A Sleep Apnoea Keeper in a Wearable Device
for Continuous Detection and Screening during Daily Life

G Angius, L Raffo

Department of Electrical and Electronic Engineering, University of Cagliari, Italy

Abstract

Sleep apnoea syndrome is one of the most common sleep disorders which affects around one out of every 100 people. There is some evidence that sleep apnoea may be linked to hypertension, strokes and heart attacks.

The aim of this work is to develop a wearable biomedical system for the continuous and real-time monitoring of the sleep apnoea disease at home.

Embedded in a comfortable glove, the proposed wearable device acquires the photoplethysmographic (PPG) signal coming from a standard SpO_2 wrapped sensor placed in one of the fingers. Real-time heart rate variability analysis is performed from NN intervals measured in the PPG signal in order to activate an alarm if the number of sleep apnoea events cross a guard level.

Through a radio frequency link in the ISM band, the glove communicates with a internet gateway connected with a remote station for continuous data analysis, monitoring and alarm catch.

1.   Introduction

Sleep Apnoea (SA) is a common sleep disorder characterized by brief interruptions of breathing during sleep, with an estimated prevalence of about 4% in men and 2% in women [1]. It can cause a total blockage of throat's airway (i.e. apnoea) or a partial blockage of the airway which reduces the amount of oxygen that is taken into the body by 50% (i.e. hypopnoea). The amount of time in which a person stops breathing during the sleep is usually 10 seconds or longer and sometimes for as long as a minute [2].

There are two major forms of SA: Obstructive Sleep Apnoea (OSA) and Central Sleep Apnoea (CSA). Obstructive apnoeas and hypopnoeas result from complete or partial collapse of a narrowed pharynx during sleep [3]. In subjects with normal pharyngeal anatomy, the partial withdrawal of pharyngeal dilator muscle tone that accompanies the onset of sleep is insufficient to cause pharyngeal collapse. However, the pharynx of patients with OSA is anatomically narrowed and highly compliant. In this setting, the superimposition of the normal withdrawal of pharyngeal dilator muscle tone at sleep onset causes the pharynx to occlude, triggering apnoea or hypopnoea [4].

Central Sleep Apnoea, commonly referred to as Cheyne-Stokes respiration, is a form of periodic breathing in witch apnoeas and hypopnoeas alternate with periods of hyperventilation. It is usually initiated during sleep by a further acute increase in ventilation and reduction in arterial carbon dioxide pressure ($PaCO_2$) because the brain fails to send the appropriate signals to the breathing muscles to initiate respiration [5]. When $PaCO_2$ falls below the threshold level required to stimulate breathing, the central drive to respiratory muscles and airflow stop, and central apnoea ensues [6].

SA is associated with a wide range of health implications and increased cardiovascular diseases and mortality. It has been linked to depression, irritability, sexual dysfunction, learning and memory difficulties, high blood pressure (hypertension), heart attack and stroke. At least 50% of patients with heart failure have OSA or CSA, responsible to the adverse consequences of the cardiovascular system [7]. It is important to notice that the effects of sleep apnoea on the cardiovascular system are not confined to sleep. Daytime sympathetic nervous activity and blood pressure, in fact, are increased in patients with OSA [8]. A continuous screening of sleep apnoea disorder is needed in order to have a major benefit of the treatment on cardiovascular outcomes.

The gold standard in diagnosing of SA is overnight polysomnography (PSG). It uses non-invasive methods for the recording of various physiological parameters including EEG, ECG, EMG, nasal airflow, abdominal and thoracic movements and blood oxygen saturation (SpO_2) [9]. However, discomfort of the electrodes and the high amount of information required to this method, make PSG an expensive and time consuming procedure.

The most promising mean for home diagnosis of SA is the Heart Rate Variability (HRV) analysis. Referred to the beat-to-beat alterations in heart rate, HRV analysis is mainly used for the non-invasive evaluation of the synergetic action of the two branches of the Autonomous

Nervous System to maintain cardiovascular parameters in their optimal ranges [10] but also for the detection and screening of sleep apnoea [11].

In this paper, we present a wearable device wich is capable of performing real-time short-term HRV analysis at home. An alarm is activated if the number of sleep apnoea events per hour cross a guard level. The use of a standard SpO_2 wrapped sensor placed in one of the fingers instead of the use of electrocardiogram electrodes makes the realized device patient safe, inexpensive and easy to use.

2. Methods

2.1. Standard measurement of HRV

HRV analysis is the standard to describe variations of instantaneous heart rate and RR intervals. Starting from the tachogram of the short-term 5-minute recordings and nominal 24-hour long-term ECG recordings, there are two main methods to perform an HRV analysis: one in the time domain and one in the frequency domain.

In the time domain method, each QRS complex is detected and the normal-to-normal (NN) intervals (all intervals between adjacent QRS complexes) are determined. Simple time domain variables generally calculated are listed in Table 1.

Table 1. Time domain measures of HRV analysis.

Variable	Units	Description
SDNN	ms	Standard deviation of all NN intervals.
SDANN	ms	Standard deviation of the average of NN intervals in all 5-minute segments of the entire recording.
RMSSD	ms	The square root of the mean of the sum of the squares of differences between adjacent NN intervals.
SDNN index	ms	Mean of the standard deviations of all NN intervals for all 5-minute segments of the entire recording.
SDSD	ms	Standard deviation of differences between adjacent NN intervals.
NN50 count		Number of pairs of adjacent NN intervals differing by more than 50 ms in the entire recording.
pNN50	%	NN50 count divided by the total number of NN intervals.

In the frequency domain, the power spectral density (PSD) analysis of the tachogram provides the basic information of how power distributes as a function of frequency. In short-term recordings, three main spectral components are distinguished: VLF, LF, and HF components [11]. The variety of frequency domain measures of HRV analysis for short-term recordings are depicted in Table 2. The measurement of VLF, LF, and HF power components is usually made in absolute values of power but LF and HF may also be normalized relatively to the total power minus the VLF component.

Table 2. Frequency domain measures of HRV analysis in a short-term recording.

Variable	Units	Description	Freq. range
Total power	ms^2	The variance of NN intervals over the temporal segment	<0.4Hz
VLF	ms^2	Power in VLF range	<0.04 Hz
LF	ms^2	Power in LF range	0.04-0.15 Hz
LF norm	ms^2	LF power in normalized units LF/(total power-VLF)*100	0.04-0.15 Hz
HF	ms^2	Power in HF range	0.15-0.4 Hz
HF norm	ms^2	HF power in normalized units HF/(total power-VLF)*100	0.15-0.4 Hz
LF/HF		Ratio LF/HF	

2.2. Detection of SA from frequency analysis of HRV

Previous scientific researches have demonstrated that HRV analysis in the time and frequency domain [11] can give reasonably high detection accuracy of the SA occurrence for manual and automatic screening. These results also show that HRV spectrum analysis give the most informative feature than the statistical method of the time domain method [12]. Patients with sleep apnoea tend to have a spectral peak lying between 0.01 and 0.05 Hz, with the width of the peak indicating variability in the recurrence rate of the apnoea [11].

In this way, by a fixed threshold of 3,15 used to discriminate the ratio of the content of two spectral regions obtained by dividing the area under the spectral curve between 0.01 and 0.05 Hz by the area between 0.005 and 0.01 Hz, an automated classification of SA events can give an overall classification score of 90%. The block diagram of the algorithm of this automatic classification procedure is depicted in Figure 1.
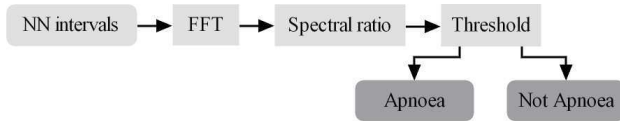
Figure 1. Automatic analysis and classification of SA events by the frequency analysis of HRV [11].

2.3. The proposed system

The proposed system is composed of two main parts hosted respectively in the Remote Monitoring Station (RMS) and at the patient's home (Figure 2).
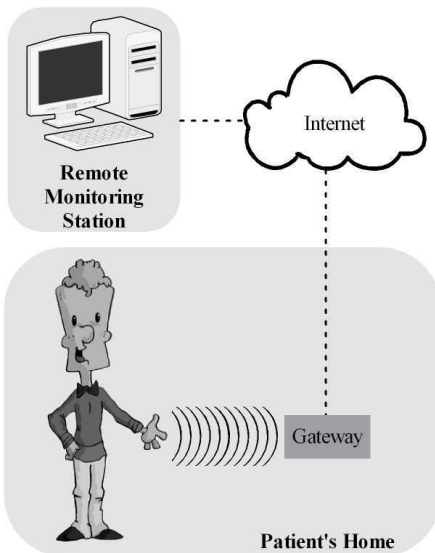

Figure 2. System overview.

On the RMS side there is only a simple PC with a TCP/IP server and a Graphic User Interface (GUI). The server receives the data stream of the patients connected and the GUI performs the HRV analysis in both frequency and time domain in order to provide to a physician the best framework for the automatic and manual detection of SA occurrence.

On the patient's side, there are only an internet gateway for the patient's data transmission to the RMS and a wearable device embedded in a comfortable glove in order to allow the continuous detection and screening during daily life.

The wearable device, battery powered for patient's safety, performs in real-time the short-term (5-min) HRV analysis from NN intervals measured in the photoplethysmographic (PPG) signal coming from a standard SpO$_2$ wrapped sensor placed in one of the fingers. Applying a fixed threshold at the frequency analysis of the heart rate variability [11], the device can continuously detect how many sleep apnoea events has

been occurred in the previous 5-min and can activate an alarm if the number of sleep apnoea events per hour cross a guard level. Figure 3 shows the glove embedding the wearable device.
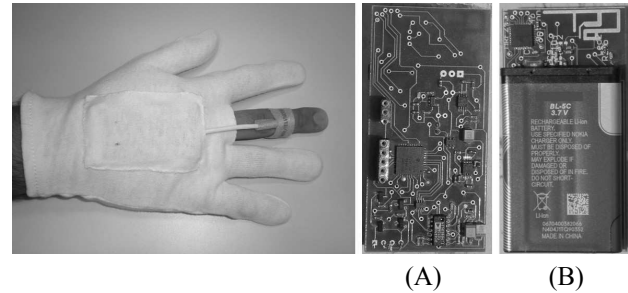

(A)   (B)

Figure 3. The wearable device (top view (A) and bottom view (B)) embedded in a comfortable cotton glove.

Based on the transmission PPG method of the digital artery in the human finger, a simple two-stage inverting amplifier with variable gain converts the photocurrent coming from the photodetector of the SpO$_2$ sensor in a voltage with a dinamic range appropriate for the A/D converter input. On the high performance and low power 16-bit digital signal controller (i.e. Microchip^{TM} dsPIC33FJ12MC202), the PPG signal is first of all filtered in order to remove motion and environmental artifacts and continuously analyzed in order to calculate NN intervals that feeds the real-time HRV algorithm. The block diagram of the wearable device is depicted in Figure 4.
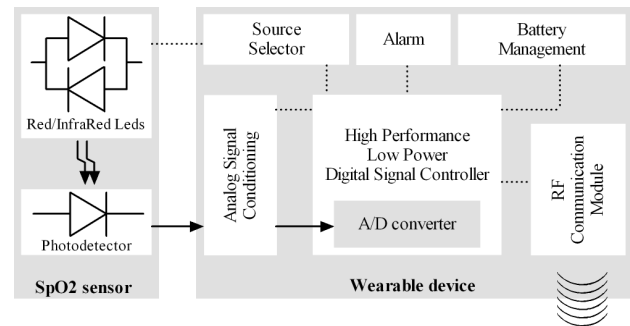

Figure 4. Block diagram of the wearable device.

Through a radio frequency link in the ISM band based on a IEEE 802.15.4 ZigBee^{TM} transceiver at 2.4GHz (i.e. Microchip^{TM} MRF24J40), the smart glove communicates with a internet gateway connected with a remote monitoring station for the continuous data analysis, clinical monitoring and alarm catch.

The picture of the realized internet gateway is shown in Figure 5. It is mainly composed of a ZigBee^{TM} transceiver at 2.4GHz connected to a IEEE 802.3 10baseT Ethernet^{TM} controller embedded in a low power
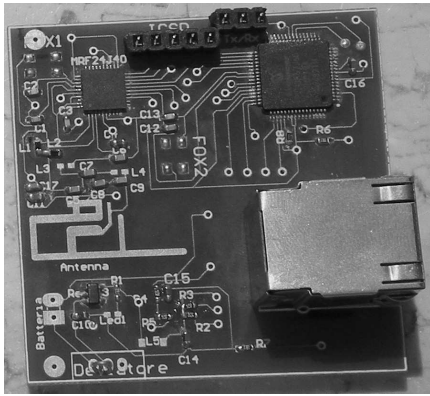
microcontroller (i.e. Microchip™ PIC18F67J60).

Figure 5. Picture of the internet gateway.

3.   Results and conclusions

Based on a battery-powered wearable device built around a high performance digital signal controller, the developed system allows the continuous, real-time and remote monitoring of the sleep apnoea disorder at home, and can trigger an alarm if the state of the disorder can be considered dangerous. Moreover, through a wireless link with an internet module, the wearable device allows a long time continuous monitoring by the RMS, which can help the patients in case of dangerous sleep apnoea.

Figure 6 shows that the detection of NN intervals from the PPG signal is equivalent to the traditional method based on a QRS detection algorithm from an ECG channel.
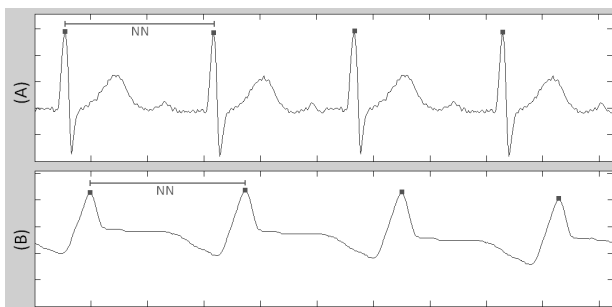

Figure 6. NN intervals detection from lead-I ECG (A) and PPG (B).

A first prototype of the wearable device was realized and used to test the proposed system on 20 volunteers. It measures 4x5 cm but dimensions can be easily reduced by using smaller batteries.

References

[1] Young T, Palta M, Dempsey J, Skatrud J, Weber S, Badr S. The occurrence of sleep-disorder breathing among middle-aged adults. New Eng. J. of Med. 1993; 328:1230-1235.

[2] Shahar E, Whitney CW, Redline S, Lee ET, Newman AB, Nieto FJ, O'Connor GT, Boland LL, Schwartz JE, Samet JM. Sleep-disordered breathing and cardiovascular disease. Am. J. Respir. Crit. Care Med. 2001; 163:19-25.

[3] Bradley TD, Brown IG, Grossman RF, et al. Pharyngeal size in snorers, non-snores, and patients with obstructive sleep apnea. N. Engl. J. Med. 1986; 315:1327-1331.

[4] Remmers JE, Degroot WJ, Sauerland EK, et al. Pathogenesis of upper airway occlusion during sleep. J. of Appl. Physiol. 1978; 44:931-938.

[5] Naughton M, Benard D, Tam A, et al. Role of hyperventilation in the pathogenesis of central sleep apneas in patients with congestive heart failure. Am. Rev. Respir. Dis. 1993; 148:330-338.

[6] Bradley TD, Phillipson EA. Central sleep apnea. Clin. Chest. Med. 1192; 13:493-505.

[7] Sin DD, Fitzgerald F, Parker JD, et al. Risk factors for central and obstructive sleep apnea in 450 men and women with congestive heart failure. Am. J. Respir. Crit. Care Med. 1999; 160:1101-1106.

[8] Somers VK, Dyken ME, Clary MP, et al. Sympathetic neural mechanisms in obstructive sleep apnea. J. Clin. Invest. 1995; 96:1897-1904.

[9] Haponik EF, Smith PL, Meyers DA, Bleecker ER. Evaluation of sleep disordered breathing. Is polysomnography necessary? Am. J. Med. 1984; 77:671-677.

[10] Levy MN, Schwartz PJ. Vagal control of the heart: experimental basis and clinical implications. Armonk, NY: Futura; 1994.

[11] Drinnan MJ, Allen J, Langley P, Murray A. Detection of sleep apnoea from frequency analysis of heart rate variability. Computers in Cardiology 2000; 27:259-262.

[12] Xu W, Liu X, Pan Z. Definition of Sleep Apnea event by one minute HRV spectrum analysis. ICBBE 2008. 2292-2294.

Address for correspondence:

Gianmarco Angius
DIEE - Department of Electrical and Electronic Engineering
University of Cagliari
Piazza d'Armi, 09123 Cagliari, Italy
Tel. +39.070.675.5774
e-mail: g.angius@diee.unica.it