A Wearable Sensor for Monitoring Kangaroo Mother Care treatment for premature neonates

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Abstract—We describe a new wearable device that has been developed to monitor the effectiveness of Kangaroo Mother Care (KMC) treatment administered to premature neonates. We identify the sensors needed to monitor KMC treatment. Our device measures the neonate’s and caregiver’s skin temperature and the neonate’s relative position during KMC. The device incorporates skin touch sensors to qualify the temperature readings, thus preventing false alarms. Design constraints related to form factor, placement and battery life and few measurement results from pre-clinical trials are provided.

Index Terms—wearable; premature neonate; kangaroo mother care; skin temperature sensor; touch sensor; tilt sensor

I. INTRODUCTION

Neonatal Mortality Rate (NMR) quantifies the number of new-born deaths (that is in the first month of life) per thousand live births and is responsible for more than 46% of all child deaths before the age of five (2.6 million in 2016) [1]. More than 77% of these deaths occur in developing nations. Reports [1], [2] have shown that India has about 10 times higher NMR compared to the western world. NMR in India was 25 as of 2016, and has reduced by 50% since 1990. Considering India’s burgeoning population, 6, 40, 000 newborns died in India in 2016, which is about 8 times more than in China [1]. The authors in [3], [4] have found hypothermia to be a major cause of neonatal morbidity and mortality, especially in rural and other resource constrained settings. Hypothermia for neonates is defined as the condition when their body temperature drops below 36.5°C [5]. Hypothermia leads to greater risk of infection and may even lead to fatality in the absence of pre-emptive care.

Premature neonates are usually treated in an incubator in an NICU (Neonatal Intensive Care Units). The incubator essentially has heating lamps and other electronics that helps to keep the baby at the right temperature. This treatment can last anywhere from a few days to a few weeks, based on their degree of prematurity. Unfortunately, in many resource constrained settings, especially in the rural areas, there are not enough NICUs or even incubators available thus preventing the delivery of this essential treatment to the premature infant.

Fortunately, a simple and effective treatment was discovered in early 1980s by Dr. Sanabria [6], who, inspired by Kangaroos, found that holding the premature infant in skin to skin contact with the caregiver, resulted in very dramatic improvements in the prognosis for the premature infant. This technique is now called Kangaroo Mother Care (KMC) and is being rapidly adopted by several hospitals. Given that almost no other equipment is required, this seems to be very suitable for use in resource poor settings. A recent study by Charpak et. al. [7] has further highlighted the long-lasting social and behavioural protective effects in the original set of patients from Columbia, even 20 years after the initial intervention.

Ideally, during this treatment, the doctors would like to monitor the temperature of the baby, whether the KMC is being applied and if so for what duration in a 24-hour period and whether the baby is being held in the correct position. Such data would help the doctor to track the progress of the health of the baby and correlate with the treatment given and take necessary actions as required. However, there is no existing technology currently to quantify the application of KMC treatment, other than manual recording by the caregivers, which is cumbersome and prone to errors.

In response to this need, we have developed a new wearable device to continuously monitor and record the KMC parameters. The parameters measured are baby and caregiver’s skin temperature (qualified by skin touch sensors for both) and the baby’s relative position. We found that the wearable’s allowable form factor (particularly device thickness that ensures user comfort) placed a severe constraint on the battery size limiting the achievable battery life. Choice of low power sensors and duty cycling of the wireless radio helped us meet the battery endurance requirement (KMC treatment period of four weeks). The constrained form factor meant that the sensors had to be packaged in very limited volume without compromising performance (due to issues like crosstalk). As the device gets sandwiched between the baby and caregiver when in KMC, the antenna placement also had to be optimised to meet wireless range and regulatory requirements (skin absorption rate).
By using the IoT (Internet of Things) approach, information from the wearable is available almost instantaneously at the remote hospital (provided network connectivity is present). Simple automated processing of the data is done to raise an alarm in case of adverse changes in the baby’s temperature, so that appropriate intervention can be taken immediately.

II. END TO END SYSTEM FOR KMC MONITORING

The basic concept of the end-to-end system is illustrated in Fig. 1. The key component of the system, is the wearable device shown in the picture on the abdomen of the baby. The device is meant to be affixed around the navel of the baby, from where it picks up the baby’s skin temperature. Since this position is also close to the liver, it gives a good approximation of the baby’s core temperature. There is another temperature sensor on the opposite side of the device, which can pick up the temperature of the caregiver. When the caregiver holds the baby to provide skin to skin contact, the device gets sandwiched between the baby and the caregiver and touch sensors are used to signal the onset of the KMC treatment. During KMC, skin touch sensors on opposing surfaces of the device validate that the temperature being measured is that of the human body. An accelerometer also measures the angle at which the baby is held when in KMC. The device measures the time for which the treatment is given. Thus, the device picks up all the parameters necessary for monitoring of the KMC treatment. The device automatically and wirelessly connects (over BLE) with a smart phone. The smart phone uses the mobile network to transfer this data to the hospital’s server. The device can store 30 hours of data sampled every 6 minutes. Technical details of the device’s design and construction are discussed in the next section.

The device dimensions are $3\text{cm} \times 1.5\text{cm}$ with a thickness of $7\text{mm}$. The dimensions were optimised to prevent any discomfort to baby or care giver and were arrived at based on feedback obtained from users of the device. The device is housed in a bio-compatible plastic shell and has two small, medical grade, stainless steel windows on each surface. ICU grade NTC type thermistors [9] attached to these windows sense the temperature on both sides of the device (baby and care giver side).

Alarms are provided in the system to detect various conditions like mild hypothermia $34.1^{\circ}C$ and $36.5^{\circ}C$, severe hypothermia $<34.1^{\circ}C$ or failure to administer KMC treatment in a six hour period.

III. KMC DEVICE DESIGN

A. Hardware Design

Fig. 2 shows the hardware implementation of our KMC device. Also indicated are the types and locations of sensors in this device.

1) Temperature Sensors: Two ICU grade NTC type thermistors are used for sensing temperature on baby and care giver side. The sensors come calibrated at $37^{\circ}C \pm 0.01\%$ and are grouped according to their resistance range to provide extreme interchangeability [9]. The thermistor’s RT characteristics are shown in Fig. 3. $R$ is the resistance of thermistor at temperature $T$, $R_0 = 29,700\Omega$ is the calibrated resistance of thermistor at temperature $T_0 = 37^{\circ}C \pm 0.01\%$, $\beta = 3950K$ is the material specific constant. The linear fit reveals the sensor’s sensitivity to be $\simeq -1768.1\Omega/^{\circ}C$. The thermistor resistance is measured in comparison to a reference grade resistor. The entire analog front end, consisting of the resistor network and ADC are powered by the same switchable power supply to minimize the impact of supply noise [8].

2) Skin Touch Sensors: Skin touch detection is based on measurement of change in capacitance when the device is brought in proximity of the human skin. The KMC device being battery operated has no reference to physical ground. Thus, a human body in proximity of the device will be at a different potential considering our battery-operated device’s floating ground reference. As a result, the human body cannot be used as a reliable second plate of a capacitor as is the case in the traditional approach to capacitive touch sensing. Instead a ground plane is kept in close proximity of the capacitive touch electrode. Proximity to a human body changes the dielectric
constant across these two plates thus changing the capacitance [9].

The onboard sensor controller measures capacitance by calculating the time it takes to charge this capacitor on passing a constant current of $1\mu A$. We have placed two such touch sensors on the baby and care giver side of the device. When the device was made thinner to meet the $7mm$ thickness specification, the two touch sensors began to experience crosstalk (touch was detected on both sides though only one side was brought in proximity of human skin). Placement of a shielded ground plane between the two electrodes helped correct this crosstalk issue. No explicit ground plane was introduced, instead a piezo buzzer was sandwiched between the two touch sensing surfaces (Fig. 2). The conductive surface of the buzzer provided enough shielding to prevent crosstalk.

3) Position Sensor: The device makes 3 axis accelerometer measurements using the onboard Invensense 9250 MEMS based Motion Processing Unit (MPU). The accelerometers' full scale range is set to $\pm 2g$. Data is captured at 16 bit resolution, with a sensitivity of $16,384LSB/g$. The sensitivity drifts with temperature at a rate of $\pm 0.026%/^\circ C$. The X, Y component level initial zero-g calibration tolerance is $\pm 60mg$. The corresponding tri-axis tilt angles are calculated using basic trigonometric equations to determine tilt angle of the baby.

4) Antenna Position: A $2.4GHz$ BLE ceramic mini antenna is placed on care giver side of the PCB. The TX power is set at $0dBm$ which corresponds to a Class 3 device (peak transmit power of $1mW$). The effective exposure (SAR) is $0.00117–0.00319W/kg$ is well below $2W/kg$ recommended by the ICNIRP [10]. The metallic battery enclosure and coin cell between antenna and baby provide further reduction in exposure on baby side.

5) Power Supply: The device is powered with a single $CR2025$ coin cell. The cell capacity is $\sim 170mAh$. The BLE advertisement and sensor controller sampling rate is duty cycled to achieve a battery life of more than 30 days. An on chip internal DC-DC converter provides a regulated DC bus.

B. Product Design

Fig. 2 shows an exploded view of the KMC Sensor device. The temperature sensors are attached to the inner side of two biocompatible stainless steel (SS) plates using thermally conductive adhesive. Two additional copper pads are bedded in the inner surface of the shell to form the two plates of a capacitor for the touch sensor. Since these plates are covered with the insulating plastic enclosure and do not make direct physical contact with the skin, we have chosen highly conductive copper as the material for these plates. This solution is low cost (avoids need for bio compatible touch sensor metal plates) and easy to assemble considering the ease of soldering a wired contact. All surfaces are bio-compatible and hypoallergenic. The PCB board houses the sensor analog front end, microcontroller, ADC, storage, position sensor and BLE communication module. A standard coin cell is used as the power source. The device may be affixed to the subject either via a belt, a tape or a bandage. The device also has a multiplicity of LEDs of different colors, that are used to indicate various events or conditions to the user. The device also has a piezo buzzer to emit various sounds upon different events or conditions.

IV. Measurement Results

This device was used for a pre-clinical study for about 11 months (Feb – Dec 2016) and has been used to monitor KMC on 73 babies during this period. Initial analysis of the field data is reported in [11]. Fig. 4 shows data from the device in comparison to standard manual method of measuring temperature from the axilla (armpit), taken from the 73 babies during the home use phase. The data is plotted using the Bland-Altman style plot and shows the tight correlation between the device data and that measurement using the standard practice. Another interesting observation from this study has been that the self-reporting of KMC duration has been consistently higher than what is measured.

V. Summary

The new wearable sensor for measuring KMC dosage for premature neonates has shown promising results in field testing. The device and system design incorporate many features for robust measurement and retrieval of data. A key feature is to predicate the readings of the internal sensors with the skin-touch sensor in order to minimize false alarms.

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