



PHYSIOLOGICAL REVIEW

The acoustics of snoring[☆]Dirk Pevernagie^{a,b,*}, Ronald M. Aarts^{c,d}, Micheline De Meyer^e^a Kempenhaeghe Foundation, Sleep Medicine Centre, P.O. Box 61, 5590 AB Heeze, The Netherlands^b University of Ghent, Faculty of Medicine and Health Sciences, Department of Internal Medicine, 25 Sint-Pietersnieuwstraat, 9000 Ghent, Belgium^c Philips Research, High Tech Campus 36 (WO 02), 5656 AE Eindhoven, The Netherlands^d Technical University Eindhoven, P.O. Box 513, 5600 MB Eindhoven, The Netherlands^e School for Dentistry, Department of Prosthodontics, University Hospital of Ghent, De Pintelaan 185, 9000 Ghent, Belgium

S U M M A R Y

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Snoring is a prevalent disorder affecting 20–40% of the general population. The mechanism of snoring is vibration of anatomical structures in the pharyngeal airway. Flutter of the soft palate accounts for the harsh aspect of the snoring sound. Natural or drug-induced sleep is required for its appearance. Snoring is subject to many influences such as body position, sleep stage, route of breathing and the presence or absence of sleep-disordered breathing. Its presentation may be variable within or between nights. While snoring is generally perceived as a social nuisance, rating of its noisiness is subjective and, therefore, inconsistent. Objective assessment of snoring is important to evaluate the effect of treatment interventions. Moreover, snoring carries information relating to the site and degree of obstruction of the upper airway. If evidence for monolevel snoring at the site of the soft palate is provided, the patient may benefit from palatal surgery. These considerations have inspired researchers to scrutinize the acoustic characteristics of snoring events. Similarly to speech, snoring is produced in the vocal tract. Because of this analogy, existing techniques for speech analysis have been applied to evaluate snoring sounds. It appears that the pitch of the snoring sound is in the low-frequency range (<500 Hz) and corresponds to a fundamental frequency with associated harmonics. The pitch of snoring is determined by vibration of the soft palate, while nonpalatal snoring is more 'noise-like', and has scattered energy content in the higher spectral sub-bands (>500 Hz). To evaluate acoustic properties of snoring, sleep nasendoscopy is often performed. Recent evidence suggests that the acoustic quality of snoring is markedly different in drug-induced sleep as compared with natural sleep. Most often, palatal surgery alters sound characteristics of snoring, but is no cure for this disorder. It is uncertain whether the perceived improvement after palatal surgery, as judged by the bed partner, is due to an altered sound spectrum. Whether some acoustic aspects of snoring, such as changes in pitch, have predictive value for the presence of obstructive sleep apnea is at present not sufficiently substantiated.

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Introduction

Snoring is a well-known phenomenon among the general population. According to the American Heritage[®] Dictionary of the English Language it is "to breathe during sleep with harsh, snorting noises caused by vibration of the soft palate".¹ Naturally occurring or drug-induced sleep is a requirement for its appearance. Snoring is a breathing noise that appears during the inspiratory and

sometimes also the expiratory phase of the respiratory cycle.² The source of the sound is the pharyngeal segment of the upper airway. Relative atonia of the upper airway dilator muscles during sleep induces narrowing and increased resistance at this level.³ As a consequence, airflow becomes turbulent and the pharyngeal tissues vibrate as the air passes through. More specifically, snoring is characterized by oscillations of the soft palate, pharyngeal walls, epiglottis and tongue.^{4,5}

From an epidemiological perspective snoring is a highly prevalent disorder. In an early population-based investigation extending to 5713 people, the prevalence of habitual snoring was found to be 19%, corresponding to 24.1% of the male and 13.8% of the female population.⁶ Increased frequency of snoring with age was another finding in this study. Many other surveys on chronic snoring have been carried out since then, yielding divergent figures of

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prevalence, ranging from 5 to 86% in the male and from 2 to 59% in the female population.⁷ Subjectivity, different target populations, the questionnaires used and whether or not the bed partner was asked to answer the questions may account for the inconsistency of these results. Combining results from all surveys that have been done so far, the most accepted estimate for the prevalence of chronic snoring is 40% in adult men and 20% in adult women, although the variability is extremely large.⁷

Whilst snoring is a ubiquitous phenomenon that is also known to occur in animals,⁸ its characteristics cannot easily be defined. Snore-related phenomena may comprise a sound spectrum ranging from modest audible breathing to loud vibratory sounds that are readily perceived as 'snores' by human observers. For the listener it is quite obvious to discern snoring from other breathing sounds such as stridor and wheezing. However, to establish a working definition that would provide a paradigm for the objective identification and quantification of snoring-related events has proven elusive so far. Early work has shown a poor correlation between measured loudness of snoring and subjective appreciation by different observers.⁹ From this study it was concluded that to a large extent snoring is "in the ear of the beholder".

Moreover, snoring is not a homogeneous acoustic phenomenon. It is subject to many influences, and therefore, its presentation may change in the course of the sleep period and it may vary from night to night. The quality of the sound is determined by many factors such as the route of breathing (oral, nasal, or both),¹⁰ the predominant sites of upper airway narrowing (palatal segment, tongue base, supraglottic space, or a combination thereof),¹¹ sleep stage and body position,¹² naturally occurring vs induced sleep,¹³ and presence or absence of sleep-disordered breathing.¹⁴ Sleep-disordered breathing (SDB) is characterized by the frequent occurrence of pathological respiratory events, i.e., apneas and hypopneas. An apnea is defined as a complete cessation of breathing of at least 10 s. During apneas there is no breathing sound. Resumption of breathing is associated with a sequence of snores. The sound quality of these consecutive interapneic snores may vary markedly.¹⁴ With partial collapse of the upper airway, airflow is decreased but not abolished. Corresponding respiratory events that last at least 10 s are called obstructive hypopneas. Snoring persists during these events and may show a crescendo pattern of increasing loudness. The number of apneas plus hypopneas per hour of sleep is the apnea-hypopnea-index (AHI). The combination of an AHI ≥ 5 per hour and excessive daytime sleepiness is referred to as the obstructive sleep apnea (OSA) syndrome.¹⁵ When no apneas and hypopneas occur during sleep and the individual has no daytime complaints, the vibratory activity of the pharyngeal airway is referred to as 'simple snoring'.¹⁶

Snoring is commonly regarded as a laughable circumstance or a source of irritation to the observer, about which little can be done but to awaken the unwitting culprit. However, its intrinsic clinical relevance has become increasingly obvious in recent years. Snoring is the audible sign of increased upper airway resistance. It is known to be an important clinical hallmark of OSA¹⁵ and, as such, may be a useful and an easily accessible marker to screen for obstructive SDB. Whilst self-reported snoring has limited accuracy in predicting the presence of OSA,¹⁷ acoustical analysis of snoring seems to carry a better potential to discriminate between 'simple snorers' and patients suffering from OSA syndrome. Some recent publications on this subject will be reviewed in this paper.

These novel directions in the investigation of snoring may disclose additional clues relevant to clinical practice. Evidence is now accumulating that snoring by itself may be linked to daytime symptoms. In apneics, an association was demonstrated between sleepiness and snoring sound intensity, and this association was independent from the AHI.¹⁸ Snoring, excessive daytime sleepiness, and learning

problems were found highly specific for SDB in 6- to 11-year old children.¹⁹ The positive likelihood ratio from the combination of these symptoms may be sufficiently high to obviate the need for polysomnography in this age group.¹⁹ Excessive daytime sleepiness and daytime fatigue were related to habitual snoring independent of the AHI, age, obesity, smoking, and sleep parameters in a population-based sample of women.²⁰ These findings would indicate that snoring is independently associated with daytime somnolence in some particular groups, and not merely a proxy for sleep apnea. Furthermore, this contention would imply that the phenomenon 'snoring' is to be acquitted from its connotation 'simple'.

Snoring may have several other side effects. Intense flutter of the upper airway structures may cause vibratory trauma, resulting in early inflammation²¹ and permanent damage of the pharyngeal tissues^{22,23} and adjacent vessels.^{24,25} To overcome increased upper airway resistance, snorers significantly increase inspiratory muscle effort, as a consequence of which nadir intrathoracic pressures may double or triple.^{26,27} Excessive negative intrathoracic pressure increases cardiac afterload by increasing myocardial transmural pressure²⁸ and may facilitate gastro-esophageal reflux.²⁹

Perhaps most importantly, snoring is a social nuisance. The loud rattling noise may keep spouses and people in adjacent bedrooms from falling or staying asleep. Bed partners may have a significantly impaired sleep quality³⁰ and suffer from secondary sleep disorders.³¹ Habitual loud snoring may be socially unacceptable, and may constitute a reason for sleeping apart, marital disharmony, divorce, and even aggression and homicide.³² If it does not disrupt a harmonious relationship, snoring may bring to the surface the underlying lack of harmony.³³ Moreover, there is preliminary evidence to suggest that chronic exposure to loud snoring may predispose bed partners to presbycusis.³⁴ Female snorers may feel embarrassed and stigmatised by their nocturnal behaviour as snoring is intuitively associated with the male gender.³⁵ In the UK each year more than 11,000 people undergo surgery to alleviate snoring.³⁶ Other non-surgical therapeutic interventions such as the use of mandibular advancement devices have become available in recent years, and are increasingly used for treatment of snoring. Whilst no information is available on prescription or consumption rates for the latter type of treatment, there is evidence to show that a substantial proportion of the chronic snorers seek medical help for their discomforting malady.

Because the perception of snoring is highly subjective, there is a need to objectively measure snoring if one wants to do accurate patient assessment and evaluate treatment effects.³⁷ Furthermore, tools to quantify the snoring-induced annoyance have to be developed, as annoyance has a broader psychoacoustic scope than the mere assessment of noise intensity and loudness.^{38,39} The aim of this article is to review the present state of scientific knowledge regarding acoustic assessment of snoring and to deal with the following topics:

- Physical characteristics of snoring sound generation in the upper airway
- Principles of acoustic measurement of sound
- Advanced analysis and modelling of snoring sounds
- Acoustics of snoring assessed vis-à-vis clinical outcomes
- Unresolved questions that are suitable for further research
- Practice points

Physical characteristics of sound generation in the upper airway

Speech and singing is produced by the vibratory excitation of a hollow anatomic system called the vocal tract. It can schematically

be presented as an acoustic box which is terminated at one end by the lips and nares and at the other end by the glottis. The thoraco-abdominal muscle-apparatus operates an air pressure system that drives the primary sound generator located within the pharynx, i.e., the vocal cords. Narrowing of the glottic aperture is caused by adduction of the vocal cords and their surrounding folds. Vibration of the vocal folds is the result of air passing through the narrowed glottis and is referred to as 'phonation'. The sound produced by the vocal folds has a character of vibrating strings, as it consists of a fundamental frequency and harmonics or overtones (a.k.a. harmonic series, Fig. 1) that defines the pitch of the voice.^{40,41}

The laryngeal sound source generates longitudinal compression waves in the vocal tract. The supralaryngeal upper airways (i.e., pharynx, oral and nasal cavities) serve as a resonating system, which filters the 'buzzy vocal sound' into a person's particular voice. This filtering is based on both attenuation and amplification of the original laryngeal sound waves. The result is a concentration of acoustic energy around a particular frequency, which is called a 'formant'.⁴² In speech and singing, different formants are produced simultaneously. Each formant corresponds to a resonance level in the vocal tract. Therefore, the voice is characterized by

a specific set of formants (F1 through F3), defining its unique aspect and explaining the audible characteristics that typify different individuals (Fig. 1). Finally, the quality of the voice is defined by the articulatory system that comprises a set of movable structures. The lips, tongue, soft palate and jaw are the so-called 'articulators' that change the shape of the resonator in accordance with the subtle anatomical changes that are required for intelligible speech.

Speech is the generic name given to sounds that carry language content. Speech has three basic components: voiced sounds, fricative sounds and plosive sounds. The vocal folds emit the so-called 'voiced sound'.⁴³ The last two sound components are not emitted by vocal cord vibration. They are produced in the laryngeal and supra-laryngeal part of the vocal tract and are referred to as 'unvoiced sounds'. In unvoiced fricative sounds, the energy is concentrated high up in the frequency band, and is quite disorganized or 'noise-like' in its appearance. Plosives, such as /p/, /t/, and /k/ are impulsive sounds which occur with the sudden release of air by using the tongue and lips.⁴³

In recent years, many authors have approached snoring from the perspective of speech analysis, because of the physiological similarities and the availability of common methods for digital

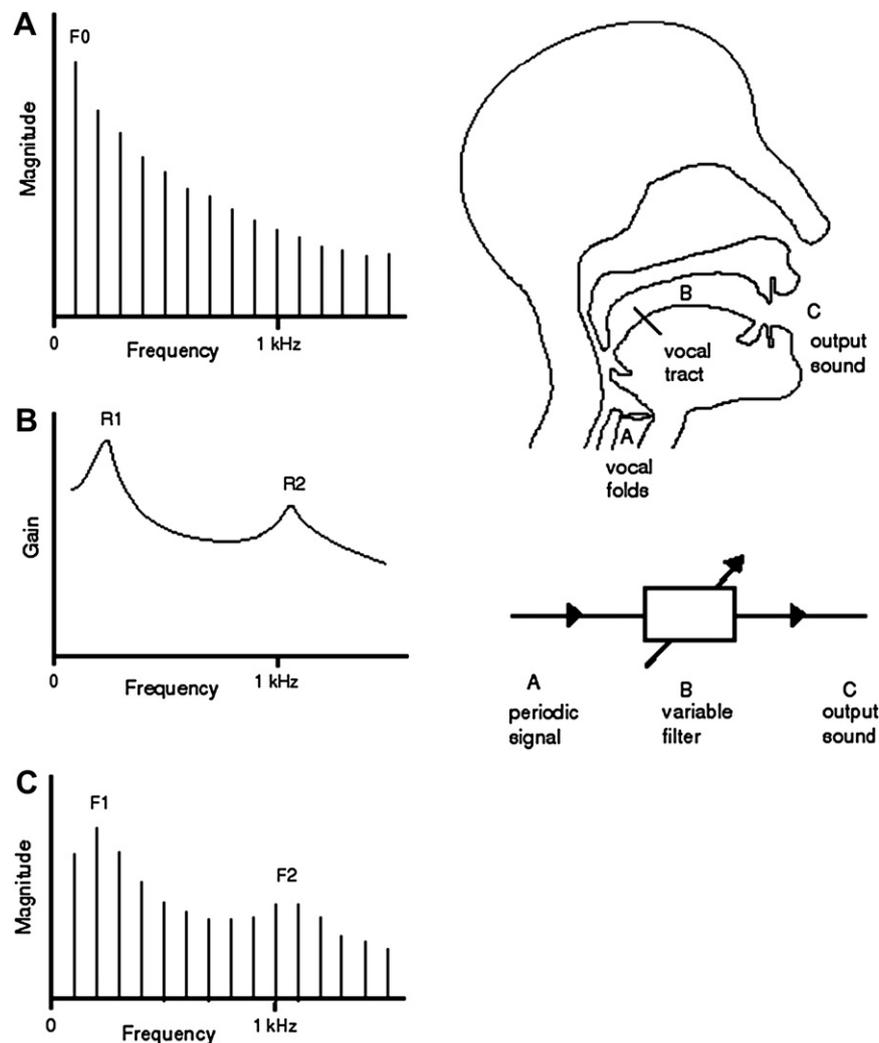


Fig. 1. The vibration of the vocal folds produces a varying airflow which may be treated as a periodic signal (A) that produces a spectrum of equally-spaced frequency peaks or harmonics, starting with a fundamental frequency (F0). This source signal is input to the vocal tract. The tract behaves like a variable filter (B). Its response is different for different frequencies and the frequency response may be further adjusted by changing the position of the tongue, jaw etc. Resonance peaks R1 and R2 add gain to specific frequencies of the harmonic spectrum. The input signal and the vocal tract, together with the radiation properties of the mouth, face and external field, produce a sound output (C). The resonances R1 and R2 can be determined approximately from the peaks in the envelope of the sound spectrum. These peaks are called the formants (F1 and F2). Figure reproduced by courtesy of Joe Wolfe, BSc Qld, BA UNSW, PhD ANU, School of Physics, The University of New South Wales, Sydney 2052, Australia.

processing and analysis. The analogy between snoring and speech lies in the fact that both are generated in the vocal tract.⁴⁴ Acoustical analysis of snoring and vocal sounds demonstrates that fundamental frequencies and harmonics can be observed in both phenomena.⁴⁵ The same holds true for formant features.⁴⁶ However, there are several dissimilarities as well. Snoring is caused by vibratory activity of pharyngeal structures, not by the vocal cords. Endoscopic evaluation of upper airway structures during snoring has revealed flutter of the soft palate, which may be combined with noise generation by vibration of other structures, such as tonsils, tongue base and epiglottis.¹¹ Snoring occurs in sleep, during which the upper airway is in a passive state. There is no articulation of the sound. Moreover, the driving pressure is directed interiorly, as snoring is mainly associated with inspiration. These physiological differences should be kept in mind when applying speech techniques to the acoustic analysis of snoring.

Several theoretical models have been developed to define the relationship between the characteristics of snoring and the functional anatomy of the human upper airway.^{47–50} Huang et al. have introduced a model implying two basic biomechanical concepts, namely 'flutter' to describe palatal snoring, and 'static divergence' to give insight into the pharyngeal mechanisms of snoring.^{47,48} Gavieli and Jensen proposed a theoretical model of the upper airways, consisting of a movable wall in a channel segment that connects to the airway opening via a conduit with a resistance.⁴⁹ The effects of different variables, such as airway wall compliance, gas density, and airway dimensions on the pressure–flow relationships were studied. The model predicts that, depending on mechanical properties of the pharynx, the walls of the upper airway may be stable (normal breathing), may exhibit vibration or fluttering (snoring), or may show repetitive closure.⁴⁹ Liu et al. applied the concept of structural intensity to a three-dimensional finite element model of a human head.⁵⁰ They observed that pressure loads in the range of 20–60 Hz yield tissue vibrations mainly in the areas of the soft palate, the tongue and the nasal cavity. To predict the snoring noise level as a function of a preset airflow loading, a three-dimensional boundary element cavity model of the upper airway was constructed.⁵⁰ Such models may be further adapted to study various snoring mechanisms for different groups of patients.

In an early study, Beck et al. characterized the acoustic properties of snoring sounds in the time and frequency domains, and correlated these properties with mechanical events relevant to the mechanisms of snoring.⁴⁵ They observed two dominant snoring patterns: the 'simple-waveform' and the 'complex-waveform'. The complex-waveform snore is characterized by a repetitive, equally-spaced, train of sound structures, starting with a large deflection followed by a decaying amplitude wave. In the frequency domain, it is characterized by multiple, equally-spaced peaks of power (comb-like spectrum). Simple-waveform snores have a quasi-sinusoidal waveform, with a range of variants, and almost no secondary internal oscillations. Their power spectrum contains only 1–3 peaks, of which the first is the most prominent. The complex-waveform snores may result from colliding of the airway walls and represent actual brief airway closure. Simple-waveform snores are of higher frequency and probably result from oscillation around a neutral position without actual closure of the lumen. Endoscopic appraisal of the pharyngeal structures during snoring has revealed that the complex-waveform is associated with palatal snoring, the simple-waveform with tongue base snoring.⁵¹ The harsh property of snoring is related to the 'explosive' feature of the sound production, which corresponds to the release of packets of sound energy. These impulses result from the repetitive opening and closure of the nasopharyngeal airway.⁵²

Principles of acoustic measurement of sound

Sound is the vibration in a physical medium. The vibration causes a propagation of pressure waves that can be measured. The unit of sound pressure is pascal [Pa]. Commonly, a given pressure level p is related to a reference pressure p_0 . By convention, p_0 is equal to 20 μ Pa, which is the average threshold of human hearing at 1 kHz. The logarithm of this ratio is the Sound Pressure Level (SPL), which is expressed in decibel (dB).

$$\text{SPL} = 20 \log_{10}(p/p_0) \quad (1)$$

Hence, an increase in the sound pressure of a factor 10 will result in a SPL increase of 20 dB. The reason to use a logarithm measure is that it fits better to the human perception of loudness than a linear measure.

A sound signal can be captured with electronic equipment. In the section below, the principles of recording, processing and analyzing sound will be briefly discussed (Fig. 2).

Sound recording

Sound waves that propagate in air are recorded with microphones. These devices convert air pressure variations into an electrical signal (Volt) and are grouped in three principal classes. Capacitor (or condenser) microphones have a membrane or flexible plate that moves with the air pressure variations. The capacitor consists of this membrane and a second plate which is fixed. A direct-current (DC) voltage, known as the polarizing voltage, is applied between the plates. The capacity changes that result from the movements of the membrane are converted into voltage signals. Capacitor microphones are high-end products, and are the most commonly used type in acoustic laboratories. Prepolarized or electret microphones are a second category. They operate similarly to a condenser microphone but require no external polarizing voltage. Electret microphones are small-sized and low budget. Piezoelectric or ceramic microphones – the third class – have a membrane that is connected to a piezoelectric element. When the piezoelectric element moves a voltage is generated.

With respect to measuring snoring, it is important that the received signal is for the major part the sound going directly from the nose and mouth to the microphone. Therefore, much attention should be given to the position of the microphone. The recording of sounds reflected by objects, like the bed, ceiling, furniture, and walls should be minimized. The space where reverberation is relevant is called the indirect field, whereas in the direct field (or free field) the relative amount of reflected sound is negligible. An ambient microphone should be placed in this free field, the range to the mouth being shorter than the critical or reverberation distance, which is at the boundary between the direct and indirect field.⁵³

The positioning of the microphone to record snoring is highly variable in published literature and, as yet, no recommendations as to standardization have been made. Possible locations for placement of the microphone include the skin regions of the larynx or trachea, in the nasal cannula, or in the ambient air. Alternatively, the microphone may be placed on the forehead.⁵⁴ In a recent study it was shown that the recorded sound frequency range may depend on the placement of the microphone, higher frequencies being lost with microphones that have contact with the skin.⁵⁵ From this study it was concluded that contact microphones might be used in screening devices, whilst for appropriate analysis of snoring sounds the use of air-coupled microphones is indispensable.

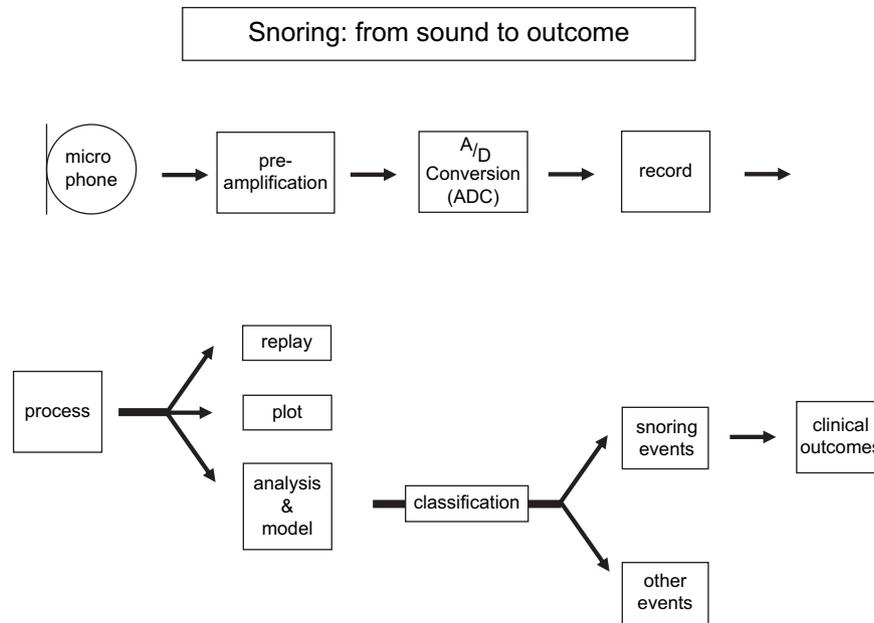


Fig. 2. Sound processing from source to clinical outcomes. The sound is captured with a suitable microphone. Before the analog signal is converted to a digital format, it is pre-amplified and filtered. Analog-to-digital conversion (ADC) means that the signal is sampled at a sufficiently high rate to enable adequate sound reproduction in the further process. The digitized record is stored as a computer file (e.g. wav-file), which may subsequently be used for several purposes. The sound may be replayed, graphically plotted or further analyzed and classified using different kinds of mathematical models. The ultimate goal is to identify individual snoring events and to discriminate them from non-snoring sounds. The true snoring events are then further classified into different categories that are relevant for specific clinical outcomes, e.g. loudness and annoyance, anatomical site of snoring, apneic versus non-apneic snoring, and prediction models for efficacy of treatment.

The amount of noise 'N', received by the microphone, like air-conditioning noise and other non-snoring related sounds, should be small with respect to direct snoring sound 'S'. The ratio

$$\text{SNR} = 20 \log_{10}(S/N), \quad (2)$$

is called the signal to noise ratio, which should be sufficiently high, preferably exceeding 20 dB. Methods to improve the SNR are mounting the microphone close to the mouth, using directional microphones which have a narrow sound recording angle, and to decrease external sounds.

Filtering and conversion to the digital domain

The signal picked up by the microphone is pre-amplified and submitted to electronic filters in order to remove very low frequencies (by a high-pass filter), and to remove high frequencies (by a low-pass filter). These two filters together are referred to as a band-pass filter. Their settings depend on the sound frequencies of interest, which are determined by the experimental objectives and modalities. A high-pass frequency of 20 Hz is largely sufficient for acquiring relevant information of snoring sounds at the lower spectral end, whereas a low-pass frequency of 3 kHz or higher is usually suitable for recording the higher frequencies.^{14,56} For a reference, the frequency range of an ordinary telephone connection has a limited bandwidth from 300 to 3400 Hz.

The filtered sound signals are subsequently digitized with an analog to digital converter (ADC). It samples the analog microphone signal at a frequency rate that is determined by the low-pass filter. To avoid spectral aliasing, the sampling frequency must be equal to at least two times, preferably 2.5 times the low-pass frequency of the signal.⁵⁷ For a low-pass value of 3 kHz, one has to choose a sampling frequency of at least 7.5 kHz. For recording of snoring sounds a sampling frequency of 12 kHz is largely sufficient. Converters sampling at 44.1 kHz comply with the musical CD standard and are widely available on PC-sound cards. They may be

used instead of lower frequency samplers, but may produce quite large amounts of data when applied in all night recordings. The converted signal can be stored as a sound record on the PC (e.g., a WAV-file).

Sound analysis: physical sound strength measures

The digitized sound record must be further processed to obtain a format that is useful for various purposes, such as sound replay, graphical plotting of the signal, sound intensity assessment, time and spectral analysis, identification and classification of events, etc. An important aim of recording snoring sound is to obtain measures of snoring intensity and quality. This implies transformation of the signal into physical and mathematical data that can be interpreted. A simple signal like a sinusoid is fully characterized by its amplitude and frequency. For more complex signals, like snoring, other measures have to be used. In the following paragraphs some basic measurement methods will be discussed.

Weighted sound intensity measurement. The reason for using weighting is to mimic the perception of loudness. Loudness is a perceptive measure, in contrast with technical and physical measures like the volt or dB discussed above. It is possible to filter or weight the microphone signal to reduce the influence of certain frequencies in the measured signal. The filter may be included in the microphone amplifier, or it can be applied in the subsequent off-line processing of the signal. Very common are the so-called A, B, C, or D-weightings. A is most often used as it reflects the human perception of sound pressures across the sound frequency range (Fig. 3).⁵⁸ The A-weighted SPL is denoted as dBA or dB(A).

Calm breathing at a 10 cm distance from the mouth is barely audible and produces sound pressure levels of 25 and 17 dBA for inhalation and exhalation, respectively.³⁸ Loud breathing measured at a 1 m distance from the mouth can reach sound levels up to

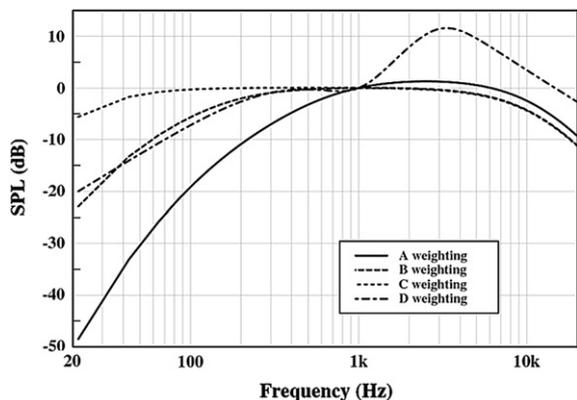


Fig. 3. Filtering or weighting the microphone signal reduces the influence of certain frequencies in the measured signal. Very common are the so-called A, B, C, or D-weightings. A is the most used one as it reflects the human perception of sound pressure across the sound frequency range. This A-weighted SPL is denoted as dBA or dB(A). A common feature to these curves is that the weighting is equal to 0 dB, or unity gain, at 1 kHz. The filter may be included in the microphone amplifier, or it can be applied in the further processing of the signal. [From Aarts R.M.,⁵⁸ Fig. 5].

40 dBA, which value is proposed by some authors as the threshold for the transition between breathing and snoring.^{37,59}

RMS value and crest factor. The root-mean-square (rms) value of a signal V , e.g., a microphone voltage, is defined as the square root of the time average value of the square of a signal.

$$V_{\text{rms}} = \sqrt{\frac{1}{n} \sum_{i=1}^n V_i^2} \quad (3)$$

For a constant signal with amplitude A , the rms value is equal to amplitude A . For a sinusoid with amplitude A , the corresponding rms value is equal to $A/\sqrt{2}$. For more complex signals this value may drop further. The crest factor is the ratio between the highest absolute value of a signal divided by its rms value. For a constant signal with amplitude A , the crest factor is equal to 1, for a sinusoid with amplitude A the crest factor is $\sqrt{2}$. A high crest factor may identify a 'peaky-signal'. Snores associated with flutter of the soft palate contain a series of impulses with high energy content. Application of crest factor analysis is suitable to recognize palatal from nonpalatal snoring sounds (Fig. 4).³⁶

Equivalent noise level. The equivalent noise level or $L_{\text{Eq,T}}$ is equal to the squared ratio of the signal and a reference signal p_0 , averaged over a time T , and then converted to a logarithmic value expressed in dB.⁶⁰ If the signal is weighted, for example by the A-weighting, it is expressed in dBA. In other words, it is the average level of a time-varying signal, which has the same level as a signal with a fixed SPL. Moreover, a rating level (L_R) can be computed that adds penalty points to L_{Eq} , for factors that are known to increase annoyance, e.g., sound impulses, tone and information content, time of day, and certain sources and situations.⁶¹

To get some insight into the statistical distribution of the signal's intensity, percentile levels (L_{Per}) are computed, indicating the sound intensity level that is reached or exceeded Per% of the time. If the signal is A-weighted, this is expressed in dBA. For instance, L_1 , L_5 and L_{10} are the sound levels that are reached or exceeded 1%, 5% and 10% of the time, respectively. They indicate the noise peaks in a sound recording.⁶⁰

Spectrum and spectrogram. The signal may contain several frequencies at the same time. It is customary to compute the

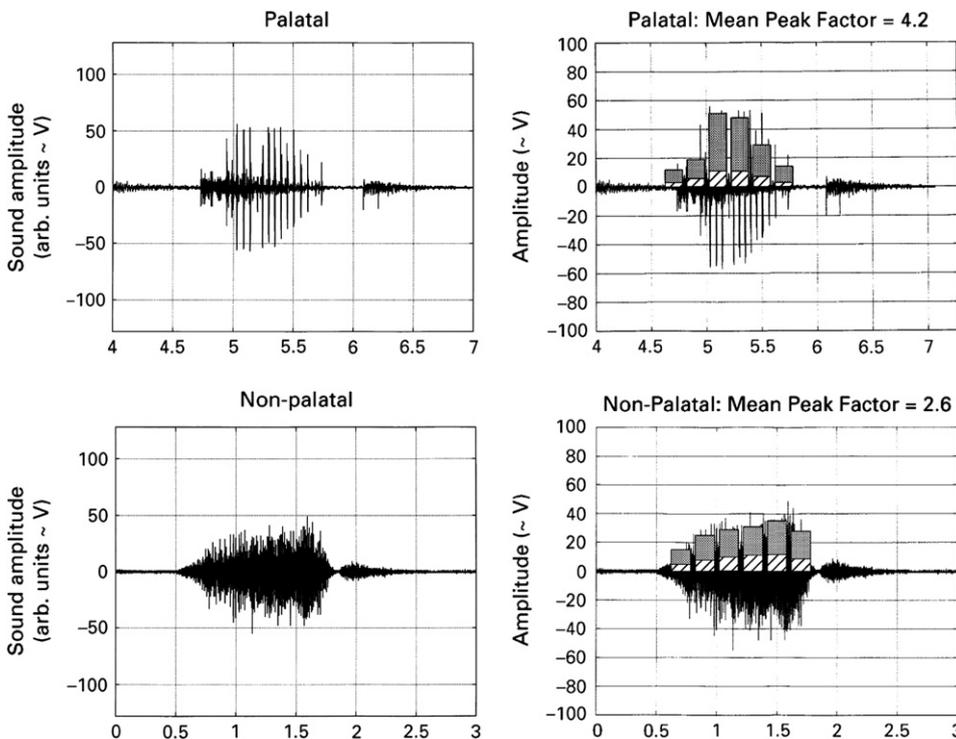


Fig. 4. Four plots in the time domain, with time (sec) in the abscissa and sound amplitude ($\sim V$) in the ordinate. Regular explosive peaks of sound at very low frequency can be seen during palatal snoring (top panel, left) but not during tongue base snoring (bottom panel, left). In order to quantify this aspect, a ratio of peak sound amplitude (99th centile measurement – gray bars) to effective average sound amplitude (rms – hatched bars) measurement was calculated during 0.2 s segments of a snore. This ratio is higher in palatal (4.2, top panel, right) than in nonpalatal snoring (2.6, bottom panel, right). [Reproduced with permission from³⁶].

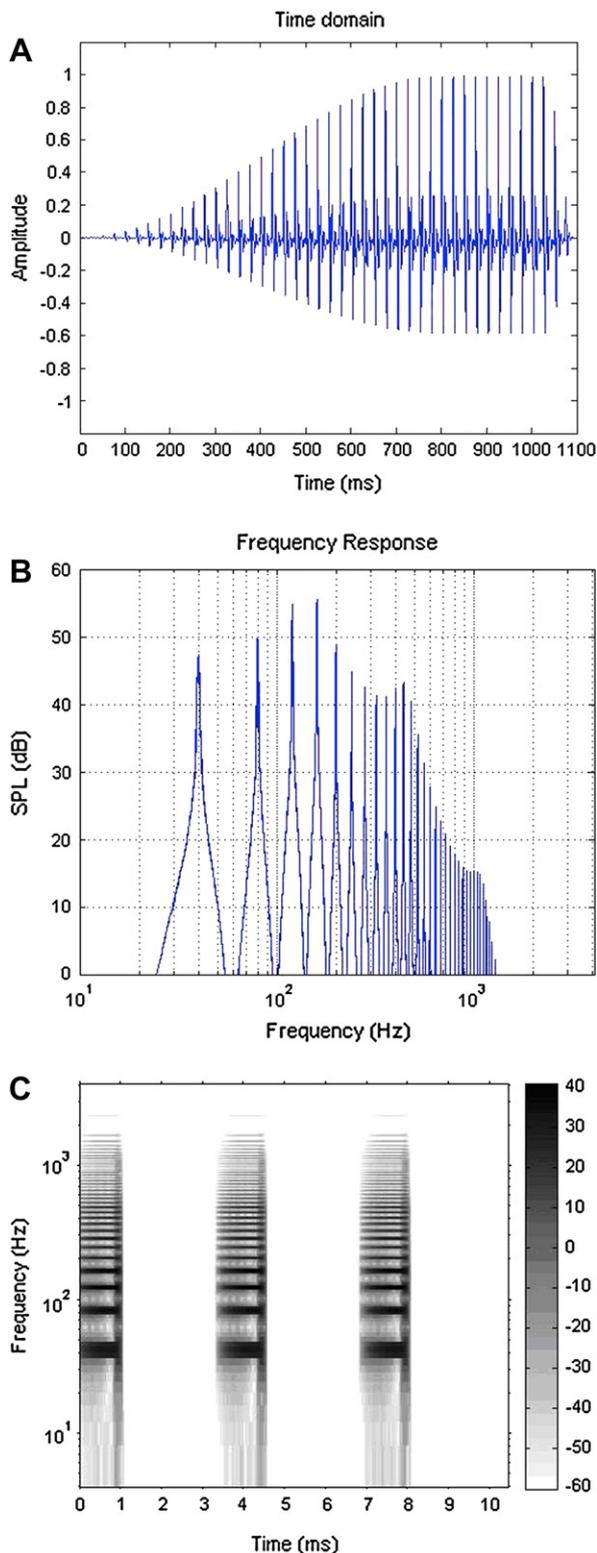


Fig. 5. Frequency analysis of a simulated mechanical palatal snoring model. A. Amplitude of the sound in the time domain. The first snore of a sequence of three. B. Frequency spectrum of the sound. The event in A is shown after Fourier analysis. Frequency (Hz) in the abscissa is plotted against power (SPL) in the ordinate. The first peak at about 40 Hz is called the fundamental frequency, the peaks at higher frequencies are called harmonics. Connecting the peaks yields the spectral envelope. Within a spectral plot different markers can be observed. The peak frequency describes the harmonic with greatest magnitude. The center frequency describes the average sound frequency for the range of frequencies over which sound occurs; it is the point at which the area under the graph is equal on both sides. The power ratio compares the

Fourier-transform or the Power Spectral Density (PSD) of a time signal (Fig. 5A) to get the frequency spectrum of that signal, which can be plotted with the magnitude of the signal (dB) in the vertical axis and the frequency (Hz) in the horizontal axis (Fig. 5B). For time-varying signals, like speech, music, and snoring, one can compute the frequency spectrum for successive parts of the signal. This results in a spectrogram, where the time axis is plotted horizontally and the frequency vertically. The magnitude is coded as a color or gray value (Fig. 5C).

Sound analysis: psychophysical measures of noise

Some aspects of assessment of strength and quality of sound involve the human ear and brain, and can therefore not be expressed in pure physical measures. The discipline that studies the relationships between acoustic stimuli and hearing sensations is called psychoacoustics.^{62,63} In this paragraph some of the important psychoacoustic measures will be addressed. *Loudness* is an attribute of the auditory sensation by which sounds may be ordered on a scale extending from soft to loud. Loudness is expressed in sone. The *loudness level* of a given sound is the equivalent SPL of a reference sound. This reference sound consists of a sinusoidal plane progressive wave of frequency 1 kHz that is administered directly in front of observers, who are otologically normal persons. It is adjusted up to a level where these observers judge that the reference sound becomes equally loud as the given sound. The loudness level is expressed in phon. To highlight the differences between physical and psychophysical measures an overview is given in Table 1.

Finally, in addition to the physical and psychophysical measures, a third level, the *annoyance* of a sound can be assessed. Annoyance may have particular relevance for snoring sounds, as it is not only related to the characteristics of the noise, but also to the psychological state of the observer. For instance, annoyance depends on psychophysiological aspects such as the mood of the listener and his or her relation to the snoring partner. Psychoacoustic annoyance (PA) can quantitatively describe annoyance ratings obtained in psychoacoustic experiments.⁶³ Basically, psychoacoustic annoyance depends on the loudness, the tone color, and the temporal structure of sounds. Whilst the mental state of the listener is of significant importance, subjective parameters are not routinely taken into account in the objective assessment of annoyance.

Advanced analysis and modelling of snoring sounds

In the following section, advanced methods for analysis and modelling of snoring sounds are addressed. These techniques allow discrimination between true snoring events and other sounds, as well as differentiation between sounds qualified as 'simple snoring' vs events belonging to the spectrum of obstructive sleep apnea.

Linear predictive coding (LPC) is widely used in advanced speech analysis. It is based on a mathematical model containing p coefficients, where p is the order of the model.⁵⁷ These p coefficients are mathematically processed in a way that the model gives an optimal

relative amount of sound emanating below and above a set frequency. C. Spectrogram. Three consecutive snores are shown occurring every 3.5 s. The vertical frequency axis is on a log scale. Within each snoring sound epoch the fundamental frequency is equal to about 40 Hz. Outside episodes of snoring there is silence represented by white columns. The bar denotes the SPL in dB. The most apparent feature in C is that the three snores are clearly visible, which is not the case in plot A and B. The spectrogram can give valuable information of the spectrum in case of a time dependent spectrum. The gray scale is a measure of the intensity of the signal, indicated by the reference bar ranging from a high (black 40 dB) to a low (white -60 dB) intensity, where the dB reference level is arbitrary.

Table 1

Physical and psychophysical measures. The mel scale, is a perceptual scale of pitches judged by listeners to be equal in distance from one another. The sone is the unit of perceived loudness. In acoustics, loudness is the subjective perception of sound pressure. The phon is the unit of perceived loudness level for pure tones. By definition, 1 phon is equal to 1 dB sound pressure level (SPL) at a frequency of 1 kHz.

Physical	Psychophysical
Frequency [Hz]	Pitch [mel]
Sound pressure [Pa]	Loudness [sone]
Sound pressure level (SPL) dB	Loudness level [phon]

description of the input signal for a certain time segment or window. As such, it is a method to estimate the signal's PSD or its spectral envelope. The spectral envelope method has been used by Sola-Soler et al. who found significant differences between simple snorers and OSA patients.⁶⁴ Ng et al. also tried to discriminate apneic from simple snorers using LPC techniques.⁴⁶

Instead of using LPC to acquire spectral information, one can transform the microphone signal directly to the frequency domain, using the Fourier-transform. A particularly fast and efficient method is the *fast Fourier-transform* or FFT.⁶⁵ Spectral analysis performed by Fiz et al. revealed that there are two different patterns.⁶⁶ The first pattern was characterized by the presence of a fundamental frequency and several harmonics. The second pattern was characterized by a low-frequency peak with the sound energy scattered on a narrower band of frequencies, but without clearly identified harmonics. The simple snorers and two of the 10 OSA patients showed the first pattern. The rest of the OSA patients showed the second pattern.

A third method is *wavelet analysis*.⁶⁷ The advantage of wavelet analysis over the Fourier analysis is that it is better suited to representing functions that have discontinuities and sharp peaks, and that it has a multi-resolution analysis and synthesis ability. It is to some extent similar to the spectrogram as discussed above. Wavelet analysis has been carried out on snoring signals to explore clinical usefulness in detecting obstructive sleep apnea.^{68,69}

In recent years, different models have been designed that allow distinction between snoring-related and other events. Only the real snores should be selected in the process, other sounds must be discarded. Furthermore, these models should be able to yield additional information on the nature of the snoring-related events and thus offer predictive value with respect to clinical outcomes.

The method of *Hidden Markov Models* (HMM) is an analysis technique that is widely used in classification problems, in particular for speech recognition.⁶⁵ It is a statistical paradigm in which the system is modeled as a number of states with unknown parameters. The challenge is to determine the hidden parameters from the observable data. From the input signal features are derived and combined by a statistical framework that eventually leads to a decision, or labeling of the input signal, which can be 'snoring' or 'no snoring', or other classes. Duckitt et al. applied HMM to automatic detection, segmentation and assessment of snoring sounds.⁷⁰ They recorded various sounds at the bedside and manually screened the recordings in the following classes: snoring, breathing, duvet noise, silence, other noise (including car noises, barking dogs, etc.). They found that 82–89% of snores could be identified correctly.

Another way to make out snoring from nonsnoring events is to analyze the *500 Hz sub-band energy distributions* in sound segments recorded during sleep.⁷¹ Snoring episodes show a regular pattern on the spectrogram, and can easily be distinguished from other sound events, based on their characteristic sub-band energy distribution. The accuracy of this method for snore episode detection was found to be 97.3% in simple snorers and 86.8% in OSA patients.⁷¹

Pitch is an important characteristic of speech. It is associated with the vibration frequency of the vocal cords and is an acoustic correlate to tone and intonation of speech. As such, pitch is the time domain counterpart of the fundamental frequency. Because speech changes over time, the pitch will change as well. In order to analyze speech, it is common to track the pitch and to display this over time.⁷² In analogy with speech, certain tools can be employed for the analysis for snoring. In particular, pitch tracking is interesting because pitch is – like in the voice – an important attribute of snoring sounds.⁷³ Recent studies have focused on the features of changing pitch in the characterization of snoring events.^{52,74}

During the last two decades, *higher order statistics* (HOS) were introduced with many applications in diverse fields including biomedicine.⁷⁵ These statistics, known as cumulants, and their associated Fourier transforms, known as polyspectra, reveal amplitude information about a process as well as phase information. Examples for the detection of sleep apnea from snoring sounds have recently been published.^{76,77}

Acoustics of snoring vis-à-vis clinical outcomes

Acoustic measurements of snoring have been applied in clinical medicine for various purposes. Because the snorer is most often referred by the bed partner whose appreciation of the snoring noise is inherently subjective, a need for objective assessment is obvious. To this goal, techniques for measurement of snoring loudness and annoyance have been employed. Furthermore, acoustic researchers have tried to identify and quantify those characteristics of snoring sounds that point towards the coexistence of OSA. Polysomnography is the gold standard for diagnosis of this disorder, but is cumbersome and expensive to perform. If useful information on SDB can be revealed by analysis of snoring events, a way to easy and affordable screening for OSA may be disclosed. In Ear-Nose-Throat (ENT) medicine, much interest is directed at identifying the primary sound-generating site in the upper airway. It is believed that if the soft palate is the principal source of snoring, surgical therapy will be more successful. Recent investigations have demonstrated that with the application of suitable acoustic analysis techniques it is possible to differentiate palatal from nonpalatal snoring. Finally, as "snoring is in the ear of the beholder", objective assessment of snoring before and after therapeutic interventions should be carried out to evidence efficacy of treatment, or the lack thereof.

Measuring snoring loudness and annoyance

Hoffstein et al. were the first to test subjective perception of snoring and to compare it with objective measurements in 25 snoring patients.³³ Comparison of the number of snores scored on polysomnography vs the count of the snores perceived at the replay of an audiotape by two technicians demonstrated that an agreement within 25% occurred in only 11 of 25 subjects. In the other patients there was a disagreement between either perceived vs objective snore counts, or between observers. The agreement between both observers in judging snoring severity was moderate (weighted Cohen's kappa = 0.49). It was concluded that perception of snoring is highly subjective and that validated methods to measure snoring had to be further developed.³³

Systematic measurement in the sleep laboratory environment of snoring sound intensity in 1139 subjects revealed a mean (SD) L_{Eq} of 46.2 (7.91) dBA.⁵⁹ L_{10} levels of 55 dBA were exceeded by 12.3% of the patients. The average levels of snoring sound intensity were significantly higher for men than for women. These findings surpass by far acceptable standards defined by the WHO (World Health Organization) for interior sound pressure levels at night, i.e., $L_{Eq} = 30$ dBA and $L_{Max} = 45$ dBA.⁷⁸ While no data on the partner's

perception of nuisance were collected in this study, it was contended that the noise generated by snoring was sufficiently loud to disturb or disrupt a snorer's sleep, as well as the sleep of the bed partner.⁵⁹

Questionnaires to evaluate and report the severity of snoring have been elaborated, but have thus far not been validated against relevant acoustic indices.^{79,80} The first attempt at objectively quantifying annoyance due to snoring noise was carried out by Caffier and coworkers.³⁸ They adapted methods developed for environmental medicine and used psychoacoustic measures to establish a new scale, which they named the 'Berlin snore score'. Free-field snore sounds were acquired in 19 habitual snorers. Out of different sound characteristics and levels, they retrieved those parameters that were most relevant for annoyance. Their final score graded objective acoustic annoyance on a scale from 0 to 100, and included the following compounds: rating level (L_R), maximum level (L_{Max}), two percentile levels for frequent maxima (L_5 and L_1) and snoring time. The scores that were observed in the 19 subjects substantially exceeded the prescribed limits defined by WHO noise guidelines.⁷⁸ The mainly affected parameters were L_{Eq} , L_R and the standard values of brief noise peaks, whose maximum was exceeded by up to 32 dBA. The Berlin snore score was proposed for inter-individual comparison and to evaluate effects of therapy. However, additional investigation is required to assess the general clinical applicability of this particular score.

Finally, annoyance is not only determined by the noise itself, but also by psychological intricacies and the mental state of the observers. In a recent study, it was shown that the mean annoyance caused by snoring differs from one kind of event to another, some snoring sounds being more 'acceptable' than others.³⁹ Taking into account the changing properties of snoring events throughout the recording period, it was found that the inter- and intra-rater reproducibility of the annoyance scores was only moderate. It was concluded that the listeners were not stable in their own ratings and that the ratings also differed between listeners. Therefore, the listeners' noise sensitivity seems at least equally relevant for the assessment of snoring annoyance as the snoring sound itself.³⁹

Snoring as a marker of the coexistence of OSA

By convention, a distinction is made between steady snoring, which shows little variation and little or no interruptions, and the irregular snoring that characterizes the resumption of breathing in between obstructive apneas. The first hint for acoustic differences between these two phenomena was provided by Perez Padilla et al.¹⁴ They analyzed snoring noise from 10 nonapneic heavy snorers and 9 OSA patients. Most of the power of snoring noise was below 2000 Hz, and the peak power was usually below 500 Hz. Patients with apnea showed a sequence of snores with spectral characteristics that varied markedly through an apnea-respiration cycle. The first postapneic snore consisted mainly of broad-band white noise with relatively more power at higher frequencies. Patients with OSA had residual energy at 1000 Hz, whereas the nonapneic snorers did not. It was found that the ratio of power above 800 Hz to power below 800 Hz could be used to separate snorers from patients with OSA. McCombe et al. employed third-octave sound analysis and calculated dB(A)/dB(SPL) for L_{Max} in 9 OSA patients and 18 subjects with simple snoring.⁸¹ They demonstrated that both groups had a large low-frequency peak in SPL at around 80 Hz. In accordance with the previous study, the OSA group displayed a substantially larger high frequency sound component. Fiz et al. studied 10 OSA patients and 7 simple snorers.⁶⁶ They observed the presence of a fundamental frequency and several harmonics in the simple snorers. Another frequency pattern was characterized by a low-frequency peak with the sound energy scattered on a narrower band of frequencies, but without

clearly identified harmonics. This pattern was present in the majority of OSA patients, and was associated with a significantly lower peak frequency of snoring. All but one OSA patient and only one nonapneic snorer showed a peak frequency below 150 Hz. In contrast with previous studies, no residual power in the higher frequency bands was observed in the OSA group. Methodological issues could have accounted for this discrepancy.

Yet another investigation in which FFT analysis was applied confirmed the presence of a high frequency, non-harmonic snoring noise pattern in OSA patients.⁸² In this study, peak sound intensity was determined from the power spectrum in sixty male patients with suspected SDB and reported snoring. Patients with primary snoring revealed peak intensities between 100 and 300 Hz. OSA patients showed peak intensities above 1000 Hz. Polysomnographical data (AHI, mean and minimum SpO₂) as well as body mass index correlated with peak intensity of the power spectrum.

Data from formant analysis also point towards the presence of higher frequencies in patients suffering from SDB.^{46,64} In a study by Sola-Soler et al., analyzing 447 snores from 8 simple snorers, and 236 normal and 429 postapneic snores from 8 OSAS patients, significant differences were found in formant frequencies variability between simple snorers and OSAS patients, even when non-postapneic snores were considered.⁶⁴ Ng et al. investigated snoring sounds of 30 apneic snorers (24 males and 6 females) and 10 benign snorers (6 males and 4 females). The snoring events were modeled using a LPC technique. Quantitative differences were demonstrated between apneic and benign snores in the extracted formant frequencies F1, F2 and F3. Apneic snores exhibited higher values than benign snores, especially with respect to F1. The study yielded a sensitivity of 88%, a specificity of 82%, and a threshold value of F1 = 470 Hz that best differentiated apneic snorers from benign snorers. It was concluded that acoustic signatures in snore signals carry information for the diagnosis of OSA.⁴⁶ Besides investigation of spectral properties of snoring events, other sound and voice analysis techniques have shown differences between apneic and nonapneic snorers as well.^{44,83}

It appears that snoring loudness and SDB are correlated. In a cohort of 1139 patients undergoing polysomnography, the levels of snoring sound intensity were significantly associated with the respiratory disturbance index (RDI), even after controlling for demographic and clinical factors.⁵⁹ Patients with L_{Eq} values ≥ 38 dBA were 3.44 (95% CI, 1.99–5.95) times more likely to have an RDI ≥ 10 after controlling for different confounders. Thirty-one patients with a documented absent history of stopped breathing during sleep had significantly lower average L_{Eq} values than 290 subjects with a known history of SDB, respectively: 44.3 (95% CI, 41.2–47.4) vs 47.7 (95% CI, 46.7–48.6) dBA ($p = 0.028$). A very significant difference in sound intensity was noted between apneic and nonapneic snoring patients. Whilst the L_{Eq} and the peak values for L_1 and L_5 were more than 5 dBA louder for apneic snoring patients with an RDI of ≥ 10 than they were for nonapneic snoring patients with an RDI of < 10 , no cut-off point was proposed that would discriminate both groups from each other.⁵⁹

In recent years, several investigators have embraced the notion that snoring carries acoustic information on the presence of SDB. Accordingly, the hypothesis has been tested that acoustic analysis of snoring may provide clues to the diagnosis of OSA syndrome, or at least to the identification of subjects who are at risk for having the disease. Abeyaratne et al. proposed a paradigm to solve the issue of defining a snore.⁵² They figured out that sounds perceived as 'snores' by humans are characterized by repetitively released packets of energy, which are responsible for creating the vibratory sound particular to snores and which define the 'pitch' of snoring. Moreover, snoring periods are characterized by discontinuities in pitch, which were termed 'intra-snore-pitch-jumps' (ISPJ). 'ISPJ

probability' was introduced as a model to assess pitch jumps and seemed to correlate with the presence of OSA. When applied to a clinical database, ISPJ yielded OSA detection sensitivity of 86–100% whilst holding specificity at 50–80%. This method thus carries the potential for the development of a suitable screening tool for OSA.⁵² Other models have used variability of snore parameters,⁸⁴ and logistic regression fed by several parameters from the time and frequency domains.⁸⁵ Such models can be adjusted to obtain maximum specificity with a sufficient corresponding sensitivity to identify good candidates for subsequent polysomnography. However, screening methods based on the analysis of snoring sounds must be validated in large target populations before they can be introduced for everyday clinical practice. Moreover, they should be further developed in a way that severity of SDB can be predicted, and not merely the presence or absence of OSA, defined by an arbitrary cut-off value for AHI.

Anatomical site of snoring

Palatal surgery is a treatment option for snoring. It is a common principle, endorsed in contemporary ENT-literature, that patients whose snoring is not associated with flutter of the soft palate should be excluded from surgery.⁵¹ It is nowadays regular practice to assess the primary snoring site using nasendoscopic examination of the pharynx under intravenous sedation. This technique was introduced by Croft and Pringle,⁸⁶ and is widely employed in ENT medicine to evaluate whether the source of the snoring sound is palatal or not. The commonly used term 'sleep nasendoscopy' is misleading because either midazolam or propofol are administered during these procedures. These drugs induce artificial sleep which may significantly alter the physiological characteristics of natural snoring, as is explained below.

Comparative research of visual and acoustic assessment techniques has been incited by the belief that sound analysis by itself could disclose the different mechanisms of snoring. Sound analysis requires neither sedation nor nasopharyngeal instrumentation, and can therefore be applied during normal night time sleep. The different trials that have compared anatomical locations of snoring with acoustic findings are summarized in Table 2.^{13,51,87–92} The key observation of these studies is that the sound energy spectrum of palatal snoring lies in the lower frequency sub-bands, whereas tongue base snoring has an energy content in the higher frequency regions. This has been shown consistently using different markers of spectral analysis, including fundamental frequencies,⁹⁰ center frequencies,^{51,87,91} peak frequencies and power ratios.⁸⁷ In one study it was noticed that the palatal flutter type of snoring occurred with the oral airway closed, whereas the mouth was open in the tongue base type of snoring.⁵¹ Whilst the acoustic spectrum of palatal vs nonpalatal snoring is clearly different, the figures on the respective frequencies vary considerably in the literature. Reported center frequencies are highly divergent (mean figures for palatal vs nonpalatal snoring): 420 vs 650,⁵¹ 391 vs 1094,⁸⁷ and 69 vs 117.⁹¹ Differences in acoustic analysis techniques or in the signal acquisition method may have accounted for these discrepancies. Furthermore, it appears that multisegmental snoring can hardly be distinguished from monolevel palatal snoring.^{87,90,91} Therefore, acoustic analysis techniques alone are insufficient if certainty about monolevel snoring is required before initiating surgical treatment.

Some authors, however, were unable to find consistent results using spectral analysis methods or observed that snoring is not steady state and thus changes in the course of sleep.³⁶ Palatal snoring is characterized by a series of high energy impulses, with frequencies ranging from 20 to 100 Hz.^{36,51} The crest factor of these snores is higher than their tongue base counterpart, the cut-off value being 2.70.^{36,88} The crest factor in naturally occurring snoring

changed significantly in an overnight study in three out of five habitual snorers.⁸⁹ The authors inferred that the snoring mechanism may change in some individuals during the night and concluded that a single recording, as in sleep nasendoscopy, may not be representative.

There is recent evidence to accept that induced sleep nasendoscopy is flawed. Naturally occurring snores have a higher energy content in the low-frequency sub-bands than snores induced by either midazolam or propofol.^{13,87} Therefore, they have a more 'palatal' character. It is likely that sedating agents add a tongue base component to snoring during induced sleep.⁸⁷ In an elegant study in which 21 patients were enrolled, overnight snore recordings and subsequent sleep nasendoscopic examination were performed using incremental steady-state sedation levels of propofol.¹³ At each sedation level snoring sound was recorded. Snoring loudness increased significantly, whilst energy ratios for low-frequency bands decreased significantly as sedation levels increased. A significant difference between natural snoring and snoring induced at the lowest sedation level was shown. As a conclusion, doubt was casted on the pretence that the technique of sleep nasendoscopy is a suitable predictor for the outcome of snoring surgery.¹³

Snoring sound analysis and outcomes of treatment for snoring

Different medical and surgical options are available for the treatment of snoring. Literature on the effect of drugs is limited to one randomized controlled crossover trial, showing a moderate effect of protriptyline on snoring in 14 nonapneic snorers.⁹³ Continuous positive airway pressure (CPAP) is the treatment of choice for OSA patients. CPAP effectively controls snoring at therapeutic pressure levels.⁹⁴ There are currently two frequently applied treatment modalities for snoring without significant SDB: the use of mandibular advancement devices (MAD) and palatal surgery.

MAD increase oropharyngeal and hypopharyngeal dimensions and may improve snoring and mild forms of SDB. High satisfaction rates have been reported in patients who continue treatment with MAD for a prolonged time.⁹⁵ However, most of the evaluations of therapeutic efficacy were based on questionnaires. Only few trials involved actual measurement of snoring noise. In one study, the effects of MAD on snoring and OSA were evaluated after a few months of treatment in 57 subjects with habitual loud snoring, 39 of whom had an AHI ≥ 10 .⁹⁶ Snores were scored where inspiratory noise was greater than 5 dB above background. Snores per sleep minute, corrected for time in apnea, and sound intensity of snores (% snores ≥ 50 dB) decreased with MAD from 11.0 ± 5.8 and $42.0 \pm 25.0\%$ to 9.0 ± 6.0 ($p < 0.01$) and $26.2 \pm 25.2\%$ ($p < 0.01$), respectively.⁹⁶ In another study, 60 patients with a chief complaint of snoring with or without apnea were enrolled.⁹⁷ Each patient underwent a home sleep test at baseline and following 3 weeks using MAD. A statistically significant improvement was found in the number of snores per hour, maximum and average snoring loudness and the percentage of palatal snoring.⁹⁷ In contrast, in a recent prospective case series of 15 individuals with confirmed simple tongue base snoring, the use of MAD resulted in a significant decrease of the 'spouse dissatisfaction scale' but no significant difference in the objectively assessed snoring index. It was concluded that the subjective benefit could have been due to a placebo effect.⁹⁸ It is obvious that further randomized controlled studies with sufficient power are needed to gauge the effect of MAD on snoring events.

Palatal surgery is frequently carried out for socially disturbing snoring. To date, there are only few rigorously performed, randomized controlled clinical trials relating to snoring surgery. Of

Table 2
Acoustic findings in snoring produced at different anatomical sites.

Publication date	First author	Subjects	Methods and outcomes	Findings	Discussion
1990	Schafer ⁹²	5 children with SDB 1 adult with chronic snoring	A comparison between time series of spectral density and mean power spectra	Simple snorer: frequency spectrum with a low-frequency component and a lot of harmonics Children with apnea: a lack of low-frequency components and harmonics	'Simple snoring' in the adult is caused only by vibrations of the soft palate 'Apneic' snoring in the children has a pathomechanism of enlarged adenoids, tonsils, causing an impeded movement of the soft palate Craniofacial anomalies are characterized by special spectral patterns
1996	Quinn ⁵¹	10 subjects with nonapneic snoring	Sleep nasendoscopy (sedative used not mentioned) and simultaneous snore sound recording Analysis of waveform and frequency to differentiate the snore sites	6 subjects: snoring at the level of the soft palate 3 subjects: snoring at the tongue base level 1 subject: snoring at soft palate and tongue base levels	Distinct difference of the waveform and frequency patterns between palatal flutter snoring and tongue base snoring Differentiation between different snoring sites seems possible
1998	Miyazaki ⁹⁰	65 male and 10 female subjects	Daytime polysomnography after administration of zopiclone and simultaneous recordings of intraluminal pressures of the UA Comparison of snoring sound with the amplitude of the respiratory pressure swings at the level of the epi-, meso-, and hypopharynx and esophagus	Snoring type strata resulting from intraluminal pressure measurement: Soft palate: 28 subjects Tongue base: 14 subjects Combined: 27 subjects Larynx: 6 subjects Fundamental frequencies of the snores: Soft palate: 102.8 ± 34.9 Hz Tonsils/tongue: 331.7 ± 144.8 Hz Combined: 115.7 ± 58.9 Hz Larynx: ± 250 Hz	Acoustic analysis of snoring sound is useful as a supportive screening method to diagnose the site and grade of upper airway obstruction during sleep Intraluminal pressure measurement and dynamic image recordings are most accurate to assess the level of UA obstruction
1999	Hill ⁸⁸	11 adults	Sleep nasendoscopy using midazolam with direct visual confirmation of snoring site, combined with crest factor calculation to measure the degree of modulation of the palatal snoring loudness	Crest factor was significantly higher in the palatal group of 6 subjects (cut-off value: 2.70) The nonpalatal group consisted of epiglottic (1), hypopharyngeal (2) and tongue base snoring (2 subjects)	The palatal and nonpalatal snorers can be distinguished by their crest factor. This method is possibly useful as a non-invasive diagnostic technique
2000	Hill ⁸⁹	3 male and 2 female subjects	Naturally occurring snores (15) were recorded at different times in the same night Crest factor was calculated	In some recordings crest factor showed good reproducibility, but in others marked changes were observed an hour apart	The snoring mechanism may change in some individuals during the night, with or without a change of the snore site A single recording, as in sleep nasendoscopy may not be representative for showing the sites of snoring overnight
2002	Agrawal ⁸⁷	16 subjects	Nasendoscopy using either midazolam or propofol to observe the site of snoring in comparison with recording of natural and sleep induced snores to compare their frequency spectra	Significant differences in MPR and CF between induced and natural snores for 12 palatal snorers, but no differences in PF Induced snores showed a higher frequency component than natural snores	Nasendoscopy may not accurately reflect natural snoring
2004	Saunders ⁹¹	27 male and 8 female subjects (mean AHI 10.4)	Nasendoscopy using midazolam and incremental doses of propofol in comparison with acoustic analysis to distinguish palatal, tongue base and multisegmental snoring	Data on CF showed values <90 Hz for palatal and >90 Hz for tongue base snoring; CF did not identify multisegmental snoring Blind assessment of waveforms of individual snores gave poor accuracy and poor interobserver agreement	Acoustic analysis will unlikely replace sleep nasendoscopy
2006	Jones ¹³	20 male and 1 female subjects (AHI < 15)	Comparison of the acoustical analysis between the inspiratory sound of natural snoring versus sedation-induced snoring (propofol) The nasendoscopy was performed at sequentially increasing, steady-state sedation levels of propofol	Loudness (dBA) increased significantly with increasing sedation levels Energy ratios for different low-frequency sub-bands decreased when sedation level increased A significant difference between natural snoring and snoring induced at the lowest sedation level was shown No significant effects were found regarding snore duration and periodicity (%)	There is a significant difference in acoustic characteristics between sedation-induced snores and natural snores Further research is needed to determine if sleep nasendoscopy is a valid predictor of outcome of snoring surgery

SDB: sleep-disordered breathing; UA: upper airway; MPR: mean power ratios; CF: center frequency; PF: peak frequency.

those that do exist, only few have utilised acoustic changes of snoring sound as objective outcome measurements. Whilst beneficial effects on objectively measured snoring were described in two publications,^{99,100} most studies reported no significant reduction of snoring sound intensity, even though subjective improvement was observed by some patients and their bed partners.^{99,101,102} In a carefully designed study, Jones et al. investigated the effectiveness of palatal surgery for nonapneic snoring in 35 patients.¹⁰³ They were admitted pre- and post-operatively for audio recording of snoring sound and video recording of sleeping position. Sound files, comprising the inspiratory sound of the first 100 snores whilst sleeping in a supine position, were analyzed for snore duration (s), loudness (dBA), periodicity (%) and energy ratios for low-frequency bands. Whilst no patient was cured from snoring, statistically significant changes were found between pre- and early post-operative recordings for snore periodicity and energy ratios in the low-frequency ranges. Only the

Research agenda

- In the literature, data on sound quality of different types of snores are inconsistent. A considerable lack of uniformity in methodological approach may account for this observation. Standardization of hard- and software as well as type and placement of microphones is necessary to allow reproducibility of data recording and comparison between groups. An international Task Force of physicians and engineers should elaborate guidelines on recording and analysis of snoring sounds. Moreover, an operational definition of 'snoring' should be provided. Appropriate methods for unequivocal classification of snoring vs other events are to be elaborated.
- It is widely accepted that subjects who show palatal snoring are the best candidates for palatal surgery. This contention is still an unproven hypothesis. Comparative studies on the effects of palatoplasty in palatal, tongue base and multilevel types of snoring are lacking. Until clear differences in surgical outcomes between these groups are demonstrated, selection of 'palatal types' of snoring patients for surgery may be superfluous.
- Most publications on the effects of palatal surgery disclose large differences between subjective (questionnaires) and objective (sound measurement) assessments of residual snoring. This may be explained as a placebo effect or perceptual adjustment of the observer. An alternative account could be the eventuality that subtle changes in quality of the noise may significantly reduce the annoying effect of snoring. This possibility deserves further investigation.
- Concealed acoustic information in snoring events that points to the presence of SDB is an ongoing line of research. The question, however, is not the presence or absence, but the degree of SDB. "Is there a correlation between snoring events suspect for SDB and the AHI?" could be a relevant research question. Moreover, the acoustic information in snoring that occurs during obstructive hypopneas (e.g., the crescendo pattern of the sound during consecutive inspiratory phases) is still a virgin territory.
- There may be a role for acoustic interventions in the management of socially disturbing snoring. Active noise reduction is a recently developed technology that is employed to diminish ambient noise (e.g., in aviation), and that may find an application in masking the snoring volume of the bed partner.

Practice points

- While the acoustics of snoring, as a medical science, is still in a stage of pioneering, some techniques can by now be applied in clinical practice. Counting the number of snores on polysomnography is feasible with modern equipment. Measuring sound pressure levels and showing snoring events in the time domain can be easily performed with commercial devices. It is recommended to perform some kind of acoustical evaluation before and after treatment with MAD or palatal surgery.
- Induced sleep is not natural sleep. Results from drug-induced sleep nasendoscopy should be corroborated with adequate nocturnal recordings of naturally occurring snores. Only if an agreement between these two evaluation methods is found, sufficient reliability about the site of snoring can be assumed.
- If acoustic assessment techniques show only mild to moderate snoring, which would be in contrast with serious complaints by the bed partner, one should take into account the psychological factors that to some extent make up the degree of annoyance. Perceptual issues and relational attitudes may be relevant. Psychoacoustic analysis of snoring sounds, though expensive and time-consuming, could be used as a more precise way to describe the symptom of snoring. Psychological counselling may be indicated in some selected cases.
- That snoring without apneas and hypopneas has no medical relevance is an oversimplification. Loud snoring in the absence of SDB may produce upper airway inflammation, and, especially in children and women, may be a cause of excessive daytime somnolence. A trial with CPAP-treatment may be warranted to prove this cause-effect relationship.

0 to 250-Hz energy ratio measurements maintained a statistically significant improvement at the time of the late post-operative recording, despite an obvious drift back to pre-operative levels. The subjective and objective results correlated poorly. The authors concluded that following palatal surgery changes in the acoustic parameters of snoring sound are demonstrable but short-lived. Finally, acoustic analysis methods have so far proven unreliable regarding prediction of treatment response to palatal surgery.^{104,105}

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