects. The main objective of this study was to distinguish between two types of snoring: palatal and non-palatal snoring considering the acoustic characteristics of the snoring signal. A key innovation is that the snoring signals are not analyzed only subjectively by a medical specialist but also objectively by analyzing recorded snoring signals. The patient's snoring has been recorded non-invasively during sleeping and processed in both time and frequency domains to determine the origin of the snore and to identify the key features useful to the medical specialist.

Keywords: Respiratory/breathing problems, Sleep apnoea, Obstructive Sleep Apnoea (OSA), Palatal snoring.

1 Introduction

Snoring can be defined as a respiratory noise generated during sleep when breathing is obstructed by a collapse in the upper airway. The sound of snoring consists of a series of impulses caused by the rapid obstruction and reopening of the upper airway. Several factors can cause snoring, including the sleep positioning, diet, drugs and allergies. It is more common in males than in females and in overweight people of both genders [1]. Some years ago it was firmly believed that snoring is nothing but a social nuisance, without any adverse health consequences to the snorer. But when the sleep apnoea syndrome (when a person stops breathing for short periods while asleep) began to be studied deeply, snoring achieved a totally different new status, being elevated from a social nuisance to an important clinical symptom. Indeed, current epidemiological data indicate that the sleep apnoea syndrome is second to asthma in the prevalence league table of chronic respiratory disorders.

Obstructive Sleep Apnoea (OSA) is a breathing disorder which occurs during sleep and is caused by the transient closure of the upper airways. At first, OSA is not

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harmful. However, irregular breathing during the night usually wakes up the patient and leads to an excess of sleepiness and overall fatigue during the day and, if not treated, it can result in serious health problems.

The severity of OSA is often established using the apnoea/hypopnoea index (AHI), which is the number of apnoeic and hypopnoeic periods per hour of sleep. A hypopnoea is a medical term for a disorder which involves episodes of overly shallow breathing or an abnormally low respiratory rate. This differs from apnoea in that there remains some flow of air. Hypopnoea events may happen while asleep or while awake. This disruption in breathing cause a drop in blood oxygen level which may disrupt the different stages of sleep. Thus, AHI gives an overall severity of sleep apnoea including sleep disruptions and desaturations (a low blood oxygen level).

For patients seeking treatment, some options available to help them sleep better and to have less breathing problems during sleep range from losing weight and moderating alcohol intake, to the use of passive devices to modify the nasal or oral airway during sleep, nasal Continuous Positive Airway Pressure (CPAP), and ultimately to surgical re-modelling of the structures involved where this is feasible. A successful surgical outcome is dependent on an accurate preoperative diagnosis of the anatomical site of snoring and the identification of the airway structures involved in producing the noise, as palatal surgery only works if palatal flutter is present. Thus, an objective measurement of snoring is required for an accurate patient assessment and the evaluation of treatment effects.

There are different methods to classify the snoring sound based on the snoring region origin, depending on the acoustic properties or according to the type of snore generation. These categories are non-exclusive as some types of snoring sounds may be described by the use of two or more of them. Endoscopic appraisal of the pharyngeal structures during snoring has revealed that the complex-waveforms are linked with palatal snoring and the simple-waveforms with tongue-based snoring [2].

The main objective of this study was to employ acoustical signal processing techniques to distinguish between palatal and non-palatal snoring from overnight audio recordings of a snorer. The patterns of snores have been recorded and examined in order to determine the snore origin and to identify the key features useful to the medical specialist.

2 Method

Direct recordings from mobile phones have been taken and studied for four different subjects. Between three to five minutes of recording have been made by a patient's relative or friend with a mobile phone placed close to the mouth and nose of the snorer. Each sound record is converted into a ".wav" format with a sampling frequency of 16 kHz and further processed using Matlab software. In order to extract snore-related parameters, the snore recordings have been analyzed in the frequency domain to determine the site where the snore is produced, and in the time domain to distinguish between simple- and complex-waveform snoring. Furthermore, the snoring signals have been analyzed regarding the periodicity of breaths and the duration of the silences between them to determine apnoea episodes. Since such a recording method could not be standardized due to different recording characteristics of each mobile phone as well as varying positions (distances and angles) of the phones from the patient's mouth and nose, it is not possible to determine the perception of loudness of the snoring signal. Initially, the aim was to record snoring signals by making a call to the hospital, but the telephone line has a bandwidth from 400 Hz to 3400 Hz while the main frequencies of all the types of snoring are in the low frequency spectrum (except for the tongue-based snoring). For instance, palatal snoring is between 105 Hz and 190 Hz, and tonsillar snores are about 170 Hz [3]. Thus, in spite of capturing all the frequencies of interest with the phone microphone, the telephone line can reduce information important for snoring analysis.

Taking the recordings directly from the mobile phone as an audio file also has limitations – most of the mobile phones use an ".amr" file format for storing speech audio filtered to 200-3400 Hz with the sampling frequency of 8 kHz and 13-bit resolution using AMR (Adaptive Multi-Rate) codec. It is also important to take into consideration that every subject has been recorded with a different device, in a different position regarding the mouth and nose, at a different distance from the sound source, during different times of the snorer's sleep, and during different lengths. All these create significant difficulty in determining a sound level reference and these pilot measurements demonstrate how different recordings can be obtained from the patients, since the method of recording cannot be standardized.

To reduce ambient noise, the recorded signals are bandpass filtered between 5 Hz and 3000 Hz. The amplitudes of recorded signals are normalized to the range [–1,1] to allow a comparison of different signals and distinguishing between breathing and snoring. The sound signal from breathing exhibits a pattern that repeats itself over subsequent breathing cycles. However, some variation in the intensity and envelope can be seen not only between different individuals but also between breathing cycles from the same individual [4].

3 Experimental Results

Relevant information about four subjects participated in this experiment is given in Table 1 and the experimental results are shown in Fig. 1. Since medical diagnoses of the subjects were not available, the investigation is based on prior research and is given as a comparison of the time and frequency domain analysis of the recorded snoring signals with the results obtained in previous investigations.

For subjects 1 and 4, the interval between frequency peaks is equal to the rate of appearance of sound structures in the snores. The first peak represents the frequency of oscillations, and it coincides approximately with the interval between frequency peaks in the spectrum and with the value calculated from the time waveform. Thus, the frequency of oscillation is around 82-86 Hz for subject 1 and 96-100 Hz for subject 4. Snoring of subject 2 is completely different from those of subjects 1 and 4, having only three main frequency peaks separated by 80 Hz and the frequency of oscillation around 400 Hz which coincides with the highest peak in the spectrum. Therefore, the interval between the frequency peaks is neither the oscillation frequency nor a main frequency in the spectrum in this case.

Table 1. Relevant information about the subjects in this experiment

Subject	Gender	Age	Height [cm]	Weight [kg]	Smoker	BMI [kg/m^2]	Weight category
1	Male	57	172	95	No	32.11	Obese (C1)
2	Female	34	164	73	Yes	27.14	Overweight
3	Female	55	170	100	No	34.6	Obese (C1)
4	Female	50	160	68	Yes	26.56	Overweight

Table 2. Types of waveform and two main frequencies of the snoring signals recorded in this experiment compared to the one obtained from the literature [5]

Waveform type	Subject	Frequency f_1 [Hz]	Frequency f_2 [Hz]
Complex	Beck et al. [5]	600	450
	Subject 1	250	164
	Subject 4	391	297
Sinusoidal simple	Beck et al. [5]	110	-
	Subject 2	407	-
Asymmetric simple	Beck et al. [5]	160	320
	Subject 3	226	461

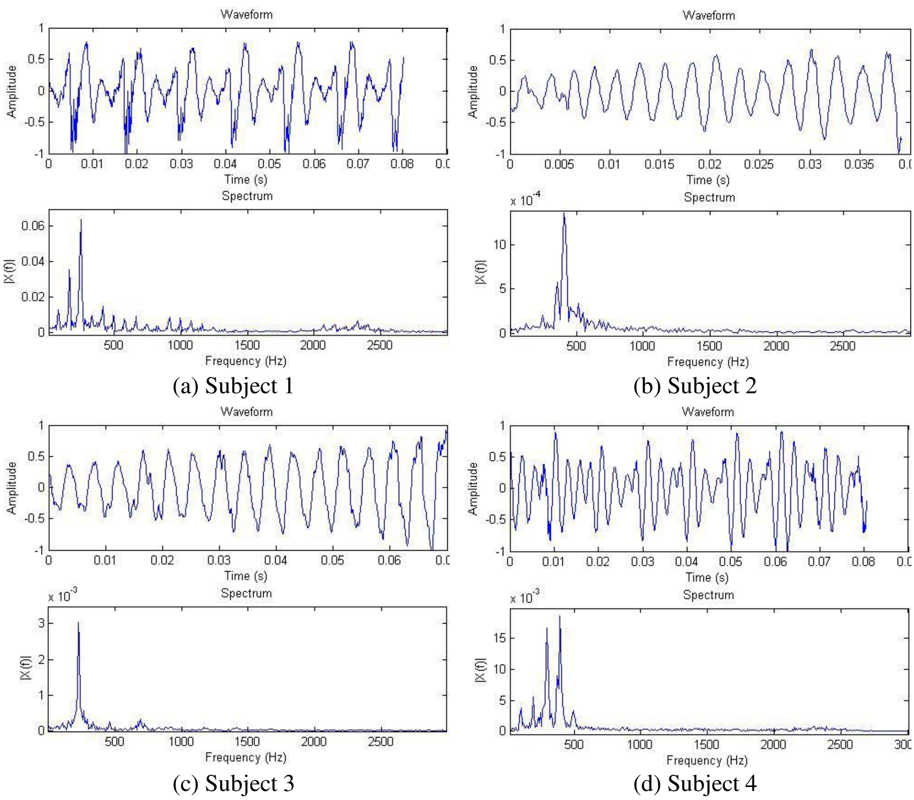

Fig. 1. Time segments (top) and frequency spectra (bottom) of the recorded snoring signals for each of four subjects

Snoring of subject 3, which is an asymmetric simple-waveform snoring, has a spectrum similar to the subject 1's one but with the energy located in low frequencies below 1000 Hz. The frequency of oscillation is 226.6 Hz, and the two next peaks are located at 461.4 Hz and 696 Hz. A separation between the peaks of 234 Hz is very close to the main frequency of 226.6 Hz, and this difference probably can be explained with a low frequency resolution.

4 Discussion

According to Osborne et al. [6], the audible rattle of palatal snoring is around 20 Hz and represents the movement of the palate itself. Since the low frequency content is omitted from the experimental results in this study due to the AMR codec, regular explosive peaks of sound at very low frequencies characteristic for a palatal snoring cannot be identified. However, as noted by Quinn et al. [2], a complex-waveform is associated with palatal snoring and a simple-waveform with tongue-based snoring. Consequently, two complex-waveform and two simple-waveform snorers are identified in this pilot experiment. Thus, the diagnoses given by medical specialist for all 4 subjects are required for an adequate evaluation of the experimental results obtained.

In prior studies, the mean frequency of tongue-based snores has been found to be over 400 Hz (Herzog et al. [7]) or around 1243 Hz (Agrawal et al. [3]). For subjects 1 and 3, some energy is located between 400 Hz and 1200 Hz meaning that those patients have some signs of tongue-based snoring. On the other hand, for three of the subjects, there is some energy in quite high frequencies comparing with prior studies – subjects 1 and 4 have a low energy activity around 2300 Hz, and subject 2 around 2500 Hz. These could be caused by the airflow through the nose or mouth (open mouth or nasal congestion). Moreover, a relation between the ends of the fall of the sound traces and the waveform of the snores could be drawn – subjects 1 and 4 show an abrupt ending of the sound trace, while subjects 2 and 3 show a smooth fall at the end of the event. Conversely, subjects 1 and 4 show an abrupt beginning whereas subjects 2 and 3 show a soft increasing of the amplitude at the beginning. The logical explanation of this is, in the second case, because the airflow is increasing gradually until the speed of the air makes the palate vibrate and it occludes the airway producing a higher amplitude snore. For subjects 1 and 4, the explanation is probably that the occlusion is already there before starting to breath, so it could be any of the non-palatal snores.

Unfortunately, none of the hypothesis described before is currently demonstrable owing to the fact that the previous scientific research is contradictory and there is not a medical diagnosis to compare the results with.

5 Conclusions

The initial idea in this study was to analyze snoring sounds for diagnosis of the underlying pathology, by making a phone call and leaving 4-5 minutes of the snoring sound as a message in a voice mail database for further processing. Although this would be an inexpensive and noninvasive method, it is not yet recommended for clinical implementation as the recorded signal would be filtered below 400 Hz by mobile phone codec or by the telephone line and this appears to be where most of the important characteristics of the snore are located.

In this investigation, the snoring recordings were obtained from the file created by a mobile phone recording, and, as a result, low frequency characteristics were not available. Moreover, the method of recording (i.e. distance, position, and device) is not standardized and therefore no information can be extracted from the amplitude of the signals.

From the available set of four recordings, two complex-waveform and two simple-waveform snorers were identified. The waveform characteristics are similar to the ones described by Beck et al. [5], however, the frequencies do not align. Therefore, there are some differences between previous studies: it has been assumed that complex-waveform is associated with palatal snoring and simple-waveform with tongue-based snoring, but the frequencies do not coincide. In our study, it was not possible to confirm the types of snoring for each patient because medical diagnosis has not been available. Also, due to the loss of low frequency information in the recordings, it was not possible to classify the types of snoring with high certainty.

Although there are some aspects which could not be determined in the present work due to low numbers of subjects in the pilot investigations, together with the number and quality of the recorded signals and due to the lack of a medical diagnosis of the available data, there are several opportunities to improve this investigation in the future. The analysis of the acoustical properties of snores may prove to be a non-invasive and reliable alternative to current diagnostic methods for breathing disorders in sleep. It is believed that this type of data analysis could lead to important conclusions if the results could be compared to a specialist's medical diagnosis.

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