Snoring: the silent signal in sleep medicine

Ronco: o sinal silencioso na medicina do sono

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ABSTRACT
Snoring is highly prevalent, increases with age and is greater in men. The prevalence rates of snoring in the general population are variable, ranging from 20 to 60%. However, all population-based studies used the subjective analysis of snoring evaluated by questionnaires. Snoring is the major reported signal that may indicate obstructive sleep apnea (OSA). The polysomnography study, which is the golden standard test for the diagnosis of OSA, frequently uses the vibration recording by a sensor located on the patient’s neck. However, this signal is not calibrated and has no correlation with sound intensity. To date, there is no consensus on the methodology of the acquisition and analysis of the snore signal. This review article evaluates methodological studies that report on snoring recording equipment and correlate the snoring signal with OSA. Using the keywords “Snoring” and “Obstructive Sleep Apnea” in PubMed, we found 602 articles, however there were only 11 studies (1.8%) that reported on technical aspects regarding snoring recording and analysis. The selected articles showed a wide variability in the method of recording, as well as analysis of the snoring signal. The lack of technical studies on snoring reflects a major gap in Sleep Medicine. Recent data obtained by objective measurements showed that snoring intensity correlates with OSA severity. In addition, snoring recordings represent a promising new noninvasive tool for the diagnosis of OSA. We conclude that snoring is a poorly monitored signal and that more studies are warranted in this fundamental area of Sleep Medicine.

Keywords: snoring; sleep apnea, obstructive/diagnosis; palate, soft/physiopathology; body mass index; polysomnography; respiratory sounds.

RESUMO
O ronco é extremamente prevalente, sua incidência aumenta com a idade, sendo mais frequente no sexo masculino. Sua prevalência, na população geral, varia de 20 a 60%. No entanto, os estudos clínicos de base populacional avaliaram o ronco de forma subjetiva por meio de questionários. O ronco é o sinal mais relatado que pode indicar a presença de apneia obstrutiva do sono (AOS). O estudo polissonográfico, que é o padrão-ouro para diagnosticar a AOS, frequentemente usa a gravação da vibração por meio de um sensor localizado no pescoço do paciente. No entanto, o sinal não é calibrado e não tem correlação com a intensidade do som. Até atualmente não há consenso na metodologia da aquisição e análise da gravação do ronco. Este artigo de revisão avalia estudos metodológicos sobre equipamentos de gravação de ronco e sua correlação com a AOS. Usando as palavras-chaves “Ronco” e “Obstrusive Sleep Apnea” na base de dados PubMed, foram encontrados 602 artigos, no entanto, somente 11 estudos (1,8%) tratavam de aspectos técnicos sobre gravação e análise de ronco. Os artigos selecionados mostraram uma grande variabilidade, tanto nos métodos de gravação quanto nos de análise do ronco. A falta de estudos técnicos sobre ronco reflete uma grande lacuna na Medicina do Sono. Dados recentes obtidos por mensuração objetiva mostraram que a intensidade do ronco se correlaciona com a gravidade da AOS. Além disso, a gravação do ronco representa uma nova e promissora ferramenta para o diagnóstico da AOS. Foi concluído que o ronco é um sinal pouco monitorado e que mais estudos estão garantidos nesta área fundamental da Medicina do Sono.

Palavras-chave: ronco; apnéia do sono tipo obstrutiva/diagnóstico; palato mole/fisiopatologia; índice de massa corporal; polissonografia; sons respiratórios.

INTRODUCTION
Snoring is the sound caused by the vibration of soft tissues from the upper airway, including soft palate, uvula¹, tonsils, tonsillar pillars, base of tongue, lateral pharyngeal walls, and mucous membranes². Snoring occurs during sleep, when the pharyngeal muscles relax and may block the airway. In addition, the tongue falls back by the action of the gravity contributing to obstruction, mainly in the supine position. The obstruction results in vibration of the upper airway soft tissue, causing vibratory trauma, resulting in inflammation³ and changes in peripheral nerves, which impair the pharyngeal reflexes⁴.

Snoring prevalence is extremely high in the general population. For instance, one study evaluated 5,713 individuals
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through a questionnaire and found that 24.1% of men and 13.8% of women were snorers. Tufik et al. performed a large epidemiological study in the city of São Paulo using full polysomnography (PSG) and they found that the prevalence of snoring, evaluated by questionnaire, in the general population was equivalent to 20.5%. Hiestand et al. observed that 59% of the 1,506 adults that were interviewed reported snoring. Despite the variability among studies, the prevalence of snoring is generally accepted to be around 40% in adult men and 20% in adult women. The wide variability between studies may reflect differences in the studied population. However, the major limitation is related to the fact that snoring analysis is subjective and relies on information from bed partners, who are the major listeners of snoring.

Snoring may represent a major health burden to the population for several reasons. Firstly, it may be a social problem. More importantly, snoring is usually the major signal indicating obstructive sleep apnea (OSA), which is characterized by repetitive upper airway obstruction during sleep, causing total or partial cessation of airflow (apneas and hypopneas, respectively). Most of OSA patients are snorers, however, not all the snorers have OSA. It is a public health problem since it has high prevalence and severe consequences, including loss of quality of life and increase of cardiovascular morbidity and mortality. If left untreated, OSA increases the risk of cardiovascular diseases, glucose intolerance may result in excessive daytime somnolence, fatigue, and lower cognitive function leading to an increased risk of traffic accidents. The major signs and symptoms of OSA are snoring, excessive daytime sleepiness, and witnessed apneas. Among all signs and symptoms associated with OSA, snoring is the most commonly reported. There is also recent evidence suggesting that it may cause atherosclerosis at the carotid level due to vibration independent of the presence of OSA.

Although snoring is one of the major complaints associated with OSA, it is frequently under estimated for several reasons. Firstly, snoring may not be reported by the patients and it is also not observed on physical exam. Thus, snoring is not necessarily a symptom or a sign because it is often dependent of a collateral history part witness. Secondly and more importantly, there is a lack of objective measurement of snoring. For instance, PSG is the golden standard test to detect OSA, but it frequently does not objectively record snoring. Most PSG studies record vibration by a sensor located at the patient’s neck. However, the signal reported in PSG studies related to snoring is not calibrated and do not accurately measure sound intensity. These limitations reduce the objective interpretation of reports related to snoring.

Therefore, development of methodologies capable of recording snoring with and without full PSG are necessary for the advancement of Sleep Medicine. Noninvasive sound recording could also be a useful tool for screening patients with suspected OSA. Hence, we performed a systematic review to identify and critically discuss studies that report on the methodological aspects related to snoring recording and analysis.

METHODS
We reviewed all titles related to snoring and OSA published in PubMed using the keywords “Snoring” and “Obstructive Sleep Apnea”, and the following parameters. The articles included clinical trial, meta-analysis, practice guidelines, randomized controlled trial, review, controlled clinical trial, guideline journal article, multicenter study, validation studies; species: humans; language: English, Spanish or Portuguese. The search was done in three steps. In the first step the titles of the studies that mentioned methodological aspects related to snoring were selected. In the second one, the abstract of the selected articles were read for further selection of the studies that focused on technical aspects of snoring recording and analysis. In the third step, the full articles selected were carefully evaluated and studies that correlated with this subject were selected and discussed in this review.

RESULTS
The Medline search using the methodology described above was done on November 25th 2010 and found 602 articles. The first step (title reading) found 52 articles of potential interest. Among these studies, 17 abstracts fulfilled our area of interest (step 2). After reading the 17 full studies, six were excluded for the following reasons: three articles measured the tracheal sounds through a microphone located at the patients neck, two studies used subjective analysis of snoring and in the last one, snoring was simulated by a loudspeaker. The 11 selected articles consisted all on clinical studies that objectively evaluated snoring. Interestingly enough, the method of analysis varied from one study to the other. We only found one study that mentioned a correlation between the perceived loudness of snoring and objectively measured snoring during PSG. However, the results of this pilot study were not shown. The flowchart of the studies evaluated and included in this review is presented in Figure 1.

DISCUSSION
Our review focused on snoring as a major symptom associated with OSA. It is remarkable that among 602 articles found in PubMed, with the keywords “Snoring” and “Obstructive Sleep Apnea”, we were able to find only 11 articles (1.8%) that reported on technical aspects of snoring recording and analyses. In addition, four out of the eight published studies were from the same group, and three studies reported different aspects of the same population. In addition, with a
The majority of studies used relatively small sample size (<40 patients). More importantly, the lack of publications is not related to the fact that snoring recording and analysis is a well-known and standardized signal. On the contrary, we observed no consensus in the methodology of acquisition and analysis of the snore signal across studies.

A summary of the main findings including first author, year of publication, the main methodological aspects and results of the selected studies is described in Table 1. The discussion that follows will be divided into technical aspects, including a few basic concepts regarding sound characteristics, sound recording, preprocessing and analysis, as well as the clinical significance of these studies.

### Sound characteristics

Sound is the vibration in a physical medium. The vibration causes a propagation of pressure waves that can be measured, and the unit of sound pressure is Pascal (Pa). Commonly, a given sound pressure level (SPL) $p$ is related to a reference sound pressure $p_0$. By convention, $p_0$ is equal to 20 $\mu$Pa, which is the average threshold of human hearing at 1 kHz (roughly the sound of a mosquito flying 3 m away). The logarithm of this ratio is the SPL, which is expressed in decibel (dB). The SPL is calculated using logarithm measure, because it fits better to human perception of loudness than a linear measure.

### Sound recording

Sound recording is extremely dependent of the distance between the snoring source (nose and mouth) and the microphone. Therefore, much attention should be given to the position of the microphone. The recordings of sound reflected by objects, like the bed, ceiling, furniture, and walls should be minimized. The space where reverberation is relevant is named indirect field, whereas in the direct field the relative amount of reflected sound is negligible. An environment microphone should be placed in this direct 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. However, most studies do not report potential problems regarding snoring recording.

We have found four main methods of sound acquisition, which include: a sound meter for measuring the snoring intensity; two microphones placed 50 cm far from the mouth of the patient; one microphone located 30 cm above the mouth of the patient; and a microphone cannula. Maimon and Hanly used a digital sound meter to record the
### Table 1. Summary of the selected articles.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Subjects</th>
<th>Recording</th>
<th>Methods</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>30 apneic snorers and 10 benign snorers.</td>
<td>One microphone 30 cm above patient’s mouth, during PSG.</td>
<td>Inspiratory snores were examined using two novel markers, namely peak frequency component at f1 (PF1) and peak sum frequency (PSF).</td>
<td>PF1 and PSF are indicative of apneic and benign snores, with optimal thresholds of PF1=285 Hz and PSF=492 Hz.</td>
</tr>
<tr>
<td>33</td>
<td>30 snorers with OSA and 10 snores without OSA.</td>
<td>One microphone, 30 cm above patient’s mouth, during PSG.</td>
<td>Recorded snore signals were modeled using a linear predictive coding (LPC) technique. Formant frequencies were extracted from the LPC spectrum for a comparison.</td>
<td>Apneic snores exhibit higher formant frequencies than benign snores.</td>
</tr>
<tr>
<td>34</td>
<td>30 snorers with OSA and 10 snores without OSA.</td>
<td>One microphone, 30 cm above patient’s mouth, during PSG.</td>
<td>Enhancement of snore signal via a LCD threshold, and identification of snore presence through a snore activity (SA) detector.</td>
<td>Proposed LCD threshold and SA detector are highly comparable to the existing denoising methodologies.</td>
</tr>
<tr>
<td>35</td>
<td>9 apneic and 7 benign patients.</td>
<td>One microphone, 30 cm above the patient’s mouth, during PSG.</td>
<td>Bispectral analysis was performed on the snores.</td>
<td>Apneic snorers have stronger presence of nonlinear interactions.</td>
</tr>
<tr>
<td>36</td>
<td>1,643 habitual snorers.</td>
<td>Digital sound meter during PSG.</td>
<td>Average peak of 30 second epochs.</td>
<td>Snoring intensity correlated with OSA severity.</td>
</tr>
<tr>
<td>37</td>
<td>16 patients as training set and 29 patients as testing set.</td>
<td>Two microphones, 50 cm far from the patient’s mouth, during PSG.</td>
<td>Novel feature termed the ISPJ.</td>
<td>Snore sounds and the proposed methods have the potential to be good candidates for a take-home device for OSA screening.</td>
</tr>
<tr>
<td>38</td>
<td>86 subjects</td>
<td>Two microphones, during PSG 50 cm far from the patient’s mouth, during PSG.</td>
<td>Novel feature that quantifies the non-gaussianity of individual episodes of snoring.</td>
<td>Apnea Count Index (ACI) could be optimized and adjusted to various diagnostic AHI values. When AHI=10, the detectability is 97.34%.</td>
</tr>
<tr>
<td>39</td>
<td>60 male patients with reported snoring.</td>
<td>One microphone, 30 cm above the patient’s head, during PSG.</td>
<td>FFT, and peak intensity was determined from the power spectrum.</td>
<td>Patients with primary snoring revealed peak intensities between 100 and 300 Hz, patients with OsAS revealed peak intensities above 1000 Hz.</td>
</tr>
<tr>
<td>40</td>
<td>456 patients (ages from 2 to 15 years old).</td>
<td>Microphone cannula device placed on the patient’s upper lip.</td>
<td>Acoustical analysis measurements: snoring index, palatal flutter snoring, average loudness, maximal loudness and palatal flutter frequency.</td>
<td>Snoring index and maximal loudness were directly proportional to AHI. BMI was associated with snoring index and predominant palatal snoring.</td>
</tr>
<tr>
<td>41</td>
<td>31 patients.</td>
<td>Microphone cannula device that is placed on the patient’s upper lip.</td>
<td>The author reported that the methods of computer and software analysis were not disclosed by the company.</td>
<td>The severity criteria accurately confirmed 35.5% of OSA diagnosis, while the scores were overestimated in 41.9%. The system used does not appear to accurately assess the severity of OSA.</td>
</tr>
<tr>
<td>42</td>
<td>5 regular snorers and 5 OSAS patients.</td>
<td>One microphone, a sound recorder recorded a one-minute episode.</td>
<td>Detection and identification of snoring and OSAS symptoms in real time by analyzing the temporal features of the snoring sound.</td>
<td>This detector showed a good performance in detecting snoring, and achieved an average sensitivity of 94.0% and an average positive predictive value of 94.0%.</td>
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</table>
snoring synchronously with the PSG recording. The authors used information about the snoring intensity to analyze and correlate them with OSA. However, the study did not clearly explain the exact position of the sound meter in relation to the patient. Similarly, Cheng et al. developed a method of telemonitoring snoring and OSA syndrome symptoms through a portable device, the limitation of this study is that the proposed device is not intended to be a diagnostic device for OSA, instead, it is to be used as a home appliance or as a precautionary measure for monitoring snoring and OSA. Two other studies used a pair of matched low-noise microphones having a hypercardioid beam pattern. The microphones were placed 50 cm from the mouth of the patient, ranging from 40 to 70 cm with the patient movements. Herzog et al. used an external microphone to record the snore signal, it was also positioned 30 cm above the head of the patient. Since the signal was not calibrated, snoring sounds were expressed as arbitrary units. Four other studies from the same group used a noncontact unidirectional condenser microphone, which was placed about 30 cm above the mouth of the patient. One alternative method of recording snoring is a microphone cannula device that is placed on the subject’s upper lip during sleep. Usually, the microphones applied in the studies detected frequencies from 20 to 20,000 Hz.

Preprocessing

Most of the analyses performed in the mentioned articles are complex to the majority of health professionals, especially those who are not used to work with mathematical equations and signal processing. However, it is clear that the technical aspects vary across studies. The common aspects are: the analog signal from microphones are pre-amplified, filtered, and converted to digital to be processed by a personal computer. A consensus among PSG technologists is that the noise is always present in the recorded signal, most coming from air conditioners and computers, without neglecting electromagnetic interferences from different sources in the hospital. In this respect, several manuscripts deal with the problem of noise elimination in order to improve the snore signal.

In two studies, the sound acquired was pre-amplified and converted using an A/D (analog to digital) converter unit, in one paper, the sample rate used was 44.1 kHz and the resolution of 16 bits/sample, while the other one used 2 kHz and 10 bits/sample, respectively. One research group used the microphone that captures snoring connected to a low-noise pre-amplifier (20 to 22000 Hz) through a double shielded coaxial cable to minimize stray electromagnetic interference.

Reporting snoring

After acquiring snoring signal, the last task is a meaningful expression of the results. There must be a balance between simplicity and clinical applicability (a snoring index similar to the apnea-hypopnea index that describes sleep apnea severity) versus the accuracy of the result, which may involve aspects that are difficult to be understood by clinicians.

Maimon and Hanly expressed the results as a mean of high values, i.e., this value represented the maximum value mean of the snoring intensity of all 30 second epoch. The positive aspect of this method is that it reports one single value, which may summarize the intensity of snoring across the night. On the other hand, this approach may damp and not fully express the intensity of snoring for several reasons, including the fact that several respiratory events are longer than 30 seconds (that would produce epochs with low-sound intensity in patients with severe OSA and intermittent loud snoring). In addition, patients may present very loud snoring during parts, but they may not be at night.

Abeyratne et al. scored the collected data into one of three classes (silence, snore and pure breathing, and speech). The authors proposed a new measure called intrasnore pitch jump (ISPJ) probability to capture intrasnore jumps in pitch to diagnose OSA.

Ghaemmaghami et al. used a new method of snore signal analysis that calculates a non-Gaussianity index (NGI) in OSA diagnosis. The NGI provides a measure of non-Gaussianity of a given signal and this feature was employed to mark possible apneic episodes in analyzed snore sound recordings.

Herzog et al. used fast Fourier transformation (FFT), which consists on a computational algorithm that decomposes a signal into components at different frequencies. The mean value of the peak intensity measurement for three to five single events of inspiratory snoring was taken for further calculation, using FFT. The author also classified the snoring periods according to their rhythmic (rhythmic snoring without apneic events) or nonrhythmic (five consecutive obstructive apneic events with an end-apneic snoring) characters.

Another approach is the use of wavelet bicoherence (WBC) analysis in the snore signal. WBC is widely accepted because of its ability to decompose a signal into both time and frequency, simultaneously. One study used WBC to carry out two important tasks, namely snore signal enhancement through a level-correlation-dependent (LCD) threshold to reduce additive noise embedded in the raw snore signals, such as the noise generated by an air conditioner; and snore activity (SA) detection that identifies the snore segments and other sleep sound boundaries. Another study used WBC analysis and performed bispectral analysis, which reveals the non-Gaussian and nonlinear information, identifying phase relationship of signals between different frequency bands. This allows the detection and characterization of nonlinear mechanisms, the upper airway in the study, which produces time series through phase relations of their harmonic components.

Oliveira CBG, Silva DGV, Moriya HT, Skomro R, Alencar AM, Lorenzi-Filho G

A different approach used formant frequencies of snore signals to diagnose OSA. Formant frequencies are resonances in the upper airway, manifested as the maximal energy at the resonant frequencies, and could be identified by peak-picking the linear predictive coding (tool used in speech analysis to define a vocal tract filter) spectrum. For each patient, 40 snores were selected over the night recording. The first 30 snores were used as training data to compute the formant frequencies and create an optimum threshold value using the receiver operating characteristic (ROC) curves, while the remaining ten snores were used as testing data to assess the sensitivity and specificity of the derived threshold value.

In conclusion, there are several formats of analyzing and expressing the snoring results. The lack of consensus across studies reflects the complexity of sound analysis and helps to explain the lack of interest in this area by the Sleep Medicine field.

Clinical relevance of measuring snoring

The lack of standardized methods to measure snoring helps to explain why the prevalence of snoring in the general population varies so widely across studies. However, snoring is an important signal to measure as it correlates with presence and severity of OSA. For instance, Maimon and Hanly recorded snoring in a large series of patients submitted to PSG. The authors found that snoring was louder in men than women, in patients with body mass index (BMI) >30 kg/m², neck circumference >40 cm, and while in the supine position and during non-REM sleep stage. The mean maximum snoring intensity (mean peak value of each epoch) increased linearly with the severity of OSA. These results may seem obvious, but it is important to stress that there is little objective report of snoring in the literature.

Analysis of snoring opens the possibility of OSA diagnosis with no manipulation of the patient. The concept behind this approach is that snoring is irregular during repetitive respiratory events (apneas and hypopneas) and that the appropriate analysis of the sound pattern may accurately predict the apnea-hypopnea index derived from full PSG. Liesching et al. found only a fair agreement between the severity of sleep apnea and the results obtained by sleep sonography using sleep apnea and snoring analysis in the investigation, through a commercial device named “SNAP” technology (developed by SNAP Laboratories), which records snoring through a microphone cannula placed in the upper lip. Ghaemmaghami et al. reported a remarkable 97%-accuracy to detect OSA using a complex analysis through the NGI. This mathematical approach is able to detect period oscillations in sound intensity, and according to the authors, it was able to accurately correlate with the apnea-hypopnea index.

In addition to the pattern of snoring periodicity that may correlate with OSA severity, more subtle information may be derived from sound analysis. Herzog et al. showed that patients with OSA had no rhythmic repetitions of sound intensities, the spectral view of the snoring event showed a broad noise between 3,000 and 4,000 Hz and harmonic intensity peaks were not seen in the FFT, while patients without OSA revealed rhythmic repetitions of sound intensity, low frequent harmonics up to 500 Hz and multiple harmonic intensity peaks in the FFT. One study using WBC concluded that the sharpest peak of apneic snore is usually located away from the origin and has higher bispectral peak amplitude, while benign snore is sited near the origin and has lower bispectral peak amplitude. Another study, which worked with formant frequencies of snore signals, found quantitative differences in the formant frequencies of apneic and primary snoring without apnea. Apneic snores occupy higher frequency ranges than patients with primary snoring. Abeyratne et al. launched the hypothesis that jumps between the snoring peaks captured by their novel device, named ISPJ probability, will enable them to diagnose OSA based on snore sounds alone.

CONCLUSION

Snoring is currently not properly recorded and analyzed by the Sleep Medicine. The use of a standardized method to record and analyze snoring is needed in order to compare studies of OSA and snoring and to advance this field. Snoring recording is also a promising, inexpensive, and noninvasive method for the OSA diagnosis.

REFERENCES


