A Wearable Diagnostic Device to Combat Children’s Pneumonia

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Abstract — Pneumonia has been labeled as the single largest cause of child mortality for the children under five in developing countries around the world. We propose a novel method to continuously monitor parameters like Respiration Rate, Heart Rate, Blood Oxygenation (SpO2) and Body Temperature in a noninvasive and nonobtrusive manner behind the ear. The data is streamed using WiFi to the parent’s smartphone or a smart gateway device which uploads it to a server. This paper also explores the opportunities for presenting patient vital signs from such a device to the remote health care workers and doctors. A prototype named Raksh was developed and various sensors were evaluated. The final bill of material cost of the device would be 23 US dollars.

Index Terms — Wearable sensor, Respiration rate, Pneumonia monitor, Remote healthcare, Raksh

I. INTRODUCTION

Pneumonia has been the cause of death for over two million children below the age of five [1]. Most of these deaths occur in developing nations in South East Asia and Africa [2]. Delay in diagnosis and lack of continuous monitoring increase the risk and cost of treatment. Early detection and providing timely treatments can reduce the mortality rate of pneumonia [3]. Community healthcare workers face a huge challenge in assessing and treating children in low to medium income countries [3]. The difficulties arise primarily due to lack of clinical and portable diagnostic tools resulting in slow diagnosis and reduces survival rate. Primary method for diagnosing pneumonia is by assessing whether the child has an elevated respiration rate greater than or equal to 40 breaths/min [4]. Table I highlight the normal and abnormal vital parameters for children with pneumonia. Clinical methods currently employed in Low and Middle Income Countries (LMIC) rely on manual counting of respiration rate using stethoscope or by observing motion of chest for the recommended 60 seconds. The method not only requires extensive training for community health workers [5] but also results in poor accuracy and high variability between operators [6].

There is a need for an inexpensive yet accurate wearable diagnostic device which can continuously monitor vital parameters like Respiration Rate, Heart Rate, Blood Oxygenation and Body temperature to accurately identify pneumonia and thus enabling timely treatment. Providing timely aid can make the difference between life or death for the child. Human and monetary resource which is limited in LMIC can be conserved by facilitating remote monitoring, thus enabling healthcare workers to provide better care to the community. The current tools used are designed for a stationary bedside monitoring purposes in LMIC and there is a lack of continuous monitoring. One popular method relies on using pulse oximetry to track hemoglobin saturation. Current systems are bedside pulse oximeters which are nonportable and are expensive [7]. Bulky and obtrusive spirometers are also used for monitoring respiration [8]. Monitoring changes in arterial carbon dioxide in exhaled gas is also a method frequently used for monitoring respiration.

We propose a novel, inexpensive ear-worn device which would noninvasively and nonobtrusively monitor vital parameters like Respiration Rate, SpO2 levels, Heart Rate, Body temperature of a child to enable rapid diagnosis wirelessly. Respiration Rate possesses immense value in clinical situation and is used to monitor patients who are in ambulatory conditions [9] and in Intensive Care Unit [10]. Continuous monitoring of Respiration Rate remotely would be monumental in combating respiratory ailments. In hospital wards in LMIC, patient monitoring is done intermittently by nurses. Deterioration in condition may go unnoticed resulting in hospital mortality [11]. Signs of respiratory distress and tachypnea can be detected by measuring respiration rate. Parameters like SpO2, Heart Rate and Body temperature are equally important and need to be continuously measured. Blood Oxygenation plays a major role in identifying Hypoxemia in children with pneumonia [12]. Hypoxemia occurs when there is an abnormally low concentration of oxygen in the blood leading to eventual fatality if left unattended. Body Temperature helps rapid diagnosis as it is one of the symptoms used in pneumonia and continuous sensing can provide insight into effectiveness of medication [13].
<table>
<thead>
<tr>
<th>Age</th>
<th>Normal Respiration Rate</th>
<th>WHO threshold Respiration Rate for Tachypnea</th>
<th>Normal SpO2</th>
<th>WHO threshold SpO2 for Hypoxemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-12 Month</td>
<td>25-40</td>
<td>50</td>
<td>&gt;93%</td>
<td>&lt;92%</td>
</tr>
<tr>
<td>1-5 Years</td>
<td>20-30</td>
<td>40</td>
<td>&gt;92%</td>
<td>&lt;90%</td>
</tr>
</tbody>
</table>

II. RELEVANT STUDIES

Recently with the advent of smart phones and wearable sensors, a range of systems have been developed for monitoring respiration and other vital parameters of a child. Mobile sensors are used to detect rapid respiratory rate in diagnosis of pneumonia [14]. Piezoresistive fabric sensors integrated into a wearable vest are used to monitor chest expansion and contraction during respiration [15]. Respiration sounds sensed by mobile phone microphone are used to detect abnormal respiration and respiratory distress [16].

Another unique approach was done by Farah and Reza to evaluate respiration rate by using thermal imaging of the nose [17]. By studying the mentioned work in this area our contributions are listed as

1) Design and development of a low cost, low power, wearable multiparameter sensor for pneumonia diagnosis and monitoring.
2) Development of a system for doctors to remotely monitor the child by sending data to the cloud through a WiFi with a mobile phone as a gateway device.

III. SYSTEM DESIGN

The Prototype currently developed and named Raksh consists of sensors to monitor vital parameters like Respiration Rate, Heart Rate, Blood Oxygenation and Body Temperature. The system block diagram is shown in Fig. 1. The data from the sensors are read by an STM32 Micro Control unit (MCU) and is transferred securely over WiFi to a server. A 3.7 V, 240 mAh Lithium Polymer battery along with power management circuit is used to power the system. The whole device sits comfortably behind the ear while being unobtrusive to the child. Table II elucidates the specification of the system.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>35x20x10mm (Central unit)</td>
</tr>
<tr>
<td>Battery</td>
<td>240 mAh</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>100 mW</td>
</tr>
<tr>
<td>Expected Battery Life</td>
<td>1 week</td>
</tr>
<tr>
<td>Unit Cost (1000pcs)</td>
<td>35$</td>
</tr>
</tbody>
</table>

A. Sensors

1) Respiration Sensor: The variation of the nasal temperature is measured accurately using the MLX90614 noncontact infrared temperature sensor which is pointed to the nasal passage. The sensor is smaller in size and comfortable when compared to nasal thermistors. As the child exhales, the nasal temperature increases which are picked up by the Infrared (IR) temperature sensor. The data is read at high speeds by the Microcontroller over the I2C bus. The sensor also detects ambient temperature which is used for calibration to identify threshold. The samples are compared with each other and the peaks are found. The internal timer is triggered to find the peak to peak time duration from which the respiration rate can be accurately found.

2) Heart Rate and Blood Oxygenation sensor: Photoplethysmography (PPG) and Pulse Oximetry (SpO2) are carried out by a single sensor which is used to measure reflectance of three LEDs of different wavelengths. SpO2 is found by measuring the reflectance of 650 nm light in comparison with 940 nm light. Heart rate is measured by PPG wherein the change in blood volume is found by measuring reflectance of 850 nm light. The measurement of vital signs by placing sensors and LEDs behind the earlobe has been validated by previous studies [18]. The Si1141 I2C light sensor was chosen for its small size and cost. The presence of an integrated amplifier and Analog to Digital Converter (ADC) has resulted in a lesser Bill of Materials (BOM). The Si1141 light sensor also has inbuilt LED drives which allow easy control over three LEDs.

3) Body Temperature sensor: The body temperature was also measured nonobtrusively by checking the ear canal temperature using the LMT70 temperature sensor. The analog signal is fed to the MCU’s Analog to Digital converter at 15Hz sampling frequency.

4) Activity and sleep sensing: An ADXL345 accelerometer is also used to provide activity and sleep data of the child. The technique of actigraphy is used to continuously record the motion data. Activity or inactivity can be quantified and shared with the doctor. Instances of abnormal sleepiness or severe restlessness can be found.
B. Data Processing & Communication

A powerful STM32F205 microcontroller is used for interfacing various sensors. Sleep modes are used frequently to increase the battery life of the wearable. A Broadcom BCM43438 module is used to provide wireless connectivity to the system and supports both Bluetooth Low Energy and WiFi. Even though WiFi is power consuming, we have used it to directly post the data to the cloud over WiFi in the prototype. The WiFi transmission is done in bursts to conserve battery. A chip antenna was used to give a low profile design to the system. Commercially available components were chosen to design Raksh. The future iterations would use a Nordic Semiconductors nRF52832 BLE Microcontroller for its extremely low power consumption and low cost. The data can either be transferred through the parent’s smartphone if available or through a dedicated gateway device bundled along with the sensor which would send the data to the cloud over Mobile Networks. Even though the availability of mobile network is limited in very remote areas, initiatives like the Google Project Loon is likely to expand connectivity to even remote locations around the world [21].

C. Power Management & Battery

A 3.7 V, 240 mAh Lithium Polymer battery is used to power the prototype. A Buck-Boost topology based converter is used to give a clean 3.3 V supply to the MCU and power various sensors. A MCP73831 IC is used for charging the Lithium Polymer battery. It can be powered from a 5 V standard USB wall plug. The future iterations would use a smaller and safer rechargeable coin cell battery such as the LIR2032 with external recharging.

D. Packaging

The comfort of the child was a priority while designing Raksh. If the design is obtrusive, the usage will be limited. So Raksh is designed with MCU, wireless unit and battery behind the outer ear helix to provide high degree of comfort. Fig. 2 illustrates a child wearing Raksh. Here, the modular nature of the device can be seen. Fig. 3 illustrates the inner view of the device. The SpO2 and PPG sensor are gently clamped to the earlobe and the body temperature sensor is integrated with an ear bud like an earphone. The IR non-contact temperature sensor is held below the nostril using a semi-rigid cable. This would resemble the microphone used with headphones. The approximate dimension of the device is 40mm x 20mm x 10mm which can be easily placed behind the ear. Length of the cable is 50mm which is adjustable according to the user preference. The system would be extremely inexpensive due to the low Bill of Materials cost and would be light to wear at 38 grams. Table III illustrates the various size and weight of the components.

E. Human Interface

The device is designed to sit comfortably behind the outer ear helix and is discrete in nature. The optical pulse oximetry and PPG sensor are gently clamped to the earlobe. The body temperature is measured with a temperature sensor in the wearable which is inside the ear bud. The respiration rate is sensed by using the non-contact IR thermopile sensor which is placed below the nostril. This thermopile array sensor is connected to the ear worn unit using a semi-rigid cable which keeps the sensor stable to measure the nasal temperature.

<table>
<thead>
<tr>
<th>Component name</th>
<th>Size</th>
<th>Weight</th>
<th>Unit cost (1000pcs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>20<em>7</em>30mm</td>
<td>7.1g</td>
<td>2$</td>
</tr>
<tr>
<td>STM32F205</td>
<td>12<em>12</em>1mm</td>
<td>&lt;2g</td>
<td>4.5$</td>
</tr>
<tr>
<td>MLX90614</td>
<td>17<em>11</em>0.7mm</td>
<td>4g</td>
<td>3$</td>
</tr>
<tr>
<td>BCM43438</td>
<td>5<em>3</em>1mm</td>
<td>&lt;2g</td>
<td>3$</td>
</tr>
<tr>
<td>Si1141</td>
<td>2<em>2</em>1mm</td>
<td>&lt;2g</td>
<td>2$</td>
</tr>
<tr>
<td>ADXL345</td>
<td>3<em>5</em>1mm</td>
<td>&lt;2g</td>
<td>2.5$</td>
</tr>
<tr>
<td>LMT70</td>
<td>0.9<em>0.9</em>0.5mm</td>
<td>&lt;2g</td>
<td>1$</td>
</tr>
<tr>
<td>Other ICs</td>
<td>&lt;2g</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Passives,LED &amp;</td>
<td>&lt;2g</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Enclosure</td>
<td>13g</td>
<td></td>
<td>1$</td>
</tr>
<tr>
<td>Total</td>
<td>38g</td>
<td></td>
<td>23$</td>
</tr>
</tbody>
</table>
F. Data Visualization

The data from the prototype are streamed over WiFi to a server and this data is viewable both by the parent and the doctor remotely on either Smartphone or a browser.

1) Parent view: Alerts will be provided on the parent’s smartphone. Status information of the sensor such as connectivity can also be viewed. Fig. 4 represents the smartphone view accessed by the parents and doctors. The data from the sensor is also viewable in an easy to understand manner. Information about the medication prescription can also be provided periodically by doctors.

2) Doctor’s view: The doctor or the health care professional can access the patient data securely through the browser. The data is viewed through graphs and doctor can set specified alerts for each parameter. If the data crosses a set limit, the doctor is alerted and that data is highlighted in graph. The doctor can further zoom in or out or specify a date and time while viewing the data. Average values of various parameters are also listed. Fig. 5 shows data viewed in the browser.

IV. USAGE

Raksh was designed for minimal intervention from the parent while monitoring the child. The doctor after primary examination of the child for pneumonia can prescribe Raksh for continuous monitoring. The length of semi-rigid respiration sensor cable can be adjusted by the professional before providing the device. The device may be given in a rental model by the Primary Healthcare Center (PHC). After the recovery, the device should be returned to the PHC. The maintenance is easy as the device is designed to be modular. The parent is given simple graphical instructions for removing and properly reattaching the device. Reminders to provide medication are given to the parents by acoustical and visual cues on the gateway device.

V. EXPERIMENTAL RESULTS

The nasal temperature was measured and plotted for a healthy adult subject using the non-contact IR temperature sensor placed below the left nostril. Fig. 6 shows the variation in temperature during inhalation and exhalation.

The respiration rate is calculated by measuring peak to peak interval as given in (1)

\[
\text{Respiration Rate} = \frac{60}{\text{Peak to Peak interval}} \tag{1}
\]

The peak to peak interval is found by using a timer in the MCU. Peak detection is used to determine the various maxima’s and minima’s in the nasal temperature plot with the threshold set to the ambient temperature of the room.
The blood oxygenation is averaged by the SpO2 sensors placed against the earlobe. A small clip was used to hold the sensor in place and to avoid ambient light from affecting the sensor. The processed data was sampled every 0.5 second and averaged over a period of 10 seconds and was sent to a remote server. Fig. 7 shows the plot of SpO2 for the duration of 20 minutes.

The Heart Rate is measured along with Blood Oxygenation in the ear lobe. The readings are sampled every 0.5 second and averaged over a period of 10 seconds and sent to a server for every 10 seconds. Fig. 8 shows the plot of heart rate for the duration of 20 minutes. The SpO2 and Heart Rate readings from our sensor were compared against a Nellcor NPB-290 finger Pulse Oximeter. Fig. 9, 10, 11 shows the comparison of Raksh data against the NPB-290. The data was collected for three different subjects, two adults and one 4 year old child who were asked to rapidly breathe under request to increase heart rate for evaluating the Raksh device in different condition. It can be easily seen from the Fig. 9, 10, 11 that the average error of Raksh device is approximately zero as compared with the conventional measuring device. Fig. 12 illustrates the system algorithm that is used to monitor the child. The sensor values are periodically sent to a remote server over a gateway to enable the doctor to remotely monitor the child.
VI. CONCLUSION & FUTURE WORK

The multi-parameter vital monitoring was conducted using noninvasive and comfortable sensors. The data was transferred over WiFi to a secure server and the data could be presented intuitively to a doctor. This data would be vital during diagnosis and while providing treatment for the child suffering from pneumonia. We have demonstrated that use of noncontact temperature sensors would be a viable way to monitor respiration. In future, we aim to produce certain number of units to gather data and compare the viability of our design in comparison to conventional sensors. The design of the sensors would be improved and optimized towards long term comfort. The cost would be reduced by using widely used MCU’s and wireless units. A gateway device would also be made to act as a bridge between the data from the device to the secure server.

Use of mobile networks or wired internet would be explored to upload data to the cloud. The gateway device would also be able to monitor environmental parameters. The doctor’s dashboard would be designed for ease of use. The data from sensors would be used to create heat maps of pneumonia occurrence in various areas to aid NGOs and Government intuitions to manage medicine supplies properly and prioritize on wellness in the areas that are affected.

REFERENCES


