

SMART MULTIPARAMETER INFANT APNOEA MONITOR

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ABSTRACT: Apnoea is a common disorder in preterm infants who may also suffer from neonatal hypertension. Conventional apnoea monitors used in neonatal intensive care units (NICUs) do not include features for measuring neonatal blood pressure and real-time remote monitoring. Smart devices to monitor this problem in resource-poor environments are expensive and sparsely available. This paper presents the development of a smart multiparameter infant apnoea monitor in a resource-poor setting. The circuit was designed and simulated in Proteus software. The signals were processed using Arduino mega microcontrollers. The microcontroller concurrently communicates apnoea events to the GSM modem and alarm which notify the doctor and caregivers by SMS alert and audible alarm, respectively. Preliminary testing on stable infants at the NICU of Lagos University Teaching Hospital showed promising results. The device can effectively be used to monitor apnoea in infants as well as transmit the results to the doctor in a remote location by SMS. It can also be used to monitor other parameters like

oxygen saturation, respiratory rate, heart rate and blood pressure. The documented experiences will provide useful insights for smart infant apnoea to monitor development in resource-poor environments.

KEYWORDS: *Infant Apnoea, Preterm, Internet of Things, Neonatal Hypertension, Pulse Oximetry Sensor.*

1.0 INTRODUCTION

Apnoea is a respiratory disorder characterized by momentary pauses in breathing or momentary or sustained reductions in breath amplitude in an individual, leading to significant arterial hypoxemia and hypercapnia [1]. In infants, this condition is commonly associated with prematurity. It is defined as the cessation of breathing for a minimum of 20 seconds or lesser periods in the presence of bradycardia, cyanosis or other evidence of oxygen desaturation [2]. The incidence of apnoea is high among critically ill babies globally [3]. In particular, it is a leading cause of perinatal and neonatal mortality in resource-poor countries [4][5][6]. The disorder has been linked to several undesirable health conditions such as repeated hypoxemia, asphyxia [1], poor neurodevelopmental outcome and even death. Preterm infants are not only prone to apnoea. Still, they are also predisposed to other respiratory diseases due to the poor development of mechanisms of respiratory control, especially in their first year of life [7][8]. Therefore, frequent monitoring of their breathing patterns, especially during sleep, is necessary.

Neonatal hypertension is common in preterm infants, which necessitates frequent blood pressure (BP) monitoring in infants admitted to neonatal intensive care units (NICU) [9][10]. Regular non-invasive BP measurements are invaluable in babies, especially in the first early days of life [11][12][13]. In addition, it is necessary to monitor their oxygen saturation and heart rate frequently. Oxygen saturation is detected using pulse oximetry and arterial blood gases (ABG) [14]. Several innovative approaches have been previously used in the design of apnoea monitors. The gold standard for apnoea diagnosis is the use of polysomnography (PSG) [15][16]. PSG involves continuous, simultaneous multi-channel measurements of eight different physiological signals, including oronasal flow, oxygen saturation and heart rate, electroencephalography (EEG, brain waves), electro-oculography (EOG, eye movements), chin electromyography (muscle

activity), electrocardiography (ECG), respiratory effort and airflow. Unfortunately, such testing is expensive, burdensome, time-consuming, and typically carried out for very limited periods in a foreign environment. It is complicated and expensive to use in resource-poor settings [17].

The project aims to develop a smart multiparameter infant apnoea monitor that can detect the incidence of apnoea in infants and monitor other important parameters such as respiratory rate, oxygen saturation, heart rate and blood pressure. The device was conceived due to the shortage of functional apnoea monitors in the NICU of a tertiary hospital in Southwest Nigeria. The main significance of this study is the potential reduction in infant mortality with successful deployment and availability of the device. Also, it can enhance the performance of physicians who would be enabled to monitor the health condition of critically ill patients remotely.

2.0 LITERATURE REVIEW

Research on apnoea monitor design and development has received significant interest [18]. A home sleep test (HST) was proposed by [19] as a well-validated alternative to PSG. HST has fewer sensors than PSG and is more compact, less expensive, and less cumbersome to use with little or no support from a technologist. Oliver and Flores-Mangas [20] built an automatic sleep apnoea detection and a monitoring system comprising physiological sensors wirelessly connected via Bluetooth. While in [21], the authors developed a sleep apnoea detection and monitoring device, which only requires two data channels: tracheal breathing sounds and pulse oximetry (SaO₂ signal). Considering the high risk of sleep apnoea, some medical device manufacturers have adopted a pulse oximeter which measures the oxygen saturation level in the blood, which is believed to decrease by 4% once there is the cessation of airflow in the lungs for at least 10 seconds [21]. Also, authors in [22] developed an IoT-based sleep apnoea monitoring system that helps users monitor different indexes of sleep and notify the physician through a mobile platform when apnoea occurs.

Furthermore, in [23], the authors proposed using multimodality sensors to observe rest by utilizing a non-intrusive and low-cost sleep-wake detection system that detects early symptoms of sleep disorders. Also, in [24], a sleep apnoea detection system was designed and developed. While in [25], wearable e-textile sensors utilized an IoT

method to collect real-time data on sleeping behaviours and respiratory rate. In another study, [26] developed a smart healthcare monitoring system based on the Internet of Things (IoT) to enable remote monitoring of patients on the internet. The device consists of pulse oximetry and temperature sensors for detecting apnoea and monitoring temperature.

In recent years, there has been a significant increase in the demand for health monitoring devices both in industry and research. The benefits of these wearable health monitoring technologies are enormous since they could enable the detection of early signs of health deterioration; notify health care providers in critical situations; enhance the sense of connectedness with loved ones by sharing real-time raw or interpreted physiological data; find correlations between lifestyle and health and transform health care by providing physicians with real-time data amongst others [27]. Garde *et al.* [28] used a phone oximeter, a portable device integrating pulse oximetry with a smartphone, to detect obstructive sleep apnoea. However, in order to make these wearable devices more practical, they need to be non-intrusive, comfortable to wear, consume power efficiently, have a user-friendly interface by preserving privacy, have a minimal failure rate and have highly accurate alarm triggers especially if used for diagnostic purposes. The available breathing monitoring systems are both expensive and invasive [20]. Tewel [29] developed an apnoea monitor for infant monitoring using a microelectromechanical (MEMS) accelerometer. The device focused primarily on monitoring the breathing movements of the infant's abdomen without considering other vital parameters.

Conventional infant apnoea monitors have limited features and cannot inform the doctor of apnoeic episodes remotely. The use of mobile phones and the internet is prevalent in Nigeria. According to the Nigerian Communications Commission (NCC), Nigeria has a high internet penetration rate of 144, 949, 194 million [30]. There is a need to develop a smart infant apnoea monitor that also includes the monitoring of arterial blood pressure of preterm infants. Blood pressure (BP) measurement is an important vital sign to monitor in infants admitted to NICU to assess adequate circulation and tissue perfusion in the newborn, which is often not measured in conventional infant apnoea monitors.

Furthermore, doctors need real-time remote monitoring of the patient by doctors, which will greatly benefit providing urgent response during an emergency. The developed device can simultaneously monitor apnoeic episodes, pulse rates, and blood pressures in infants and is suitable for home and hospital use to send instant messages to the doctor in a remote location using the Internet of Things (IoT). To the best of our knowledge, there is no commercially available smart infant apnoea monitor which combines respiratory rate, heart rate and blood pressure monitoring in infants with IoT capability with considerations for unstable electricity supply.

3.0 MATERIALS AND METHODS

3.1 Device design and requirements

The study was approved by the College of Medicine, University of Lagos Health Research and Ethics Committee (CMUL/HREC/03/18/342). Informed consent was obtained from the parents of the participants. Device requirements are summarized based on the American Society for Testing and Materials (ASTM) standard requirements in Table 1. Identified risks for the device and mitigation measures are shown in Table 2.

Table 1: Device requirements

S/N	Characteristics	Requirement
1	Medical	User-specified SPO ₂ , heart rate, respiratory rate and blood pressure
2	Economic	Low cost
3	Mechanical	Portable DC Powered
4	User-interface	Visual display of settings and status
5	Repeatability	Indicators within 10% of correct reading

Table 2: Risk mitigation strategies

Risk	Mitigation Measures
Inadequate Alarms	A red LED indicator is used as a visible alarm to indicate apnoea An audible alarm is activated once apnoea occurs
Electrical Shock	The device is powered by low power DC batteries and adequately insulated to prevent exposure to electric shock
Inaccurate Detection	Signal amplification and filtering were incorporated into

	the design to enhance detection accuracy.
	The sensor measurement interface was designed to improve contact with the subject.
Tissue Reactivity	The device was built with biocompatible materials with no tissue reaction

The translation of ideas into preliminary rough sketches is the first step. Afterwards, computer-aided design (CAD) was developed. The benefits of CAD in product development are well known. Hence, a 3D CAD design for the device was produced, as shown in Figure 1.

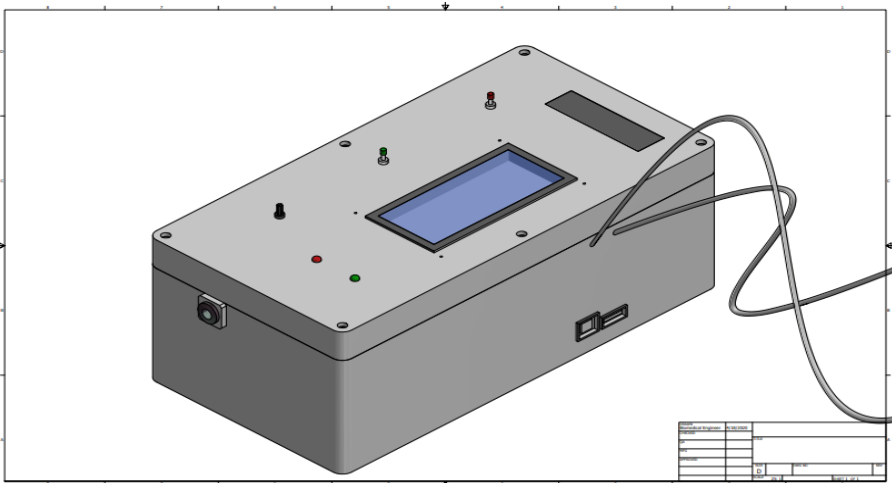


Figure 1: 3D CAD Design of Infant Apnoea Monitor

3.2 Device description

The device consists of the following sections; power supply, sensors, signal amplification and filtering, microcontrollers, graphical display, alarm and GSM module. The block diagram of the device shown in Figure 2 describes the entire system.

The device was powered by rechargeable Lithium-ion cells. The circuit included three sensors: an accelerometer, pulse oximetry and heart rate biosensor, and a blood pressure sensor. The accelerometer (ADXL335) was used for measuring respiratory rate (RR) as well as

apnoea detection, pulse oximetry and heart rate biosensor (MAX30100) was used for oxygen saturation and heart rate measurement, and the blood pressure sensor was for blood pressure measurement. Signal conditioning was achieved with signal filtering and instrumentation amplifier circuit. The circuit was constructed with an Arduino Mega 2560 microcontroller board which operates as a master and interfaced with four slave ATMEGA 328 microcontrollers. The master coordinates the communication and drives the display. The first slave was dedicated to the accelerometer sensor. The second slave was connected to the pulse oximetry and heart rate biosensor module, and the third slave, was connected to the pressure sensor, while the fourth slave microcontroller ensured an uninterrupted connection with the online server. The output includes a graphical liquid crystal display (GLCD), an audible alarm and the GSM module. The GSM module includes a registered subscriber identity module (SIM) card configured to send instant messages to a mobile phone once apnoea occurs through a Thingspeak IoT platform.

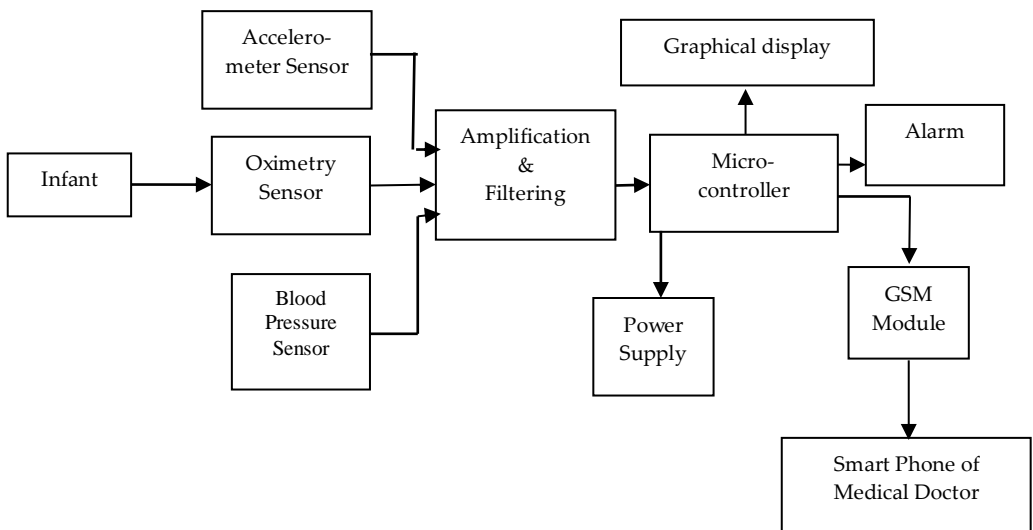


Figure 2: Block Diagram of the Smart Multiparameter Apnoea Monitor

3.3 Theoretical Framework

Apnoea detection is based on the ability of the accelerometer to measure the rate of change of the velocity of people and objects by sensing either static or dynamic forces of acceleration. It is generally

used to measure acceleration on one, two, or three axes [31]. In healthcare systems, accelerometers are combined with light, and flexible, electronic components that do not interfere with normal human motion and activities [32]. The design of an accelerometer is based on Newton's law of mass acceleration and Hooke's law of spring action, which implies that the mass undergoing acceleration exerts a force opposed to the restraining effect of spring [33]. For spring of mass M , damping coefficient D , spring coefficient K , external force F , and acceleration a , the movement of the spring is modelled by a second-order differential equation (1):

$$M \frac{d^2x}{dt^2} + D \frac{dx}{dt} + kx(t) = Ma(t) \quad (1)$$

The device was developed using a microelectromechanical sensor (MEMS) accelerometer, which operates based on the principle of capacitive sensing. In this study, the principle is applied to the conversion of body displacement of the MEMS accelerometer caused by breathing movements of the user to a change in capacitance which can be expressed as:

$$\Delta C = C_1 - C_2 \quad (2)$$

But,

$$C_1 = \epsilon \frac{A}{d - x} \quad (3)$$

$$C_2 = \epsilon \frac{A}{d + x} \quad (4)$$

Where, C_1 and C_2 = capacitances of the plates of the two capacitors.

A = Area of the plates

d = proof mass displacement

When apnoea occurs, there is no acceleration. Hence, $C_1 = C_2$. Therefore, $\Delta C = 0$. However, the differential capacitance increases when breathing is restored as $\Delta C > 0$. Signals from the accelerometer are sampled at a frequency of 3.4 Hz based on the sampling theorem. Given that a continuous signal does not have a frequency component higher than W Hz, the sampling frequency, f_s of the signal is calculated as:

$$f_s \geq 2W \quad (5)$$

Conversely, the integrated pulse oximetry and heart rate biosensor

module monitor oxygen levels and pulse rate. The principle of pulse oximetry is based on the absorption of different wavelengths of light. Red and infrared light is absorbed by oxygenated and deoxygenated haemoglobin differently. The sensor determines oxygen saturation in the blood using red and infrared light frequencies. The ratio between red and infra-red light is defined in equations (6) and (7) [34]:

$$R = \frac{AC_{RMS\ RED}/DC_{RED}}{AC_{RMS\ IR}/DC_{IR}} \quad (6)$$

$$R = \frac{\log(I_{AC}) + \lambda_1}{\log(I_{AC}) + \lambda_2} \quad (7)$$

Where I_{AC} = Light intensity where only AC is present

λ_1 = Wavelength of red light

λ_2 = Wavelength of Infrared light

R = Ratio of ratios

The oxygen saturation is therefore calculated as shown in (8):

$$SpO_2 = 110 - 25 \times R \quad (8)$$

Blood pressure monitoring was implemented based on the oscillometric method, one of the most widely used blood pressure measurements in automatic cuff devices [35]. The blood pressure is measured non-invasively by occluding the brachial artery using external neonatal cuffs [36]. Mean arterial pressure (MAP) is attained [37]. While systolic and diastolic pressure are empirically estimated in accordance with the fixed ratio algorithm [38]. Enhancement of signal quality and noise removal was achieved by filtering. The fourth-order active bandpass filter was designed using multiple feedback (MFB) topology in accordance with methods proposed by [39]. Further processing of signals was achieved using the moving average digital signal processing (DSP) method. This technique takes an average of prescribed points in the signal to yield each point in the output signal [40]:

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i + j] \quad (9)$$

Where $x[i + j]$ = input signal

$y[i]$ = output signal

M = Number of points

Thus, the moving average filter smoothed the signal and decreased random noise. The mode selector chooses the parameters to be tested to test the device. The first mode includes respiratory rate, oxygen saturation and heart rate. At the same time, blood pressure is the only parameter included in the second mode. Apnoea condition is determined by placing the accelerometer around the abdomen to detect abdominal movement during breathing. The infant must lie in a supine position. When apnoea occurs, the regular abdominal movement ceases for at least 20 seconds. The accelerometer is unable to detect any abdominal movements. Hence, this information is transmitted to a buzzer alarm. The alarm is activated to notify nurses and caregivers that apnoea has occurred.

Similarly, the physician receives an instant SMS notification on their mobile phone. Instant SMS notification was achieved with a Sim800L GSM module configured to send data to the Thingspeak IoT platform. This configuration enables the doctor to access and store the results from a remote location. The device is reset after turning off the alarm before using it again.

The blood pressure circuit includes a pressure sensor that detects the pressure and transmits the results to the microcontroller, which sends it to the visual display. In testing the blood pressure, the neonatal cuff with a limb circumference of 6 to 11 cm is attached to the neonate's arm and inflated. The pressure sensor detects the differential pressure between atmospheric and blood pressure. The systolic and diastolic blood pressure is displayed on the digital display.

4.0 RESULTS AND DISCUSSION

The proof of concept (POC) was subjected to pilot testing in the NICU of Lagos University Teaching Hospital. The preliminary tests were performed on only stable infants for safety reasons, and there were no reported side effects. Fig. 3 shows the POC with the values of the heart rate, SpO₂, and respiratory rate of a sample test indicated respectively by the visual display.



Figure 3: The POC Smart Infant Apnoea Monitor

Regular breathing in humans is associated with abdominal movements. The 3D printed casing of the accelerometer is placed on the subject's abdomen to detect regular abdominal movements to detect apnoea. The cessation of the abdominal movement for at least 20 seconds is an indication that apnoea has occurred. The accelerometer detects this. The alarm turns on, and the device also sends an SMS to a phone configured Arduino program. The mean SPO₂, respiratory rates and heart rate results are shown in Table 3.

Table 3: Results of SPO₂, RR and HR

	SpO₂	Respiratory Rate (RR)	Heart Rate
Mean	95.17	30.08	81.33
Standard Deviation	1.53	3.34	14.13

Table 4: Results of Blood Pressure Measurements

	Systolic	Diastolic
Patient A	96	62
Patient B	82	63
Patient C	85	64

The mean \pm standard deviation observed for SpO₂ (%), RR (cycles per minute), and HR (Beats per minute) for the POC were (95.17 \pm 1.53; 30.08 \pm 3.34 and 81.33 \pm 14.13). The blood pressure readings from three infants are shown in Table 5. The results were comparable to that of a standard device. Some innovative features have been incorporated into the device to improve its usefulness. Regular monitoring of apnoea occurrence in a neonate is essential as nursing documentation has been considered inadequate [41]. This will help the physician to independently assess the progress made in treatment even while not physically present. However, the design also includes an audible alarm which notifies medical personnel or caregivers physically present to enable them to provide quick intervention. Biological signals are not only weak but also non-deterministic and thus generally produce varying output values. We demonstrated that signal quality could be enhanced by digital signal processing and an efficient filtering system. Figure. 4 shows the output analogue voltage produced by the MEMS accelerometer when the accelerometer is placed on a subject. As observed, the signal is characterized by noise. However, the application of moving average filtering to the raw signalled improves signal quality and noise reduction, as observed in Figure 5.

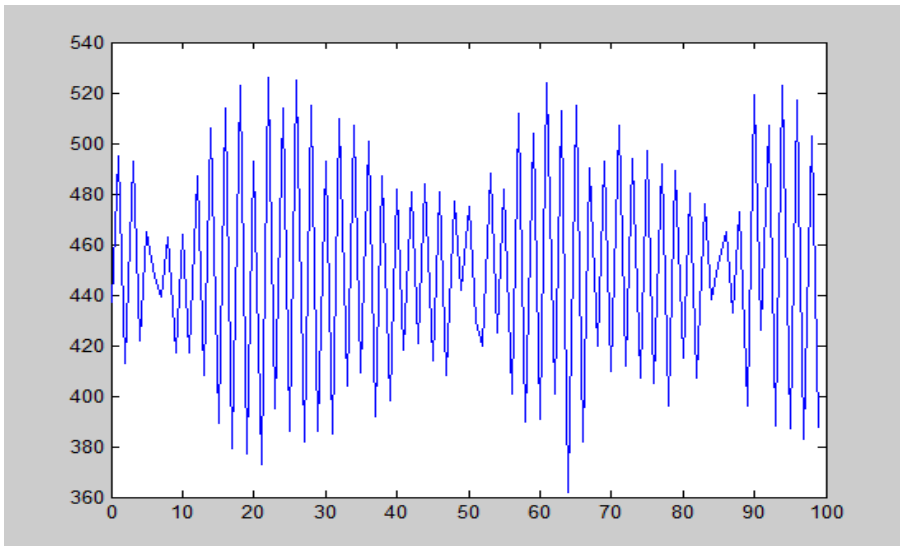


Figure 4: Raw Data from Y-axis of stationary sensor

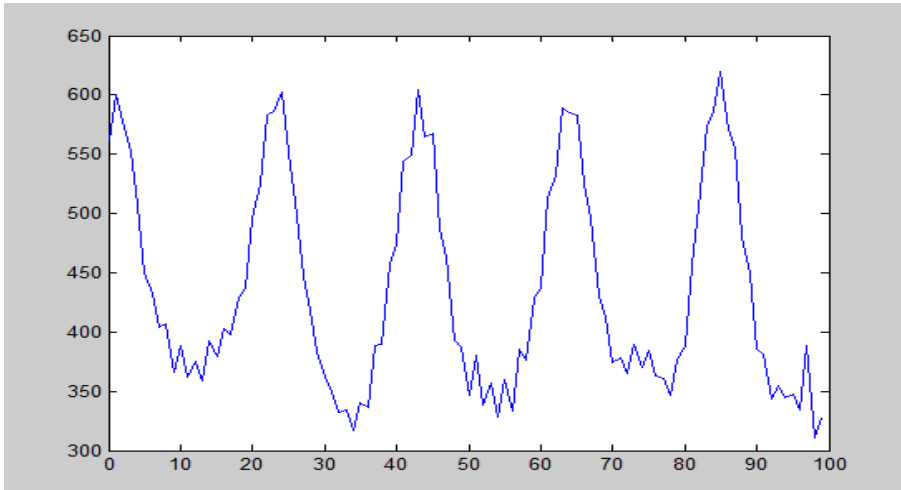


Figure 5: Moving average filtered data from Stationary object z-axis

Furthermore, 3D printed sensor casing was shown to provide a smooth measurand-sensor interface, enhancing the device's effectiveness. To the best of our knowledge, this study is one of the few to develop a smart multiparameter infant apnoea monitor for neonates in a resource-poor environment. The benefits of this device include its ability to send instant SMS to notify the physician of apnoeic episodes. It can also be used at home to monitor infants' apnoea and basic vital signs even after being discharged from the hospital. When there is a need to return to the hospital based on the regular alerts received by the physician, the parents can be called to return the baby to the clinic for further observations and treatments.

The development of smart infant apnoea monitors has enormous prospects and huge market potential, given the prevalence of the disease in resource-poor settings. We also observed significant improvements in signal quality using high gain instrumentation amplifiers for signal amplification. This agrees with previous studies that described the benefits of instrumentation amplifiers for biomedical applications [42]. The use of a biocompatible, non-toxic sensor casing is an important factor to consider in developing medical devices, particularly in infants, for obvious safety reasons. Product development processes for such medical devices require effective project and supply chain management strategies. Proactive measures to mitigate the supply chain gaps in component sourcing will greatly

impact product development. The main limitation is the occasional inability to detect precise breathing movements. Also, the alarm is beeping when apnoea is detected and needs to be reset.

5.0 CONCLUSIONS

In this paper, we discussed the development of a smart multiparameter infant apnoea monitor in a resource-poor setting and an evaluation of its performance. The study presented documented problems experienced in the device development, especially those peculiar to resource-poor settings and their possible solutions. The developed device showed good prospects when tested. Further investigations will be done on the utility of the device.

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