AUTOMATIC SCORING OF SLEEP APNEA AND HYPOPNEA BY ANALYSIS OF MANDIBULAR MOVEMENTS

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ABSTRACT
In this paper, we propose a method for sleep apnea and hypopnea detection by analyzing the mandibular movements recorded during sleep. This signal, highly correlated with the esophageal pressure during apnea or hypopnea, is a good marker of respiratory efforts. The respiratory efforts and their background activity are used to detect salient mandibular movements that occur after sleep apnea and hypopnea, to delineate and to recognize episodes of sleep apnea and hypopnea. The method presented may be extended to others breathing disorders such as Respiratory Efforts Related Arousals (RERA).

KEY WORDS
sleep apnea, mandibular movements, esophageal pressure, respiratory efforts, snoring.

1 Introduction

More than 4% of adult males and 2% of adult females of Western countries suffer from the Obstructive Sleep Apnea/Hypopnea Syndrome (OSAHS). Sleep apnea and hypopnea (SAH) belong to a wider family known as Sleep Disordered Breathing (SDB). SDB has many origins: a partial or total occlusion of the upper airways causes obstructive apnea and hypopnea, a lack of central motor-neural respiratory drive causes central apnea, etc…SDB can bring about severe damage to central nervous system and physical disorders.

An apnea occurs when someone stops breathing while sleeping. By definition, an episode of apnea occurs if the magnitude of the respiration movements are decreased to less than 20% of the normal values for at least 10 s. Similarly, an episode of hypopnea occurs when the movements are decreased below half the normal values [1]. The severity of the OSAHS is measured by the apnea-hypopnea index (AHI), the number of apnea and hypopnea per sleep hour.

The effects of SAH can be seen on many physiological signals. In addition to the variations of the nasal airflow that define sleep apnea and hypopnea, the obstruction leads to an increase of the esophageal pressure manifested as respiratory efforts. Blood oxygen saturation (SaO2) falls because no gas are exchanged. Heart rate and blood pressure are also increased leading to possible cardiovascular damage. The central nervous system is also disturbed at the end of more than 70% of all apnea [2, 3]. Such micro-arousals, whose latency and intensity depends on the type of sleep disorder, fragment the sleep structure [4, 5].

The common signals used to screen apnea and hypopnea, both in polysomnography and in ambulatory screening method, are SaO2 and heart rate (both recorded by a pulse oxymeter), nasal airflow and abdominal and/or thoracic movements [6]. However, another physiological signal is very useful for screening SDB: the esophageal pressure. On the one hand, it is probably the best signal for screening all types of breathing disorders. On the other hand, the sensor must be placed in the esophagus; it is invasive and may alter sleep.

However, R. Poirrier showed that vertical mandibular movements are correlated with the esophageal pressure during sleep apnea and hypopnea [7]. For his study, an ambulatory medical device with a non-invasive sensor has been developed to record the jaw motion during sleep [8].

Even if SDB can be screened through the analysis of mandibular movements, no consensus presently exists regarding visual scoring rules for all breathing disorders, especially for Respiratory Effort Related Arousals (RERA) [9–11] and for snoring, except for apnea and recently for hypopnea [12]. Thus, the method proposed here applies only to SAH. More specifically, screening of other breathing disorders is outside the scope of this paper.

K. Miyamoto et al. [13] have reported a statistical analysis of the mandibular posture for patients with obstructive sleep apnea. Their study shows that vertical mandibular posture is more open during sleep apnea than in healthy patients. The study also points out significant mandibular opening during obstructive apneas in NREM sleep. In REM sleep, the muscle atony attenuates these movements.

In this paper, the vertical mandibular posture signal is analyzed to delimitate regions related to SAH using a time-domain rule-based approach. This approach allows interpretation and easy modification of the decision rules.
Figure 1. Each subfigure shows mandibular opening (in % of mouth closure) as a function of time. The four typical patterns of SAH are obstructive apnea (a and b), central apnea (c) and hypopnea (d). The clinical score of SAH made with the nasal airflow (not shown here) appears as a line labelled A for apnea and H for hypopnea. The salient mandibular movement, pointed by a bold arrow and appearing after the offset (or end) of the SAH, can be a Hard Closure Transition (a), a Hard Opening Transition (b) or a Smooth Closure Transition (c and d). Respiratory efforts appear as oscillations of the mandible and are correlated with esophageal pressure. Typical patterns of non-SAH events are (e) healthy sleep, (f) snoring, (g) awake and (h) artefact (swallowing).

The signal is sampled at 10 Hz. This is a higher rate than in [13] (0.5 Hz), so that faster movements can be tracked. In addition to the mandibular movements correlated with the respiratory efforts (RE), three salient events appear after a SAH. They have been called hard closure transition (HCT), hard opening transition (HOT) and smooth closure transition (SCT). Thus, the method described here successively detects these three salient events, delineates regions of interest (ROI) likely to contain a SAH, and classifies simply ROI as SAH or not. The end of a ROI is given by the salient event and its beginning is found by a backtracking analysis of the RE starting at the salient event. The classification is performed by a local and contextual analysis of RE on several successive sufficiently close ROIs. Currently, the classification step is a dichotomic problem: a ROI is either a SAH or not. Although physicians’ observations seem to mean that classification of SAH into obstructive apnea, central apnea or hypopnea is possible (see Fig. 1), this problem is quite difficult and it is not addressed here. However, the presented method provides encouraging results making a good starting point for such a finer classification.

2 Methods

2.1 Subjects and recordings

Twenty cases of OSAHS were studied. For all of them, a standard polysomnography (PSG) was recorded in a hospital setting. The PSG is a multichannel recording composed of at least the electroencephalogram (EEG), electro-oculogram (EOG), electromyogram (EMG), electrocardiogram (ECG), nasal airflow, blood oxygen saturation (SaO2), thoraco-abdominal movements, snoring sounds, and body position. SAH are visually scored according to standard rules.

The mandibular opening is measured with a sensor made of two coupled resonant circuits, respectively placed just above the upper lip and below the lower lip perpendicularly to the medium line of the face. The output voltage is a cubic function of distance between them [8]. This voltage is sampled at 10 Hz, digitally linearized (voltage is now proportional to the distance), and stored in the computer synchronously with the standard PSG channels.

The resulting mandibular opening signal is subsequently normalized so it corresponds to the percentage of
mobilier

movements

For adaptive
threshold of matched filters

Extract
BAORE

Combine
thresholded outputs
of matched filters

Find the end
and the beginning of ROI
likely to contain a SAH

Perform a local and
contextual analysis of RE
and a periodicity test

Mandibular Movements

Detection of salients events

Delimitation of ROI

Classification of ROI

Figure 2. System for detecting sleep apnea/hypopnea (SAH) on the basis of the analysis of mandibular movements. Salient events that occur at the end of the SAH are detected at first. Then, regions of interest, likely to contain a SAH, are delineated and finally classified as SAH. BAORE = Background Activity Of Respiratory Efforts - MaMA = Maximum Mandibular Activity - ROI = Regions Of Interest - RE = Respiratory Efforts. See text for details.

mouth closure. Zero % corresponds to a wide open mouth and 100% to a full closed mouth. Normalization is performed in a two steps manual calibration. First, at the beginning of the recording, the patient opens his/her mouth fully and then closes it fully. Second, when reading the data for the first time, the operator must choose the two amplitudes of the data corresponding to a "wide open mouth" and a "full close mouth". Data are normalized between the two chosen amplitudes and saved in an EDF file (European Data Format) with other channels if desired.

2.2 Typical patterns and their main features

According to [7] and to our own observations, there are four significant classes of mandibular movements patterns one should look for. They are illustrated in Fig. 1 (two successive examples are shown for a better view). They correspond to the following three SAHs: obstructive apnea (1.a and 1.b), central apnea (1.c) and hypopnea (1.d). The clinical score made with the nasal airflow (not shown here) underlines the apnea (A) or the hypopnea (H) and defines its onset (beginning) and its offset (end). The oscillations (frequency band [0.2-0.4] Hz) clearly visible in Fig. 1.d are those correlated with esophageal pressure. Thus, these oscillations are characteristic of the respiratory efforts (RE). These respiratory efforts are increasing during SAH, except for the central case where no movement occurs and a burst of respiratory efforts appears after the offset. Besides, a salient event occurs after the offset of SAH (HCT in Fig. 1.a, HOT in Fig. 1.b and SCT in Fig.1.c and d are pointed by a bold arrow).

In addition to the four SAH patterns, Fig.1 also shows four normal patterns encountered in recordings: healthy sleep, Excessive Ventilatory Effort (EVE: all respiratory efforts that are not considered as SAH; there is no distinction between ventilatory and respiratory efforts in this paper), awake state and isolated artefacts (yawning, swallowing, ...). Presence, increase and high variations of RE are the three criteria for the classification of SAH (see table 1).

During a SAH, RE are present (but not in healthy sleep), increase (although movements in the frequency band [0.2-0.4] Hz may exist in the awake state, they have a "chaotic" feature) and vary sufficiently (whereas the amplitude of the RE are almost constant for EVE).

<table>
<thead>
<tr>
<th>Criteria on RE</th>
<th>Presence</th>
<th>Increase</th>
<th>High variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAH</td>
<td>y</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>Healthy sleep</td>
<td>n</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>EVE</td>
<td>y</td>
<td>(y)</td>
<td>n</td>
</tr>
<tr>
<td>Awake/Artefacts</td>
<td>(y)</td>
<td>n</td>
<td>(y)</td>
</tr>
</tbody>
</table>

Table 1. The three main criteria on respiratory efforts (RE) for sleep apnea/hypopnea (SAH) classification.

2.3 Signal processing

The proposed method is based on the analysis of the respiratory efforts (frequency band [0.15-0.8] Hz) and its background activity. The block diagram describing the method is shown in Fig. 2. The main processing steps are:

- Detection of salient events by analysis of the Background Activity Of Respiratory Efforts (BAORE) with two matched filters where an adaptive threshold ruled by the Maximum Mandibular Activity (MaMA) give the relevant events.
- Delimitation of Regions Of Interest (ROI) by analysis of the salient events giving the end of the ROI, and the respiratory efforts envelope giving the beginning.
- Classification of ROI as a SAH or not by a local and contextual analysis of respiratory efforts and by periodicity tests on RE and BAORE previously computed.
2.3.1 Detection of Salient Events

This first step plays a major role in the processing as the detection of a salient event assumes the presence of a SAH and marks the end of a ROI.

As shown in Fig. 1, the mouth is opening and then closing during and after the SAH. This movement can be symmetric (c and d) or asymmetric (a and b). Therefore, two matched filters are designed so they highlight respectively symmetric movements ("opening following by a closure" shape) and asymmetric local movements ("fast movement" shape). Moreover, the output amplitude corresponds to the relative difference of mouth closure. The behavior of the two outputs depends on the type of salient event, e.g., in the case of a HCT, a maximum of the output of local fast movement is detected after the maximum of the output of symmetric movement, and these two maxima have similar values (see Fig. 3 at time 11:14:30). Similar reasoning leads to rules comparing values of maxima and their relative position for the characterization of the three salient events.

The detection of salient events consists in the extraction of the BAORE, the application of two matched filters outputs to BAORE and the combination of the two outputs.

First, the BAORE is extracted from the input signal with morphological operators as it is done for impulsive noise suppression and background normalization in ECG [14]: opening and closing operation, performed with a unit rectangular structuring element ES1 of size a bit higher than the maximum period of respiratory efforts, are averaged

$$BAORE = \frac{opening[ES_1](\text{sig}_{in}) + closing[ES_1](\text{sig}_{in})}{2}.$$

Then, the two matched filters are applied to the BAORE. The threshold applied to the two outputs is adapted as the activity in REM sleep is lower than in light sleep because of difference in muscle tone, thus the threshold has to be lower for low amplitude activity than for higher amplitude activity. The threshold depends on the Maximum Mandibular Activity (MaMA) over one minute

$$MaMA = opening[ES_2](\text{sig}_{in} - closing[ES_1](\text{sig}_{in})).$$

with $ES_2$ an unit rectangular structuring element of one minute.

Lastly, scanning the relevant events on one output then comparing amplitude and relative position to the closest relevant event on the other output leads to the detection and the characterization of salient events.

As the role of this step is to detect a maximum of salient events related to SAH, rules and thresholds are optimized to maximize sensitivity with a reasonable specificity. To reduce false alarms, successive salient events must be distant for at least 8 seconds instead of 10 seconds by definition of an apnea or a hypopnea (as it is assumed that a SAH may exist between two successive salient events). Such consideration is very useful to detect very short SAH and to reject artefacts (swallowing for instance) occurring just after a SAH.

Background activity, matched filters outputs and salient events are depicted on the figure 3 (second and third graphs).

2.3.2 Delimitation of Regions Of Interest

As RE increase during SAH and decrease afterward, variations of these efforts are dedicated for the delimitation of regions of interest (ROI) classified as SAH in the next section.

When a salient event is detected, that event is considered as the end of a ROI. The beginning is found as the local minimum of RE envelope occurring before the previous salient event. Similarly to the detection of salient events, any ROI of less than 8 seconds are discarded. The maximal duration of a ROI is arbitrarily fixed at 90 seconds.

2.3.3 Classification of Region Of Interest

The last step is to classify ROI as a SAH or not. ROI are classified dynamically with local and contextual information on several ROI in such a way that our certainty on the past is higher than for the future. In other words, when a ROI is classified, the weight given to past information is higher than to future information since classification is already done for the previous ROI but not yet for the next ROI.

Associated with all ROI and initially set to 0, a score is computed containing an intrinsic score and a contextual score. The intrinsic score measures the increasing feature of RE with the comparison of successive maxima (and minima) of the RE. The contextual part is computed as follows: ROI are scanned and classified iteratively. At step $i$, the $i$-th ROI is classified,

- consider only $n$-successive ROI within 4 minutes centered on the $i$-th ROI (n=5). If some ROI do not exist, create empty ones. Intrinsic score and mean increase of maxima and minima of RE are already available.
- compute the contextual score for the $i$-th ROI with :
  - a periodicity test on the respiratory efforts envelope (search for a significant period with the FFT) and on the salient events (search for a significant period in the temporal distribution of local salient events);
  - a neighborhood test consisting in the comparison of own score of neighboring ROI (final score for the two previous ROI and intrinsic score for the two next ROI) and their own mean increase of RE
- add the intrinsic and contextual score of the $i$-th ROI and compare the sum to an optimized threshold to classify the ROI as a SAH.
Figure 3. Illustration of the mandibular movements analysis. The mandibular movement, visual (dash line) and automatic (solid line) scoring are given on the first graph. On the second graph, salient events come from the analysis of the background of respiratory efforts (third graph) whereas regions of interest (ROI) come from the analysis of the envelope of respiratory efforts (fourth graph). Classification of ROI is a result of a local and contextual analysis of the respiratory efforts.

The whole processing is illustrated at Fig. 3. A sequence of awake state precedes a sequence of SAH (central and obstructive apnea). Visual (dash line) and automatic (solid line) scorings are shown on the first graph where the first central apnea is missed because of the higher weight given for past information relative to well rejected awake state. Then, the next SAH are correctly recognized as the signal become a periodic sequence of SAH with increasing RE. Salient events, regions of interest and the signals used to find them are also given.

3 Results

Thresholds of decision rules have been optimized on nine recordings to maximize sensitivity and specificity. The last eleven recordings were used as a test set. Comparison of the automatic scoring and the visual scorings allows to compute the confusion matrix, the sensitivity and the specificity of the proposed method. Sensitivity and specificity are defined as:

\[
Se_{SAH} = \frac{TP}{TP + FN}, \quad Sp_{SAH} = \frac{TN}{TN + FP},
\]

where TP are the true positives, FN the false negatives, TN the true negatives and FP the false positives (or false alarms). The detailed results are given at table 2. This method is shown to be more specific (Sp = 76.8\%) than sensitive (Sc = 71.8\%).

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Table 2. Confusion Matrix, sensitivity and specificity for SAH detection by analysis of mandibular movements.

<table>
<thead>
<tr>
<th>Class Test →</th>
<th>SAH</th>
<th>NOT SAH</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAH</td>
<td>2628 (TP)</td>
<td>1032 (FN)</td>
<td>3660</td>
</tr>
<tr>
<td>NOT SAH</td>
<td>1320 (FP)</td>
<td>4369 (TN)</td>
<td>5689</td>
</tr>
<tr>
<td>Total</td>
<td>3948</td>
<td>5401</td>
<td>9349</td>
</tr>
</tbody>
</table>

Sensitivity $S_{SAH} = \frac{TP}{TP + FN} = 71.8\%$
Specificity $S_{PSAH} = \frac{TN}{TN + FP} = 76.8\%$

4 Conclusion

Esophageal pressure should be a favoured signal for screening SDB. However, the sensor is invasive and may alter the sleep of the patient. The measure of esophageal pressure can be replaced by the measure of the mandibular movement as these two signals have been shown to be correlated. The mandibular movement is recorded by a simple and ambulatory device. Sleep apneas, hypopneas, snoring and others breathing disorders can be screened by mandibular movements analysis. In this paper, the detection method deals only with sleep apnea and hypopnea (SAH) because no consensus exists for visual scoring for all breathing disorders, except for SAH. The salient mandibular movements that occur at the end of SAH are detected at first. Then, regions of interest likely to contain a SAH are delineated and finally classified as SAH. The sensitivity of the proposed method reaches 71.8\% with a specificity of 76.8\%. The method proposed here could apparently be less predictive than other ones applied to physiological signals different from ours (see [15] for instance). Nevertheless, at this stage, it is a matter of extraction and analysis of data rather than a matter of the signal nature itself. Our approach of the signal was limited to a rule-based time-domain reasoning. We are confident that the use of other methods such as wavelets and machine learning could by far enhance the efficiency of our screening system. Moreover, the respiratory efforts extracted from the mandibular movements, as well as the typical patterns related to SDB, are a complementary helpful source of information for the detection and the classification of SDB.

References


