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Detection of apnoeic and breathing activity through pole-zero analysis of the SpO_2 signal

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***Abstract*— A new method using autoregressive modelling and pole tracking is proposed to detect cyclical activity within the oxygen saturation signal, SpO_2, for subjects with Obstructive Sleep Apnoea (OSA). OSA is a sleep condition whereby the upper airway is obstructed and a cessation in respiration (apnoea) occurs. The three types of detected activity include: *apnoea*, *mix*, and *normal breathing*, where '*mix*' refers to breathing with a low-frequency component. Overall classifications produced by the analysis are in close agreement with expert scoring of the database. Furthermore, the pole-zero analysis method allows, for the first time, the *mix* sections to be identified automatically.**

I. INTRODUCTION

A. OSA, definitions and polysomnography

Obstructive Sleep Apnoea (OSA) is a condition whereby the upper airway is obstructed and a cessation in respiration (apnoea) occurs. Each apnoea is terminated by an arousal in the sleeping individual; i.e., the sleeping person is woken up even though he/she might not be aware of it. This may occur up to several hundred times a night, leading to very disturbed sleep. Overall, it is estimated that 18 million Americans suffer from OSA syndrome, costing $42 million US annually in hospitalisation alone. The American Academy of Sleep Medicine (AASM) Task Force defines an apnoea as a complete or near complete cessation of airflow that lasts for at least 10 seconds or longer [1], divided into one of three types [2]:

Obstructive Apnoea - ventilatory effort exists but there is no airflow, as there is an obstruction in the upper airway. This type of apnoea is usually associated with excessive daytime sleepiness (EDS). It is the most prevalent sleep disorder seen in diagnostic sleep laboratories worldwide, accounting for 75 to 80% of diagnoses [2].

Central Apnoea - ventilatory effort is completely absent. This type of apnoea is usually associated with insomnia. It is considerably less prevalent with the exception of specific patient populations, such as patients with chronic heart failure or patients with neurological disorders.

Mixed Apnoea - this type of apnoea is initially due to absent ventilatory effort (a 'central' pattern) and subsequently persists despite resumption of ventilatory efforts (an 'obstructive' pattern).

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A hypopnoea is less serious than an apnoea. Again, it can be obstructive or central and is defined by the AASM Task Force as an event that lasts for at least 10 seconds or longer and satisfies one of the two criteria. First - a clear decrease from baseline ($< 50\%$) in the amplitude of a valid measure of breathing during sleep (respiratory effort or airflow measurement). Baseline is defined as the mean amplitude of stable breathing and oxygenation in the two minutes preceding onset of the event (in individuals who have a stable breathing pattern during sleep) or the mean amplitude of the three largest breaths in the two minutes preceding onset of the event (in individuals without a stable breathing pattern) [1]. Second - a clear amplitude reduction of a valid measure of breathing during sleep (respiratory effort or airflow measurement) that does not reach the above criterion but is associated with either an oxygen desaturation of $> 3\%$ or an arousal [1].

The current gold-standard method for the accurate diagnosis of OSA and other sleep-related disorders is the 'sleep test' or polysomnography (PSG) - a multi-channel recording of sleep signals (such as the electroencephalogram 'EEG') and breathing variables traditionally performed overnight, including the non-invasive and continuous monitoring of blood oxygen levels by pulse oximetry, SpO_2. The replacement of full PSG with the more simple and convenient pulse oximetry, especially for home studies, is a current issue amongst sleep researchers. In 2000, Vázquez *et al*. produced an oximeter derived respiratory index that was highly correlated ($R = 0.97$) with the PSG derived apnoea-hypopnoea index, with 'excellent' sensitivity and specificity for diagnosing OSA in their database of 326 patients [3]. More recently, Magalang *et al*. (2003) showed that oxygen saturation variability (as measured by taking the average of absolute differences of oxygen saturation within successive 12-second intervals) provides an oxygen desaturation index with a similar level of diagnostic accuracy as found with PSG [4].

B. Oxygen saturation signal, SpO_2

The oxygen saturation signal, or SpO_2, is the simplest to acquire (using an ear or finger pulse oximeter) PSG signal [1]. In a normal healthy adult, the normal operating range for SpO_2 is greater than 90%, usually between 96 and 100%. Arterial saturations between 70 and 80% result in drowsiness, dizziness and visual impairment, and any further decrease in saturation results in deterioration of mental function and coordination [5].

In subjects with OSA, the SpO_2 signal exhibits a distinct

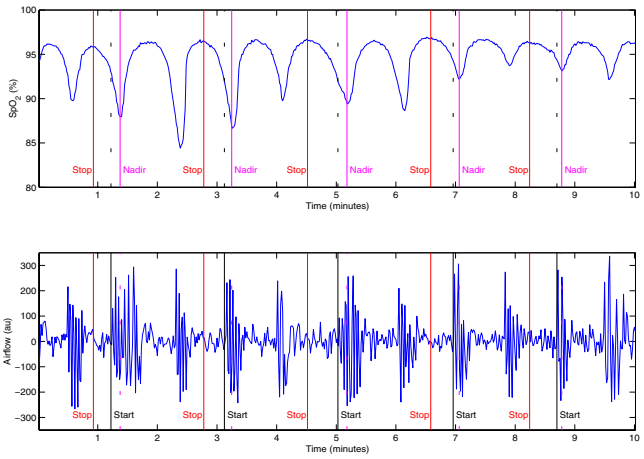

Fig. 1. Plot of arterial oxygen saturation measured by finger pulse oximetry in a patient with OSA, showing recurrent episodes of desaturation and corresponding airflow. 'au' = arbitrary units; 'Stop' = cessation of airflow; 'Start' = resumption of airflow; 'Nadir' = nadir level of SpO_2. In the top figure, the 'Start' points are indicated by vertical dashed lines. In the bottom figure, the 'Nadir' points are indicated by vertical dashed lines. Every other event only is shown to improve clarity.

cyclical pattern. During OSA, airflow ceases because of complete occlusion of the upper airway (nasopharynx and oropharynx), by the movement of the tongue and palate into apposition with the posterior pharyngeal wall. A cessation of airflow results, despite continued respiratory efforts and activation of inspiratory muscles [6]. Subsequently, asphyxia develops, but only until there is a brief arousal from sleep, restoration of upper airway patency, and resumption of airflow. During asphyxia, the oxygen level drops and continues to decrease even past the resumption of breathing. The oxygen saturation nadir level is reached within (typically) 30 seconds of the resumption of breathing (or equivalently, the termination of the obstructed breath) [1]. The subsequent delay is due to the time needed for oxygen to flow from the lungs to the periphery; i.e., ear/finger where the pulse oximeter is located taking the oxygen measurements. Although the AASM stipulate that the minimum duration for an apnoeic event is 10 seconds, the most common minimum duration of apnoea is 25 seconds long (during non-REM sleep) [7]. The maximum duration of apnoea is approximately 120 seconds long (during REM sleep) [7].

The response time of the ear/finger pulse oximeter is sufficiently rapid to follow the changes in oxygen saturation associated with apnoea or hypopnoea, as illustrated in Figure 1 where the difference between the resumption of airflow ('Start') and the nadir level achieved ('Nadir') is of the order of 30 seconds. It has recently been shown (Zamarrón *et al*., 2003) that the frequency of cyclical (apnoeic) activity corresponds to a spectral peak in the periodogram of the SpO_2 signal within the 0.014 to 0.033 Hz range [7]. More recently, a new method has been developed to detect the same frequency peak, using autoregressive (AR) modelling. In this paper, we show that AR modelling and pole tracking can be used to identify both apnoeas and the frequency of breathing during non-apnoeic episodes directly from the SpO_2 signal.

II. Method

A. Subjects

The database investigated is the 'MIT-BIH Polysomnography' database, which was originally developed for inclusion in the PhysioNet archival system developed by Moody *et al*. in 2000 [8]. PhysioNet is a large research resource, complete with an archive of well-characterized digital recordings of physiological signals and related data for use by the biomedical research community. Of the 16 continuous PSG recordings, six include the SpO_2 signal (all male subjects who suffer from OSA). The six recordings are between one and seven hours in duration and are digitized at 250 Hz with a resolution of 12 bits/sample. Each record was annotated by two or more experts; discrepancies were resolved by consensus, or by another expert if the original annotators were unavailable. The 'Expert Scores' include sleep stages, movement time, and the following events - with and without an associated arousal: obstructive apnoeas, central apnoeas, hypopnoeas, leg movements (plus unspecified arousals). Each annotation is assigned to 30-second segments of non-overlapping data. The annotation coding scheme is such that one or more events may be assigned to any one 30-second segment. For example, the annotation 'H OA' means that a hypopnoea and obstructive apnoea have occurred in succession within the same 30-second segment. Both events start within the segment, but do not necessarily have to finish within this segment; i.e., the last recorded (OA) may begin within the segment of interest, but not end until the following segment. In this study, the apnoeas (obstructive, central) are considered as one entity as the analysis focuses on the AR modelling of the SpO_2 signal; and at least two physiological signals are required to differentiate between apnoea types according to the AASM definitions above.

B. Signal Processing

First, each oxygen saturation signal is downsampled from $Fs = 250$ Hz to $Fs = 1$ Hz, for reasons given below. Second, each downsampled SpO_2 signal is segmented into overlapping windows 2 minutes in duration, with 1-minute overlap. A segment length of two minutes is selected to make sure that even the longest apnoea cycle is captured in its entirety within a window. Third, the trend of each windowed signal is removed. Fourth, a Hamming window is applied, so that ripples in the frequency domain - created by the signal segmentation - are reduced.

Next, each segment is modelled autoregressively as a rational transfer function, where the denominator is factored into p terms that correspond to p poles; i.e., the roots of the polynomial (denominator) constitute the magnitude and phase angle of the p poles, each of which is a complex-conjugate pair [9]. The relative amplitudes at the resonant frequencies are estimated by tracking the relative magnitudes of the corresponding poles, and the angle on the pole-zero plot is computed as follows:

$$\Theta = 360^\circ * \frac{F_{res}}{Fs} \quad (1)$$

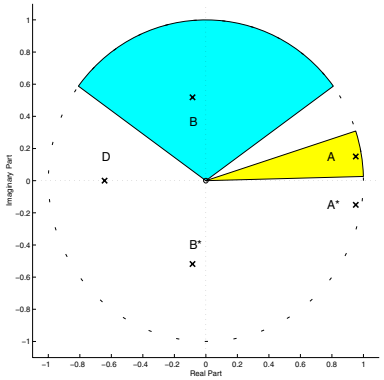

Fig. 2. A pole-zero plot of the 5^{th}-order AR-model for one segment of the SpO_2 signal depicted in Figure 1. Pole 'A' falls within the acceptable angular region for an apnoea with magnitude $r = 0.96$. Pole 'B' falls within the acceptable angular region for normal breathing with magnitude $r = 0.53$. Pole 'D' falls on $\Theta = 180°$, or DC. A* and B* are the other poles for the complex-conjugate pairing.

where Θ is the angle sub-tended by the pole, F_{res} is the pole frequency, and Fs is the sampling frequency. The SpO_2 waveform is downsampled in order to make it easier to identify the low-frequency pole which lies close to DC ($\Theta = 0°$) on the pole-zero plot. For example, if in one segment under analysis, there is one apnoeic cycle per minute (period $T = 60$ sec and $F_{res} = 1/60$ Hz), for $Fs = 250$ Hz, $\Theta = 0.024°$ whereas for $Fs = 1$ Hz, $\Theta = 6°$.

For the SpO_2 signal, there are two possible dominant frequencies: (i) corresponding to apnoea, (ii) corresponding to normal breathing. With two dominant frequencies, two poles (complex-conjugate pairs) fall between 0 and 180°. Additionally, another (single) pole exists to model the DC value, at $\Theta = 0°$ or $\Theta = 180°$. The requisite model order is therefore $p = 5$.

The use of AR-modelling to track resonant frequency is illustrated in Figure 2, which shows the poles of the AR-model in the complex plane for one (2-minute) segment of the SpO_2 signal given in Figure 1. In Figure 2, Pole 'A' falls within the acceptable angular region for an apnoea; Pole 'B' falls within the acceptable angular region for normal breathing; and Pole 'D' falls on $\Theta = 180°$, or DC. The AASM Task Force stipulates that an apnoea must be at least 10 seconds in duration; with $T/2 = 10$ sec, $T = 20$ sec, this corresponds to $\Theta = 18°$ (1). (The apnoea corresponds to the desaturation portion of the SpO_2 signal; i.e., $T/2$.) Conversely, the maximum duration of an apnoea is 120 seconds; with $T/2 = 120$ sec, $T = 240$ sec, which corresponds to $\Theta = 1.5°$. Thus, the acceptable range of angular position on the pole-zero plot for an apnoea is from 1.5 to 18°. Similarly, the breathing rate of the subjects in the study is assumed to range from 6 breaths per minute ($F_{res} = 6/60$ Hz) to 24 breaths per minute ($F_{res} = 24/60$ Hz); therefore, the acceptable range of angular position on the pole-zero plot for normal breathing is from 36 to 144°. In Figure 2, both acceptable regions are shaded accordingly.

Each pole within a two-minute segment of the SpO_2 signal is marked according to its angle on the pole-zero plot; i.e., the poles are marked as apnoeic, normal breathing, DC (0° or 180°), or other (falling outside of the acceptable regions). Next, the apnoeic and normal breathing poles are compared in terms of the magnitude of their pole radius, r. The closer a pole lies to the unit circle, the stronger its resonant frequency is. For example, in Figure 2, Pole 'A' is clearly the dominant pole. According to pole magnitude, an overall classification is assigned as follows:

$$r_{apnoea} >> r_{breath} \quad \rightarrow \quad apnoea, \tag{2}$$

$$r_{apnoea} \approx r_{breath} \quad \rightarrow \quad mix, \tag{3}$$

$$r_{breath} >> r_{apnoea} \quad \rightarrow \quad normal\ breathing; \tag{4}$$

where the 'mix' classification refers to breathing with a low-frequency component, and where the values of r for the two poles must be within 30% of each other. When more than one pole falls within the same angular region, the pole with the largest r is used in the analysis. If neither an apnoeic nor normal breathing pole is present, the segment is classified as 'other.'

III. Results

All six SpO_2 signals were analyzed as described above. For five of the six subjects, apnoeic events (obstructive and central) took up 30% to 40% of the total signal time as scored by the experts. The sixth signal, however, was made up of mostly hypopnoeic events (49%) and very few apnoeic events (3%). For a more uniform analysis, this sixth signal was not employed any further in this study.

Figure 3 shows a 1.25-hour section of the SpO_2 signal from Patient 1, the corresponding Expert Scores, two highlighted sub-sections magnified and their corresponding airflow signal. The 'Expert Scores' are scaled for convenience, with '1'=obstructed apnoea, '0.75'= central apnoea, and '0.5'= hypopnoea. Consider firstly the left-most highlight; the *apnoea* sub-section. The Expert Scores indicate a predominance of apnoeic events within this sub-section, and the SpO_2 signal clearly demonstrates low-frequency cyclical activity. The airflow signal confirms that the subject is breathing irregularly. In total, this section includes ten two-minute segments, for which $r_{apnoea} >> r_{breath}$ in nine segments; in the other segment, only one pole pair is found other than at $\Theta = 0°$ or $\Theta = 180°$ and the relevant pole lies within the acceptable angular range for apnoea.

The second sub-section of interest is the right-most highlight; which is a *mix* sub-section. The magnified SpO_2 signal shows a low-frequency variation between 93% and 95% saturation caused by the subject's Heart Rate Variability (HRV). (The subject's airflow signal was used to confirm that the low-frequency component was due to HRV and not irregular breathing.) The Expert Scores indicate a number of hypopnoeic events throughout the four two-minute segments. In two segments, $r_{apnoea} >> r_{breath}$; and in the other two segments, the one valid pole is within the acceptable range for breathing.

Figure 4 shows the SpO_2 signal from Patient 2, the corresponding Expert Scores, and one highlighted sub-section,

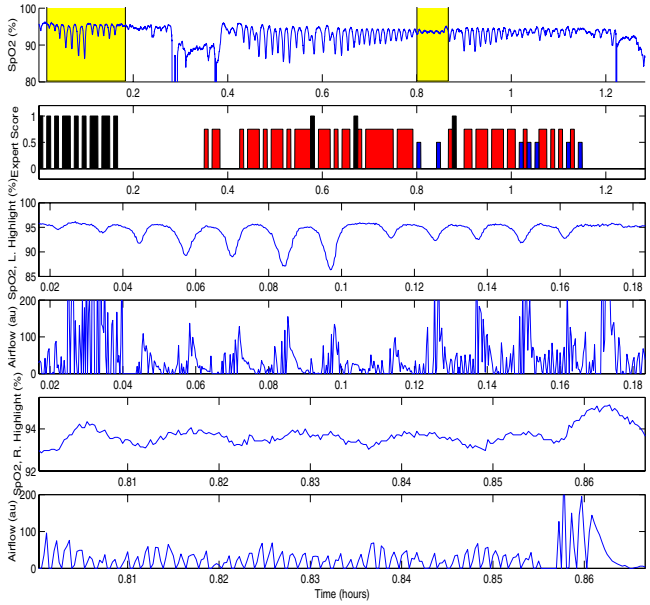

Fig. 3. Patient 1. From top to bottom: SpO_2 signal in its entirety (left highlight: apnoeic section, right highlight: mixed breathing/apnoeic section); Expert Scores corresponding to signal in its entirety ('1'=obstructed apnoea, '0.75'= central apnoea, and '0.5'= hypopnoea); SpO_2 of apnoeic section (left highlight magnified); airflow of apnoeic section; SpO_2 of mixed section (right highlight magnified); airflow of mixed section. 'au' = arbitrary units, 'L. Highlight' = left highlight; 'R. Highlight' = right highlight.

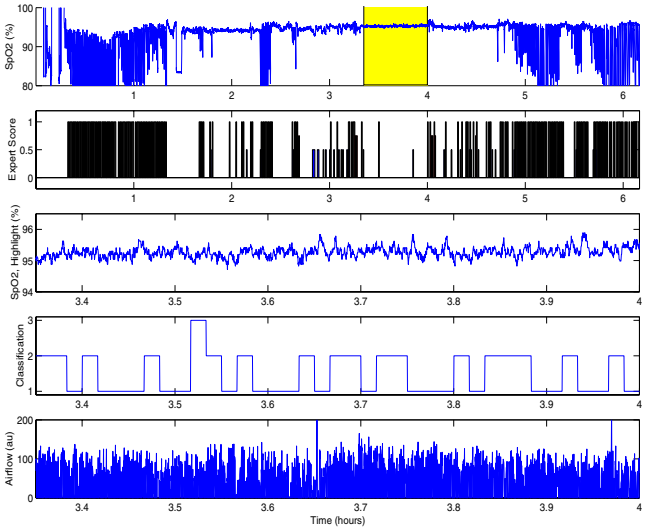

Fig. 4. Patient 2. From top to bottom: SpO_2 signal in its entirety (highlight: breathing section); Expert Scores corresponding to signal in its entirety ('1'=obstructed apnoea, '0.75'= central apnoea, and '0.5'= hypopnoea); SpO_2 of breathing (highlight magnified) - below which are the classification assignments ('3'=*apnoea*, '2'=*mix*, and '1'=*normal breathing*); airflow signal. 'au' = arbitrary units.

normal breathing - below which are the corresponding classification assignments and airflow signal. The classification scheme assigns a '3' for *apnoea*, '2' for *mix*, and '1' for *normal breathing*. The Expert Scores indicate only two events for this section. In total, this sub-section includes 39 two-minute segments. In one segment, $r_{apnoea} >> r_{breath}$; in 17 segments, $r_{apnoea} \approx r_{breath}$; in two segments, $r_{breath} >> r_{apnoea}$; and in 19 segments, the one valid pole is within the acceptable range for breath. The one segment classified as *apnoea* correlates with the apnoea event scored by the experts. The large number of *mixed* events is due to the high-frequency component corresponding to HRV. The airflow signal confirms that the subject is breathing regularly.

IV. Conclusion

Zamarrón *et al*. (1999) investigated the power density of SpO_2 signals using the Fast-Fourier Transform (FFT), whereby OSA was suspected if a peak in the spectrum was observed (of a subject's entire SpO_2 signal) between 0.014 and 0.033 Hz (corresponding to a period range between 30 and 70 seconds) [10]. Their database included 233 subjects clinically suspected of having OSA, 27 of whom had underlying lung diseases. In a subsequent paper, Zamarrón *et al*. (2003) looked for a peak (between 0.014 and 0.033 Hz) in *both* the SpO_2 spectrum and the HRV spectrum (also obtained from the pulse oximetry recording).

The pole-zero analysis presented here allows for three types of activity to be tracked minute-by-minute: *apnoea*, *mix*, and *normal breathing*. Classifications produced by this analysis were in close agreement with expert scores in the MIT-PSG database. The pole-zero analysis method allows, for the first time, the *mix* sections to be identified automatically. Future work includes further understanding of physiology and its relation to other parameters, such as the electrocardiogram 'ECG' and airflow.

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