ACTA SCIENTIFIC MEDICAL SCIENCES (ISSN: 2582-0931)

Volume 4 Issue 6 June 2020

Research Article

Combining ECG and Pulse Oximetry for Newborn Cardiovascular Screening

Rene Gonzalez-Fernandez[1]*, Luis Reyes-Morales[1], Alejandro Torres-Fortuny[2] and Jose L Hernandez-Caceres[3]

[1]Department of Medical Electronic, Cuban Center for Neurosciences, Cuba

[2]Department of Clinical Medicine, Cuban Center for Neurosciences, Cuba

[3]Department of Neuroinformatics, Cuban Center for Neurosciences, Cuba

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

Received: February 27, 2020

Published: May 12, 2020

Abstract

The aim of this paper is to present the main features of a new approach to cardiovascular screening in newborns. The proposed system is made up of the Recorder and the Analyzer. The former is a medical device able to acquire two channels of pulse oximetry data and lead II from the standard ECG simultaneously; allowing the combined study of these variables with a minimum amount of electrodes connected to the patient's skin. Data transmission to the Analyzer is supported by the Bluetooth standard. The Analyzer is an Android application run in a mobile device to analyze several ECG and plethysmography parameters that allows newborn´s classification as cardiovascular "healthy" and "no healthy". QRS complexes are detected as the first step to study the cardiac rhythm looking for arrhythmia events. QT interval duration is measured to check if the studied newborn is prone to sudden death. Pulse oximetry values are measure in finger and leg to detect dangerous differences. PWTT index computation offers an indirect estimation of cardiac output; this index is inversely proportional to the cardiac output. A prototype was developed and tested at laboratory level. Results indicate that the developed device is safe according to the IEC 60601-1 standard, and sensitivity in QRS complex detection was 99.36%, enough for the intended use of the proposed system.

Keywords: Cardiovascular Screening in Newborns; Sudden Death; QRS Complex Detection; Ventricular Arrhythmias in Newborns; Long QT Interval; Classification of QRS Complexes; Oxygen Saturation in Newborns

Abbreviations

ECG: Electrocardiogram; PWTT: Pulse Wave Transit Time; PPG: Plethysmography Signal

Introduction

Cardiovascular newborn screening is an essential tool to minimize morbidity and mortality in the first years of life [1,2]. Many specialists consider that every newborn requires a brief physical examination within the first few minutes after birth and then a full and detailed assessment within the next 48 hours and prior to discharge from hospital. This is the reason why many governments have begun to consider the possibility of introduction in their National Health Services the performance of an ECG during the first month of life in all newborns, as part of a cardiovascular screening program. Several cardiovascular diseases can be identified with simple tests before newborns are discharged from hospital; hence, their life quality can be guaranteed without large investments.

Unexpected early sudden collapse resulting in death or prolonged need for resuscitation occurs in 0.15 to 0.4 per 1,000 live births [3]. In addition, congenital heart disease (CHD) occurs in approximately eight of every 1,000 live births according to information published by the U.S. Department of Health and Human Services [4]. Also, other disturbances such as dangerous ventricular arrhythmias could be identified in the first hours of life. In the other hand, screening based on pulse oximetry has been put forth as a useful strategy for detecting defects with decreased arterial oxygen saturation (SpO_2) before heart failure and circulatory collapse develops. Pulmonary diseases and other disorders may also be detected minimizing the risk for serious complications or death within the first weeks of life.

Typically, cardiovascular screening of newborns is based on inexpensive techniques such as pulse oximetry and standard twelve-lead electrocardiogram (ECG) well-known by physicians [5,6]. Both techniques are non-invasive and require a minimal paramedic personnel´s training, important features for their wide use.

Pulse oximetry is preferred by many specialists because low oxygen saturation values indicate hypoxemia, an early clinical sign of critical congenital heart defects, as well as other disorders that require immediate follow-up. Moreover, other disturbances can be detected studying plethysmography signal (PPG). A large prospective multicenter study conducted in 14 hospitals in Norway concluded that early pulse oximetry screening promotes early detection of critical CHDs and other potentially severe diseases with a high sensitivity detecting critical CHDs and a low false-positive rate [7]. Nonetheless, other specialists favor ECG because a deeper arrhythmia analysis can be done, the signal morphology provides important information about the cardiovascular system and the QT interval can be studied as a very important sudden death pre-

dictor. The main disadvantage of the standard ECG is the damage provoked by the ten electrodes to be placed on the newborn's skin. This potential damage is accentuated in preterm infants who have even more delicate skin.

Pulse oximetry and standard ECG are useful for cardiovascular screening, so the combination of both techniques would be a powerful tool if the main ECG disadvantage is reduced drastically. Reducing ECG to one channel, the number of required electrodes decreases from ten to three, even two, thus minimizing its main disadvantage. The ability to study the ECG morphology from different electrical point of view is lost, but it is possible to examine the cardiac rhythm and the QT interval, recognized as an important sudden death predictor. At the same time, it is possible to analyze variables which can be computed only when ECG and pulse oximetry signals are acquired simultaneously.

Aim of the Study

The aim of this paper is to discuss the main characteristics of a new approach to the newborn´s cardiovascular screening based on the analysis of two simultaneous pulse oximetry measurements and a simplified ECG.

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.

Figure 1: The proposed system.

The recommended procedure to use this system starts with the Recorder's data setup checking because all data should be configured according to the intended use and the operator's work habits. A nurse prepares the newborn and places the electrodes, previously connected to the Recorder, on the newborn´s skin. Once the nurse turns on the Recorder, it automatically connects to the Analyzer by Bluetooth. Signal acquisition process is initialized sending a command to the Recorder after the operator chose the corresponding option. Samples of the two plethysmography signals (PPG) and the ECG are sent together with values of oxygen saturation and pulse rate to the Analyzer to be displayed in real time; sampling rate is 250 Hz. In addition, ECG is filtered using a band pass FIR approach with cut-off frequencies of 0.6 Hz and 37 Hz.

When an electrode disconnects, the Recorder sends a command to the Analyzer to restart the data acquisition after this condition is fixed. The acquisition of valid signals is essential for the digital processing that is carried out later. When the acquisition process ends successfully, all data is processed and stored in a database. If errors persist in the signal´s acquisition, the study of the patient is cancelled and the system is reported as out of service due to technical problems.

The Recorder´s electronic design can be divided into the following blocks: the processing unit, the power supply, the oximetry modules and the ECG amplifier, as presented in figure 2.

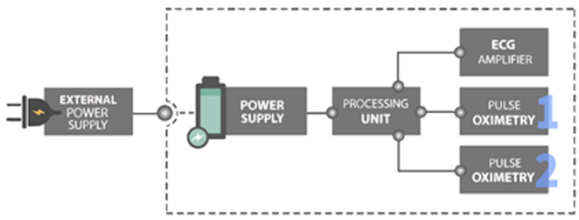

Figure 2: The Recorder divided in functional blocks.

The STM32F407 microcontroller was selected as the processing unit of the Recorder due to its high level of integration and performance, embedded memories and rich peripheral set. This microcontroller guarantees the necessary level of computing power and peripherals for all the tasks to be performed.

The main features of the processing unit are the following:

- A SD memory controller that stores all the data corresponding to each studied patient. It provides a backup to restore Analyzer´s database.
- A programmable timer to synchronized events and activities such as data acquisition and serial communication.
- Internal memory that allows storing Recorder's setup data.
- A fully integrated Bluetooth serial port module.
- An UART (Universal Asynchronous Receiver and Transmitter) controller for serial communication that enables to read data from oximetry modules.
- A driver for input/out lines used in the implementation of communication protocols.
- A twelve-bit analogue to digital converter for ECG acquisition.

The power supply block is composed of two elements. The first component is an external medical grade power supply able to guarantee the requested electrical isolation and the Recorder´s power consumption. This external power supply works with input voltages from 90V to 240V and its output voltage is 12V DC. The second element is an electronic circuit implemented into the Recorder to get 5V and 3.3V from the 12V previously mentioned. These voltages are required for other Recorder´s blocks.

The Recorder includes two oximetry modules to measure oxygen saturation in the right hand and on one of the feet of the studied newborn simultaneously. Many pulse oximetry modules are available in the market, so it is better to select one instead of start a new design to measure this variable. The E305654 module from Mindray, an acknowledged Chinese medical devices manufacturer, was selected because of its high performance in previous monitoring devices developed by the authors.

The communication between the processing unit and the pulse oximetry modules is implemented as a serial channel for each one; data transmission rate is 115200 bauds following a protocol set by the module´s manufacturer. Pulse rate value, oxygen saturation value and samples of the digitized plethysmography signals are transmitted.

Data acquisition time is set between one and five minutes in the Recorder´s setup. Lead II from de standard ECG is sampled at 250 Hz while pulse oximetry information, signal samples and parameter values, are read from the modules. A digital moving average filter is applied to each ECG sample to minimize the noise negative effects. The expression of this bandpass digital filter seems very complex, but it can be implemented in real time with some arithmetic transformations combining with dynamic data structures to archive the appropriated performance:

$$y(k) = \frac{1}{K^2} \sum_{m=k-K+1}^{k} \sum_{n=m-K+1}^{m} x(n) - \frac{1}{L^2} \sum_{m=k-L+1}^{k} \sum_{n=m-K+1}^{m} x(n) \quad (1)$$

Where:

x(n): Input signal.

y(k): Output signal.

K, L: Filter constants.

The Recorder´s goal is the acquisition of high quality signals to guarantee a reliable data input to the processing algorithm. On the other hand, the Analyzer is focused on the processing of the incoming cardiovascular data to extract the following information:

- Cardiac rhythm: Events such as bradycardia, tachycardia, asystole and ventricular arrhythmias can be detected when ECG samples are analyzed.
- QT interval duration: This parameter is recognized as a sudden death predictor [8].
- Pulse oximetry values: A difference of 3% of oxygen saturation between the right hand and any foot is an indicator of cardiovascular disturbance.
- PPG wave shape: A small amplitude might be associated with a low perfusion index, a negative condition for the metabolism. In addition, the PWTT (Pulse Wave Transit Time) index is computed to identify important changes in cardiac output.

All the signal processing, excluding digital filtering, is done offline, at the end of the signal acquisition process. Cardiovascular signals, pulse rate and oxygen saturation values are displayed on the Analyzer´s screen during the data acquisition process.

The ECG processing starts with QRS complex detection; this process in based on the Teager Operator. This operator mainly shows the frequency and instantaneous changes of the signal amplitude that is very sensitive to subtle changes. Although Teager Operator was first proposed for modeling nonlinear speech signals, it was later widely applied in the audio signal processing. Using this operator can minimize the effects of P and T waves on QRS complex detection.

The Teager Operator is computed for each ECG sample and these values are integrated into a moving window to emphasize the high energy zones associated with the QRS complexes. Two thresholds are applied; the first one set a frontier between signal segments candidates to be a QRS complex and the rest of the signal. The second threshold is combined with the signal slope to identify the onset and offset for each QRS complex. The expression 2 shows how to compute the Teager Operator in time domain:

$$T(i) = x(i)^2 - x(i-1) * x(i+1) \quad (2)$$

Where:

T(i): Teager operator for each sample.

x(i): ECG sample.

When QRS complexes are detected, RR interval duration is computed for each complex and a mean value is calculated to get the heart rate value. RR interval duration is the primary information to define if a QRS complex is premature.

The QRS complexes are classified as normal (N), ventricular premature (VP) and other complexes (OC). It is essential because QT interval duration and PWTT index are measured in N complexes only while VP complexes are related to dangerous arrhythmias. A QRS complex will be considered as N when its duration is between the 80% and 120% of the mean duration and the complex is not premature. A VP complex will be premature, wide and different in amplitude from the mean of the studied signal. QRS complexes that are not classified as N or VP will be considered as OC.

The arrhythmia analysis is based on the duration of RR intervals and the QRS classification results. The fulfillment of the following criteria is sought:

- Bradycardia: When heart rate value is below a preset limit.
- Tachycardia: When heart rate is higher than a preset limit.
- Asystole: Absence of QRS complexes in a preset period.
- Frequent VP: When the VP rate is higher than a preset limit.

The cardiac rhythm is normal when none of the above conditions is met. Other disturbances such as edema and intraventricular conduction disorders are studied. Edema is associated with low

voltage QRS complexes while a continuous wide QRS complex pattern with a stable rhythm is related to the cited conduction disorders.

QT interval duration for each normal QRS complex is measured. This process is based in an algorithm described by the authors in previous papers [9,10]. The essence of the algorithm is to find the moment after the T wave peak when the difference between the baseline and the ECG stops decreasing. If the signal voltage is very low, this parameter is not measured to avoid measurement errors.

PWTT index is computed combining features of the ECG and PPG waves; it is measured only for normal QRS complexes. The R wave peak is used as start point to find the maximum positive slope in the plethysmography wave before the next QRS complex, the distance between these points is the PWTT index. In addition, pairs of pulse oximetry values and their differences are studied to detect cardiovascular disturbances according to findings reported previously [5,6].

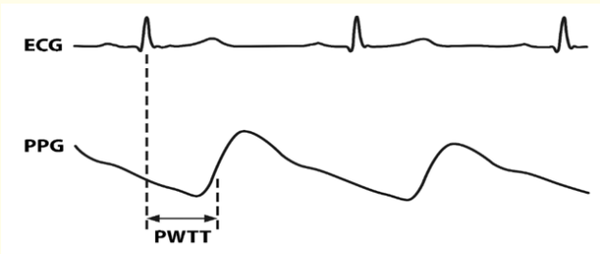

Figure 3: PWTT index as the time from the R wave peak to the most positive slope of the PPG cycle.

When all the measures and analysis described above indicate normal results, the analyzed newborn is classified as "cardiovascular healthy". If any of the analyzed measures is out of their respective normal ranges, the corresponded test should be repeated or a more detailed tests and analysis should be indicated.

Results and Discussion

A prototype of the proposed solution has been developed and tested at laboratory level because national regulatory body approval is mandatory for the application of medical technology to humans. Currently, the authors are working in compliance with the requirements demanded by the regulatory body.

The Recorder has been tested as a whole according to the IEC 60601-1 general safety standard for medical devices. Pulse oximetry modules are supported by international certifications, such as CE mark, guarantying compliance with current standards, but the ECG amplifier was developed by the authors, so a standard for one-channel ECG device should be applied. The most significant technical results are shown in table 1.

All technical results meet the applied standard but it was impossible to show them all due to the limits of the paper. Combining certified pulse oximetry modules, a certified medical power supply and a well-designed ECG amplifier, the authors have developed a safe medical device. The detection of QRS complexes was tested using the MIT-BIH Arrhythmia Database which is considered as a gold standard for this purpose. Table 2 shows the results for each ECG. These signals include a representative variety of waveforms and artifact that any detector could encounter in routine clinical use.

Test	Result
Dynamic input range	±5 mV
Input impedance	Greater than 2,5 MΩ
Maximum DC input level	320 mV
Internal noise	21 µV
Patient auxiliary current	Less than 0,01 mA
Common Mode Rejection Rate	Greater than 90 dB

Table 1: Main technical results according to IEC 60601-1 standard.

Record	QRS	TP	Sensitivity	Record	QRS	TP	Sensitivity
100	2273	2273	100.00%	201	1963	1960	99.85%
101	1863	1861	99.89%	202	2136	2127	99.58%
102	2187	2160	98.77%	203	2980	2963	99.43%
103	2084	2084	100.00%	205	2656	2624	98.80%
104	2229	2220	99.60%	207	1860	1833	98.55%
105	2572	2549	99.11%	208	2955	2933	99.26%
106	2027	2007	99.01%	209	3005	2996	99.70%
107	2137	2120	99.20%	210	2650	2631	99.28%
108	1762	1741	98.81%	212	2748	2746	99.93%
109	2532	2507	99.01%	213	3251	3220	99.05%
111	2124	2111	99.39%	214	2262	2241	99.07%
112	2539	2538	99.96%	215	3363	3360	99.91%
113	1795	1794	99.94%	217	2208	2177	98.60%
114	1877	1860	99.09%	219	2154	2136	99.16%
115	1953	1951	99.90%	220	2048	2046	99.90%
116	2412	2398	99.42%	221	2427	2407	99,18%
117	1535	1520	99.02%	222	2483	2466	99.32%
118	2278	2253	98.90%	223	2605	2581	99.08%
119	1987	1981	99.70%	228	2053	2018	98.30%
121	1863	1861	99.89%	230	2256	2253	99.87%
122	2476	2475	99.96%	231	1571	1568	99.81%
123	1518	1516	99.87%	232	1780	1772	99.55%
124	1619	1592	98.33%	233	3079	3036	98.60%
200	2601	2576	99.04%	234	2753	2750	99.89%

Table 2: Results detecting QRS complexes from MIT-BIH Arrhythmia Database.

The sensitivity of the proposed QRS complex detection algorithm was 99.36%. This measure was over 99% in 38 ECGs and never was less than 98.30%. The algorithm performance was highly stable; it is very important for the intended use of the proposed solution. Newborns are non-cooperative patients and signal acqui-

sition process could be hard, although MIT-BIH database includes signals acquired in worse conditions.

QRS complex classification process was not evaluated with the same criteria used in MIT-BIH database because the authors are focused on normal and ventricular beats only. The evaluation of the QRS complex classification was implemented using the conclusions of a specialist as golden rule. A software tool was developed by the authors for the ECG reviewing process and the specialist classified the QRS complexes in the same groups as the proposed solution: normal (N), ventricular contractions (VC) and other contractions (OC). It is impossible to include the complete results, but the authors summarized the evaluation in the following sentences.

Regarding the classification of N type QRS complexes, there was a full coincidence between the algorithm conclusions and criteria emitted by the specialist. However, there were 32 QRS complexes classified as OC by the algorithm that the specialist considered as N. This error is not determinant in the effectiveness because QRS complexes type OC do not influence the final evaluation of the analyzed newborns.

Regarding the classification of VC type QRS complexes, there was a full coincidence in all those who were premature. The proposed algorithm was not able to classify the non-premature ventricular QRS complexes, but this kind of complexes are exceptions. Nevertheless, authors will work to solve this weakness in the future. The results obtained confirm that the QRS complex classification process is appropriate for the intended use.

A complementary test was developed with the Preterm Infant Cardio-respiratory Signals (PICS) database available in Physionet website [9]. Only QRS complex detection have been tested and sensitivity was 99.21%; very close to the result with MITBIH Arrhythmia Database shown previously. The next step will be test the QRS complex classification process with the same data.

The algorithm to compute PWTT index was tested with simulated signals. A ProSim 8 Vital Signs Simulator was used to generate ECG and PPG signals simultaneously with heart rate between 100 and 180 beats per minute. The identification of R wave peak was always correct as well as the moment of maximum slope in the PPG, so the PWTT index measurement was successful.

Conclusion

The proposed solution seems a useful approach to the cardiovascular newborn screening because advantages of ECG and oximetry ate mixed in a single method while patient discomfort is minimized. PWTT index can provide valuable information on the cardiovascular system of the studied newborn. More tests are necessary, 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.

Bibliography

1. J Bruno and T Havranek. "Screening for Critical Congenital Heart Disease in Newborns". *Advances in Pediatrics* 62 (2015): 211-216.
2. I Zeltser., *et al*. "Lessons learned from preparticipation cardiovascular screening in a state funded program". *American Journal of Cardiology* 110.6 (2012): 902-908.
3. J Rodriguez-Alarcon., *et al*. "Early neonatal sudden death or near death syndrome. An epidemiological study of 29 cases". *Acta Paediatric* 83.7 (1994): 704-708.
4. JL Hoffman and S Kaplan. "The incidence of congenital heart disease". *Journal of the American College of Cardiology* 39.12 (2002): 1890-1900.
5. VL Vetter. "Should Electrocardiographic (ECG) Screening of All Infants, Children and Teenagers be Performed?" *Circulation* 130.8 (2014): 688-697.
6. PJ Schwartz and M Kotta. "Sudden Infant Death Syndrome and Genetics". *Journal of the American College of Cardiology* 71.11 (2018): 1228-1230.
7. Jean-Marc Lupoglazoff., *et al*. "Long QT Syndrome in Neonates". *Journal of the American College of Cardiology* 43.5 (2004): 826-830.
8. R Gonzalez-Fernandez. "Computerized Analysis of the Electrocardiogram". *Caderno de Engenharia Biomédica* (1997): 139-148.
9. R Gonzalez-Fernandez., *et al*. "QT Dispersion Monitoring as a Coronary Disturbance Prediction Tool". Computers in Cardiology. Boston, USA: IEEE Press (2005): 507-510.
10. AH Gee., *et al*. "Predicting Bradycardia in Preterm Infants Using Point Process Analysis of Heart Rate". *IEEE Transactions on Biomedical Engineering* 64.9 (2017): 2300-2308.