

Respiratory Diseases follow-up based on the Extraction of Plethysmography Signal Parameters

Rene Gonzalez-Fernandez*, Jose L Hernandez-Caceres and Jorge G Perez-Blanco

Department of Medical Electronic, Cuban Center for Neurosciences, Cuba

*Corresponding Author: Rene Gonzalez-Fernandez, Department of Medical Electronic, Cuban Center for Neurosciences, Cuba.

Received: February 01, 2022

Published: March 03, 2022

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Abstract

The aim of this paper is to discuss an approach to the monitoring of respiratory diseases based on the combined study of heart rhythm, respiratory rate and pulse oximetry (SpO₂). Respiratory diseases can arise from pulmonary, cardiovascular and other causes, and can be fatal. Worldwide, 235 million people have asthma and 64 million suffer from Chronic Obstructive Pulmonary Disease (COPD). The respiratory system works in coordination with the cardiovascular system and respiratory insufficiencies are compensated by an increase in heart rate, which can lead to heart disorders. The combined study of both systems would allow to know accurately how a respiratory patient evolves. A prototype was developed based on the E305654 module, which on-demand delivers SpO₂, photoplethysmography signal samples and pulse rate values, and the STM32L073CZTx processor. A vector was computed every thirty minutes; it is composed by respiratory rate, derived from metrics calculated from the plethysmography signal (PPG), the SpO₂ mean value and the pulse rate. 10 healthy volunteers and 6 people with COPD, including one suffering COVID-19, and three asthmatics were studied. The dispersion inside each patient's group was not significant, but a remarkable difference can be observed between the healthy volunteers and the other studied persons. A "normal region" can be defined with clearly defined frontiers. The proposed solution seems promising to assess respiratory function even when it is compensated by a cardiac response.

Keywords: Respiratory Disease Monitoring; Pulse Oximetry; PPG Signal; PPG Derived Respiratory Rate; Analysis of Chronic Obstructive Pulmonary Disease

Abbreviations

PPG: Photoplethysmography; RR: Respiratory Rate; HR: Heart Rate; PPG: Signal

Introduction

Acute respiratory diseases have a growing impact on the worldwide morbidity and mortality. According to data from the World Health Organization (WHO), there are 235 million people suffering asthma and 64 million with Chronic Obstructive Pulmonary Disease (COPD) [1]. Today, the impact of COVID-19 in all countries has dramatically increased the number of people treated for re-

spiratory disorders [2,3]; It is usual that while suffering from the disease or in the post-disease period, severe complications could be lethal [3].

It is well-known that the respiratory and cardiovascular systems work in strongly coordination to transport oxygen throughout the body as a primary element for metabolism. Blood oxygenation tends to decrease in persons suffering respiratory disorders; this deficiency is compensated automatically by an increase in respiratory rate and heart rate. That is why it is said that human organism tries to cover respiratory deficiencies with a cardiac overload in order to supply the required oxygen. This cardiorespiratory com-

compensation masks the respiratory deficit and allow this condition to evolve towards more serious states because the respiratory deficiency is not solved and the heart is overloaded. Based on the previous explanation, it is clear why cardiorespiratory function must be studied comprehensively, with photoplethysmography (PPG) as the best non-invasive option to achieve this goal. The required instrumentation and connections to the patient are minimized while sufficient information is collected for the intended analysis [4,5].

Respiratory rate (RR) is studied at different levels of health systems with different objectives. This parameter can be a highly sensitive indicator of an acute deterioration in the health status of the patient. Apart from indicating respiratory deficiency, it is a predictor of severe cardiac disorders due to the close relationship between the respiratory and cardiovascular systems. On the other hand, at the primary health level, the RR study is used for the diagnosis of pneumonia and sepsis, hence its importance.

Pulse rate (PR) indicates how many times the heart beats per minute, hence its importance in the cardiovascular system study. It is also important in the respiratory system analysis because many times the human organism tends to compensate for respiratory insufficiencies increasing pulse rate and this generates a cardiovascular overload that can lead to subsequent cardiac disorders.

Pulse oximetry (SpO₂) allows estimating the arterial blood oxygenation percentage and is therefore a vital parameter for any human body study. When there are respiratory disorders, less oxygen is transported by arterial blood and metabolism is affected, so human automatism mechanisms increase heart rate to pump more blood and transport the requires oxygen.

The combined study of SpO₂, pulse rate and heart rate values could be a powerful tool for a comprehensive analysis of the functioning of the cardiovascular. A "healthy space" can be set in a tridimensional axis system to set the borders among normal and abnormal functioning of the cardiorespiratory system. The implementation of this approach can be a low-cost solution because it can be based on a pulse oximetry module controlled by a general-purpose microcontroller, two low-price items nowadays. A quantitative evaluation can be done and a follow-up is easy to set.

The aim of this paper is to discuss the approach described previously. A reliable, comfortable and low-cost follow-up process can

be implemented for patients suffering from acute respiratory diseases such as COPD, bronchial asthma or complications of the COVID-19 disease, caused by the SARS-CoV-2 virus.

Materials and Methods

The proposed system is composed of the Recorder and the Analyzer. The Recorder is a medical device that allows the acquisition of II from the standard ECG and two channels of pulse oximetry information simultaneously. A Bluetooth channel is enabled for data transmission between both parts of the system as shown in figure 1. A pairing process between the Recorder and the mobile device running the Analyzer is a mandatory for this type of wireless communication.

The proposed approach for monitoring acute respiratory diseases is based on the acquisition of the PPG signal and the extraction from it of the following parameters: pulse rate (PR), respiratory rate (RR) and periodic values of oxygen saturation (SpO₂). With these variables, a three-dimensional space is built in order to study the patient evolution; it is expected that a region of normality can be set.

The variables mentioned above can be get implementing a low-cost electronic solution and the properly software. The authors developed a prototype composed by the following items

- An embedded pulse oximetry module, model E305654, from the Chinese company Mindray.
- A processing unit based on the STM32L073CZTx microcontroller embedding memory, interrupt management, I/O lines, communication and other capabilities.
- A base board to implement voltage supply and connection between pulse oximetry module and processing board.
- A medical grade power supply to guarantee the safety of the patients and conversion for alter current to direct current to get the needed voltages.

The block diagram shown in figure 1 represents the design of the developed prototype. On the other hand, an embedded software was developed to control the prototype operation, to implement the necessary methods to compute the studied variables and to set communication with a personal computer. This software was programmed in C++ language.

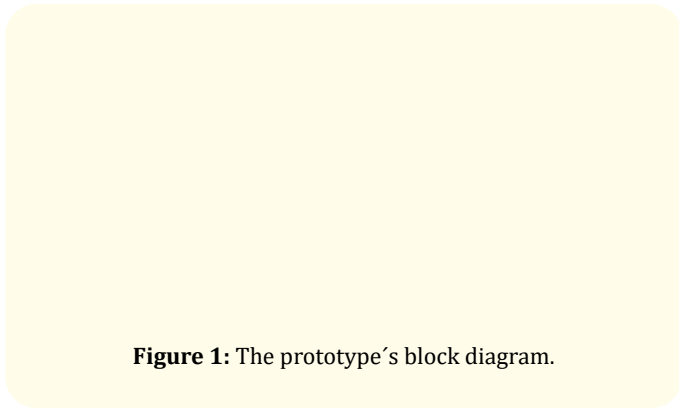


Figure 1: The prototype's block diagram.

The E305654 oximetry module has a serial interface that allowing to get PPG signal samples and values of SpO2 and PR on request. The PPG sampling rate was set to 250 Hz, SpO2 and PR values were read every ten seconds, obtaining an average value minute by minute.

Also, PR was computed using an algorithm developed by the authors and taken as Golden Rule the values read from the oximetry module. It was done for a future implementation in a smart wrist device in development. Peak identification on PPG signal is decisive for PR computing, since the distance between them is the basis for this calculation. Figure 2 shows the PPG signal and the peaks marked with the letter P.

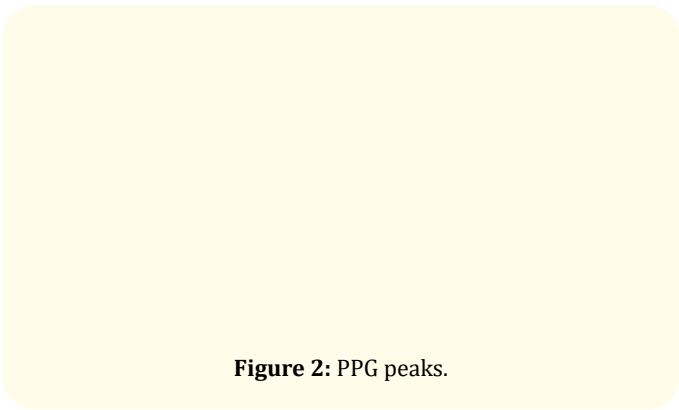


Figure 2: PPG peaks.

A derivative function, as shown in expression 1, is calculated for peak identification. The zero crossings of this function allow the peaks identification since on both sides of these there must be derivative function values of opposite polarity.

where:

$$deriv(i) = (2x(i) + x(i - 1) - x(i - 3) - 2x(i - 4))/8 \dots \dots \dots (1)$$

deriv (i): derivative function value.

X (i): PPG signal sample.

Every ten seconds, the average PR interval is calculated and rate is computed using expression 2.

$$PR = \frac{1000}{API} * 60 \dots \dots \dots (2)$$

where:

PR: Pulse Rate.

API: Average Pulse Interval for ten seconds.

Multiple algorithms have been proposed in the specialized literature to obtain the RR from the ECG or PPG [6-8]. Generally, these algorithms are based on the Fast Fourier Transform (FFT) and other spectral procedures that represent a considerable processing load for microcontrollers [xx]. Other authors have used wavelet decomposition and digital filtering strategies that minimize the error, reporting an error of less than 0.5 breaths per minute [9], although better results have been obtained with autoregressive approaches [10].

Madhav, *et al.* [10] proposed a method based on the Empirical Mode Decomposition (EMD) for RR estimation based on PPG signal peak to peak series. EDM allows extracting signals from a noisy non-linear and non-stationary process. This ability is based on the identification of oscillatory modes at different time scales. The EMD is an iterative process based on local maximum and minimum peaks identification, creating of corresponding upper and lower envelopes of the studied signal, computing of a mean signal form the envelopes, subtraction this mean signal from the studied signal and a repetition of these steps until the different between the studied signal and the computed mean signal is not significant. The authors preferred to stop at the first loop, the mean envelope calculation, as proposed Fusco, *et al.* [11]. This improvement reduces the algorithm complexity and the computational overload. RR estimation is based on the mean envelope frequency analysis. The power spectral density (PSD) of the respiratory component is used to evaluate the dominant frequency peak who is associated with RR. The exposed approach was tested with from PhysioBank MIMIC II Waveform Database [12], and a good performance was

revealed in estimating RR values from PPG signal. The reported Mean Absolute Error (MAE) was 0.0027 Hz, corresponding to 0.19 breaths per minute, and the Spearman's correlation coefficient was 0.962.

As previously stated, RR, PR and SpO2 values are obtained every 10 minutes and averaged for each hour. Important differences between healthy people and others, suffering respiratory diseases, can be observed representing the results graphically or on tables. The results are transmitted to a personal computer to facilitate their representation and analysis.

Results and Discussion

A prototype of the proposed solution has been developed and tested at laboratory level successfully. Tests were done following the IEC 60601-1 general safety standard for medical devices. The OEM pulse oximetry module and the medical grade power supply are supported by international certifications, such as CE mark, guarantying compliance with current highest quality and safety standards, so patient safety is guaranteed in the proposed solution.

Taking in count the international medical community criteria, a healthy region was set using the following values as frontiers: SpO2 from 96% to 100%; RR from 12 to 18 breaths per minute and HR from 60 to 100 beats per minute. The first remarkable outcome is that all the values recorded from healthy volunteers keep inside the region defined as healthy. For these people, HR was always between 70 and 90 beats per minute, the SpO2 values were between 97% and 99% and respiratory rate between 13 and 16 breaths per minute. However, it should be noted that the values corresponding to the studied asthmatic patients, without crisis and under long-term medication, were also within this healthy region in approximately 40% of the measurements made and the rest were above the normality limits, but very close. A clear difference between asthmatics and healthy people cannot be set, but it is expected that parameter values from asthmatics tend to move far from healthy region. COPD patients have a quiet different performance; they have always two parameters out of healthy region at least.

Table 1 clearly shows the difference between healthy people and people with COPD. While healthy people achieve SpO2 values above 97% with a normal cardiorespiratory function, in people suffering COPD, heart rate and respiratory rate increase markedly to

achieve much lower SpO2 values. This difference can be translated as a dangerous cardiorespiratory overload, it could be the origin of several cardiac disturbance such as ventricular hypertrophy and arrhythmias. A graphic implementation of these values and differences can be a useful tool for an inexperienced medical staff, a very useful feature for primary health level screening purposes.

	Healthy			COPD		
	RR	HR	SpO2	RR	HR	SpO2
1	14	80	96	18	97	94
2	13	84	97	18	98	94
3	14	84	98	20	101	93
4	13	84	98	20	97	94
5	13	85	96	18	90	93
6	13	80	98	20	100	93
7	13	81	97	19	105	93
8	14	82	97	18	103	93
9	15	84	98	20	103	93
10	14	85	96	22	100	93
11	14	78	98	22	98	94
12	14	84	98	20	99	94
13	14	85	98	20	101	92
14	14	78	98	18	98	94
15	14	84	97	19	98	93
16	14	84	98	21	98	94
17	14	85	98	19	101	93
18	16	84	97	19	103	94
19	15	84	98	22	102	93
20	15	84	97	18	100	93
Mean	14.00	82.95	97.40	19.55	99.60	93.35

Table 1: Twenty measures from healthy and COPD persons.

The same difference cannot be observed between the studied healthy people and asthmatics, although the latter tend to parameter's values very close to the upper limits of the healthy region. This is why it is to be expected that if asthmatics in crisis or in allergic states are studied, their parameters should be considerably far from the healthy region and a clear difference could be established. This fact could make it possible to study how a given anti-asthmatic drug can bring a patient in crisis closer to the healthy region, that is, the proposed solution could be useful to follow-up the emergency attention of asthmatic patients.

Conclusion

The proposed solution seems to be a powerful approach to study people suffering from respiratory diseases. Low cost and simplicity are significant features of the proposed solution, there are low-priced OEM pulse oximetry modules on the market and the same goes for microcontroller-based processing units and medical grade power supply blocks. The combined study of respiratory and cardiac variables does not allow respiratory deficit can be masked by a cardiovascular overload without this condition be revealed. Due to its simplicity and low cost, the proposed solution can be extended to the respiratory diseases screening, being ideal for its implementation in low-income countries. More tests are needed, but the results obtained to date are very promising.

Acknowledgements

The authors wish to thank the economic support of the Ministry of Science of the Republic of Cuba for the successful development of this project. In addition, they want to highlight the support provided by the colleagues of the Cuban Center for Neurosciences who contributed their experience and technical criteria to obtain the solutions described in this paper.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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