Monitoring Body Temperature of Newborn Infants at Neonatal Intensive Care Units Using Wearable Sensors

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ABSTRACT
Body temperature is one of the key parameters for health monitoring of premature infants at the neonatal intensive care unit (NICU). In this paper, we propose and demonstrate a design of non-invasive neonatal temperature monitoring with wearable sensors. A negative temperature coefficient (NTC) resistor is applied as the temperature sensor due to its accuracy and small size. Conductive textile wires are used to make the sensor integration compatible for a wearable non-invasive monitoring platform, such as a neonatal smart jacket. Location of the sensor, materials and appearance are designed to optimize the functionality, patient comfort and the possibilities for aesthetic features. A prototype belt is built of soft bamboo fabrics with NTC sensor integrated to demonstrate the temperature monitoring. Experimental results from the testing on neonates at NICU of Máxima Medical Center (MMC), Veldhoven, the Netherlands, show the accurate temperature monitoring by the prototype belt comparing with the standard patient monitor.

Keywords
Neonatal monitoring; wearable sensors; skin temperature; conductive textile wire; design process.

1. INTRODUCTION
Critically ill or premature new born infants are usually admitted at the Neonatal Intensive Care Unit (NICU) of a hospital. Fig. 1 shows the NICU environment at Máxima Medical Center (MMC), Veldhoven, the Netherlands. Vital physiological parameters of these neonates, such as body temperature, electrocardiogram (ECG), respiration, and blood oxygen saturation, need to be monitored continuously for urgent diagnosis and adequate medical treatment [1]. Advances in medical treatments over the last decades resulted in a significant increase of survival. As a result, a major part of neonates born after 25 weeks of pregnancy can survive with appropriate medical care at NICU [2].

Presently, body temperature is monitored with adhesive thermistors; ECG and respiration are obtained by adhesive skin electrodes; and a pulse oximeter is applied on the foot or palm of the neonate [3]. Placement of these sensors and the presence of all the wires lead to discomfort and even painful stimuli when the sticky sensors have to be removed. The disturbance to infants, interruption of sleep, and lack of natural communication with parents all interfere with the babies' normal growth and development [4]. As the survival rate of neonates has increased significantly in the last decades, the quality of life of NICU graduates becomes an important issue as well [5]. Alternative, non-invasive monitoring of vital physiological functions is a pressing need to provide convenient care and hence, may lead to improved developmental outcome of the neonates.

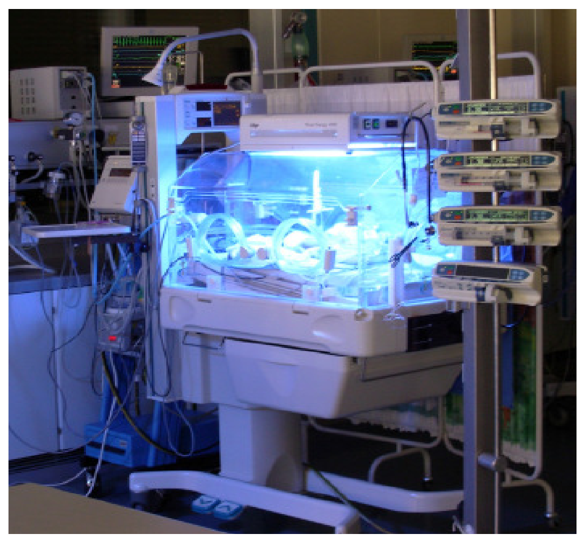

Figure 1. The NICU environment at MMC, Veldhoven, the Netherlands.

Recent advances in sensor technologies [6-8] and wireless communication technologies [9] enable the creation of a new generation of healthcare monitoring systems with wearable electronics and photonics. The Eindhoven University of Technology (TU/e) in the Netherlands has started a 10-year project on non-invasive perinatal monitoring in cooperation with the Máxima Medical Centre (MMC) in Veldhoven, the Netherlands. The goal of this project is to improve the healthcare of the pregnant woman, and her child before, during and after delivery [10]. The area of non-invasive health monitoring involves multi-disciplinary research and collaboration, including

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sensor technology, medical science, industrial design, electrical engineering, etc. A couple of intelligent designs have been developed in the project, for example, a smart jacket integrated with textile sensors [11], SpO2 monitoring with reflectance pulse oximeter [12], wireless transmission for NICU [13], a power supply based on contactless energy transfer [14], and a device to support medical staff to perform cardiopulmonary resuscitation of neonates [15].

In this paper, we focus on the body temperature monitoring of neonates at NICU. Body temperature is one of the vital signs for continuous neonatal monitoring. Body temperature serves as an indicator for an impeding infections and general stability of the infant. Temperature is typically measured at one site of the body. Moreover, the parameter is used to determine adequate environmental temperature for an optimal growth and development of neonates. Both electrical and optical devices [16, 17] can be used for temperature measurements. Transcutaneous thermometry [18] is currently used in hospitals for core temperature monitoring. A thermistor is placed between the infants back and the mattress of the incubator, attached to the skin with a foam adhesive disk insulator.

We present and demonstrate a design for monitoring the body temperature of neonates at NICU. A negative temperature coefficient (NTC) resistor [19] is used as the temperature sensor, because NTC provides accurate measurements and is available in small size, which makes the NTC sensor compatible for the integration into a wearable non-invasive monitoring platform, for example, the smart jacket [11]. To optimize functionality and patient comfort, relevant practical issues are studies and well considered in the design, such as location of the sensor, conductive textile wires for the connection, materials to choose, and appearance of the prototype.

For implementation of the design concept, a soft belt is built with bamboo fabrics. A NTC Mon-A-Therm 90045 temperature sensor (2mm x 3mm) is incorporated into the belt. There are no hard wires in the belt. Flexible and soft conductive textile wires made of Shieldex® Silver Plated Nylon yarn are applied in the prototype belt. Sensor testing and user testing were carried out to demonstrate the performance of the design. Experimental results from the testing on neonates at NICU of Máxima Medical Center (MMC), Veldhoven, the Netherlands, show that comparing with the standard patient monitor, the prototype belt achieves accurate temperature monitoring.

The paper is organized as follows. Section 2 describes the design process and design concept. Section 3 presents the prototype. Section 4 demonstrates experimental setup and user testing results. Section 5 draws conclusion.

2. DESIGN PROCESS & CONCEPT

The goal for the non-invasive body temperature monitoring is to design a wearable device that provides stable and accurate measurements, and at the same time is comfortable for the neonates. The device should also be compatible for the further integration into a non-invasive health monitoring platform, such as the smart neonatal jacket [11]. In this section first the design process will be discussed and then the design concept.

2.1 Design Process

Methodologies from the field of Industrial Design are applied in the design process of neonatal body temperature monitoring, which involves a unique integration of knowledge from medical science, design, and sensor technology. Fig. 2 shows the design process, which consists of scientific research based on literature review and user research (e.g. interviews with doctors and nurses), idea generation & selection, prototyping with technology integration and clinical validation. The iterative process begins with scientific research that includes user research involving doctors and nurses at MMC in Veldhoven and gathering of information on body temperature monitoring for neonates. The scientific research gives insight into the clinical needs, technologies for neonatal body temperature monitoring and where the sensor should be placed for accurate measurements. Requirements are derived from the information search, forming a base for brainstorm sessions which resulted in ideas about technological challenges, functionality issues within NICU as well as form and senses. Design choices and prototypes are then made through an iterative process in which proof of technology and user feedbacks provide clues for further development. In this phase, the prototyping and clinical testing are important to evaluate and validate the proposed design as well as obtain valuable feedback from the medical staff and parents. Improvements are then made based on the evaluation and user feedback.

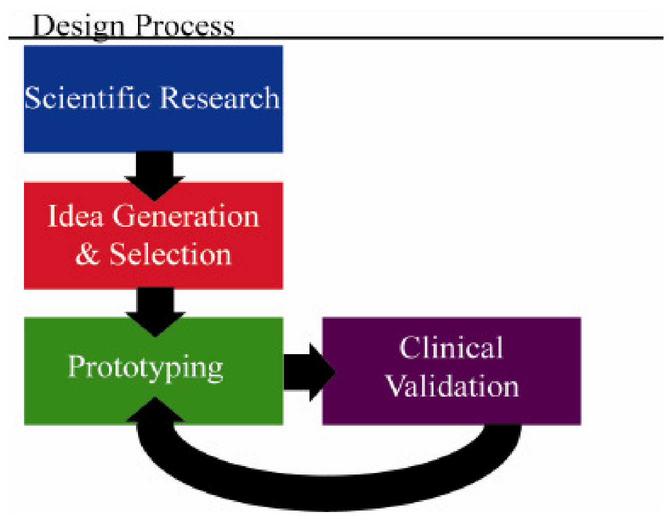


Figure 2. Block diagram of design process.

2.2 Design Concept

Considering both user aspects and technical functions, a list of requirements is setup for the design. They are as follows:

- provide accurate continuously body temperature measurements both inside the incubator and outside the incubator during Kangaroo mother care;
- be safe to use at NICU;
- be comfortable for the neonates (e.g. avoid adhesive parts and sharp edges);

- the placement of the sensor should not be above bones;
- easy to use for the medical staff;
- easy to clean, easy to disinfect;
- aesthetically pleasant for the NICU environments, parents and medical staff.

With the above requirements in mind, brainstorm sessions were carried out to generate ideas. The proposed final concept is a soft belt made of bamboo fabrics as shown in Fig. 3. A small temperature sensor is incorporated into this belt. According to the information obtained from doctors at NICU, the sensor is located above the liver to provide optimal body temperature measurements. The temperature sensor is isolated using soft cotton foam as shown in Fig. 4 to limit the external influence (for example, the room temperature) of the temperature measurement. To optimize functionality and patient comfort, the design moves sensors and foam to an invisible background for user friendly interface and better parent-children bonding, and therefore, the happy frog appearance is chosen for aesthetic purpose. There are no adhesive components and hard wires in the belt, and instead, flexible and soft conductive textile wires are applied as connections. Furthermore the location of the belt does not interfere with other measurements and routine clinical examination of the neonates. Moreover, in a later stage the design can be incorporated into an all in one solution for monitoring of all the vital parameters of the neonates, including ECG, respiration and SpO_2.

Figure 3. The proposed belt on a baby doll.

Figure 4. The isolation of the sensor inside the belt.

3. PROTOTYPE

A prototype belt integrated with sensor for neonatal temperature monitoring as shown in Fig. 5 was built to demonstrate the design concept and experimentally validate the design. The prototype is fully functional and the results of temperature measurements can be displayed in real time on a computer. In this section, the detailed implementation of the prototype will be explained, including the sensor technology, conductive textile wires, materials and the form design.

Figure 5. The prototype belt.

3.1 Temperature Sensor

According to the design requirements, the sensor should be non-invasive, accurate and small size for integration. For neonatal monitoring, the sensor needs have an accuracy of 0.1 degrees Celsius. For enhancing the patient comfort, the sensor should be small size and easy to be integrated into comfortable fabrics. We chose a NTC sensor for the prototype because it satisfies the accuracy and design requirements. The NTC sensor integrated into the prototype has a dimension of 2mm x 3mm and is derived from a Mon-A-Therm 90045 temperature sensor. For future development of the temperature monitoring solution, smart textiles which can achieve at least the same measurement accuracy will be applied for more patient comfort and more compatibility of integration into fabrics.

A sudden temperature change can be an early indication of an infection. One of the most active organs is the liver. Therefore the temperature around the liver is relatively high. By measuring the skin temperature above the liver the skin temperature is measured that is close to the core temperature. Therefore the sensor was placed above the liver in the prototype.

3.2 Conductive Textile Wires

The current body temperature solutions often use hard wires which can cause discomfort when the baby is lying on the wire. In addition, sharp edges can occur when bending the wires. Smart textiles are flexible, lightweight, non-irritating, and therefore suitable for the non-invasive health monitoring platform, such as the smart jacket and the temperature belt. For the prototype, we used conductive textiles in stead of the hard wires for improving patient comfort. Shieldex® Silver Plated Nylon yarns as shown in Fig. 6 (a) were woven in the prototype as soft and flexible wires. Fig. 6 (b) shows the connections between the NTC sensor and the conductive textile wires, which were made by knotting the conductive yarns onto the sensor.

(a) (b)

Figure 6. (a) Conductive textile yarn and (b) the connections of the conductive textile wires and the NTC sensor.

The attachment of the NTC sensor on the prototype belt was done by stitching the sensor on the belt and isolating the sensor with the foam. To make sure the conductive textile wire would not come in contact which each other, each wire was stitched on several points of the belt.

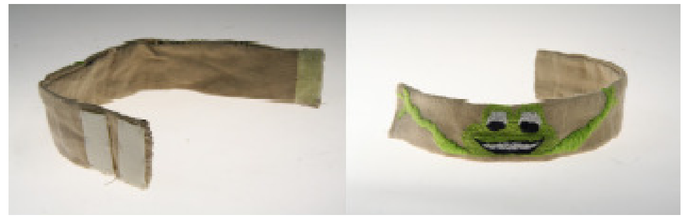
3.3 Material

The material used for the belt has significant influence on how comfortable the measurement of the skin temperature will be for the neonate. Besides comfort, the material should also be safe and breathable for the premature baby. Various types of textiles were considered and compared for making the prototype. The properties of different textiles as well as the related ecological aspects were all taken into account.

Bamboo textiles were chosen as the material for the prototype belt. Bamboos are fast growing natural plants. The growth of a bamboo plant takes around five years. During the growth of a bamboo, the plant absorbs much more CO_2 than a cotton plant does, which makes growing bamboos environmental friendly. One of the positive aspects of bamboo textiles is the anti-bacterial properties, which other materials like linen and wool do not have. Bamboo textile is very breathable which makes it more comfortable to wear. The softness of bamboo textile can be compared with silk.

3.4 Belt Design

The final prototype belt was made of bamboo textiles. The ends of the belt were designed using Velcro with a very fine texture, which is similar to the Velcro found on diapers. After considering different possible shapes of the belt, the choice was made for a straight belt as shown in Fig. 7 (a), which is the most comfortable for the child and the most suitable for the temperature measurement. The belt is wrapped around the baby with the sensor located above the liver. If wanted in the future, the belt can be integrated in to other non-invasive monitoring platforms, for example the smart jacket. Another part of the design was the image or pattern on the belt. For user friendly interface and better parent-children bonding, the sensor, the conductive textile wires and the foam were all integrated into the belt, and thus they are invisible to users. As shown in Fig. 7 (b), a happy frog appearance is chosen for aesthetic purpose.



(a) (b)

Figure 7. (a) Inner side of the prototype belt and (b) outside of the prototype belt with the happy frog appearance.

4. EXPERIMENTS AND USER TESTS

Validating and evaluating the performance of the proposed design is an important part of the process. Various experiments were carried out to test the functionality and behavior of the prototype and some other tests focused on sensors and conductive textiles for the prototype. The experiments and user tests consist of several phases. First of all the NTC temperature sensor in combination with the conductive textile wires was calibrated. Second the measurement accuracy of the prototype belt was validated by tests on premature babies at NICU.

4.1 Demonstration Setup

Before presenting the results of sensor tests and user tests on neonates, we demonstrate the whole system including sensing, data acquisition, processing and displaying. Fig. 8 shows a diagram of the setup for demonstrating the temperature monitoring system. First the sensor needs to be calibrated. Then the prototype belt is connected to a digital oscilloscope for data acquisition. A PC is used for processing the data and displaying the measured temperature.

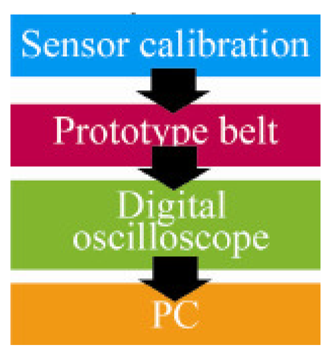


Figure 8. Diagram of the demonstration setup.

Fig. 9 shows the setup of temperature monitoring demonstration, consisting of the prototype belt, digital oscilloscope and a PC as a display for the monitored temperature.

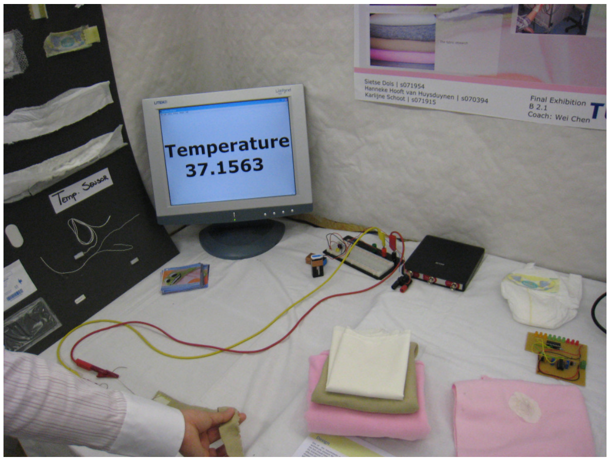


Figure 9. The setup of temperature monitoring demonstration.

4.2 Sensor Tests

Various measurements were done to determine the resistance of the sensor at different temperatures between 25 degrees Celsius and 43 degrees Celsius. The NTC sensor was tested connecting with the textile wire, as well as with the use of the regular wire. Fig. 10 and 11 show the resistance measurements of the NTC sensor with the conductive textile wire (i.e. the configuration in the prototype belt) and the resistance measurements of the NTC sensor with regular wire (i.e the current hospital sensor configuration), respectively. Five measurements on each temperature point for both configurations were recorded. Based on the measurements a formula was derived for the prototype belt and the temperature can be calculated using the resistance value of the sensor. The resistance of sensor connecting with the conductive textile wire and the resistance of sensor connecting with the regular wire were compared. We can see from Fig. 10 and Fig. 11 that as the temperature increases, the resistance decreases, and the resistance of the prototype belt is slightly higher than the resistance value of the current hospital sensor. This is because the resistance of the conductive textile wires is higher compared to the regular wire.

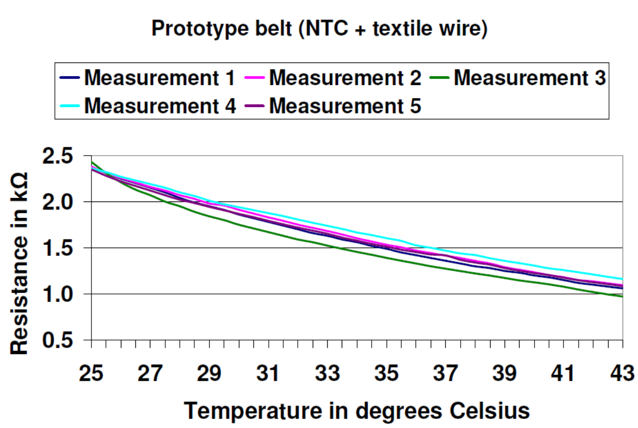


Figure 10. Resistance measurements of the sensor with conductive textiles.

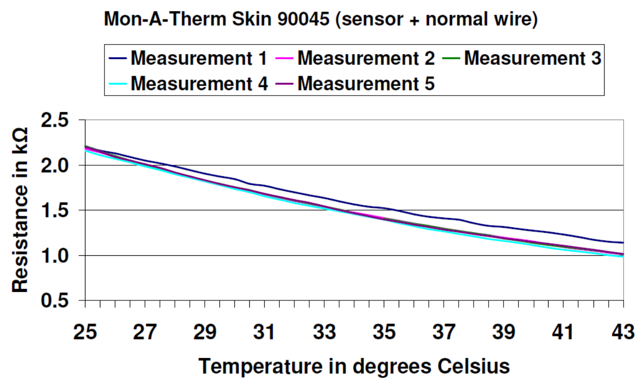


Figure 11. Resistance measurements of the sensor with regular wire.

4.3 User Tests

The goal for conducting a user-test on babies in the incubator of NICU is to validate the function of the prototype. In this subsection, we report the tests on a premature baby with the prototype belt for temperature monitoring. For validating the testing results, the conventional NICU sensor was attached to the baby for skin temperature monitoring, and the temperature readings from the conventional sensor and the monitoring belt were compared to verify the results of the test.

The test was conducted at NICU of MMC Veldhoven, the Netherlands. The prototype belt was tested on a premature infant, born after 30 weeks gestation in stable health condition. A neonatologist and an NICU nurse from MMC were present during the testing. After obtaining permission of the parents, the prototype belt was placed on the neonate's body. The belt was tested for a period of 45 minutes on the baby to see whether the signals from the belt remained stable for a longer period when a baby wears the belt. Fig. 12 shows an instance of the test on a baby inside an incubator in the NICU at MMC Veldhoven.

Figure 12. User testing on a neonate at the Máxima Medical Center Veldhoven, The Netherlands.

Table 1 shows the monitored temperature in degrees Celsius by both the conventional NICU sensor connected to the Solar® 8000M patient monitor and the prototype belt with NTC sensor integrated and conductive textile wires as connection. The data were collected from the last 20 minutes of the user testing and the time interval between two temperature readings was about 2 minutes. We can see that the monitoring error is within 0.1 degrees Celsius.

Table 1. Temperature Measurements on a Premature Baby

Monitored Temperature in Degrees Celsius		
Prototype belt	***Conventional NICU monitor***	***Error***
36.9	36.8	0.1
37.0	36.9	0.1
37.0	36.9	0.1
36.9	36.9	0.0
37.0	36.9	0.1
37.0	37.0	0.0
36.9	36.9	0.0
36.9	36.9	0.0
37.0	37.0	0.0
37.0	37.0	0.0

5. CONCLUSION

Non-invasive neonatal monitoring at NICU is important for healthy development of the neonates and their quality of life later on. In this paper, we present our iterative design process and demonstrate a design of temperature monitoring belt for neonates at NICU using wearable sensors. The design aims to provide accurate as well as comfortable temperature monitoring for neonates. A prototype belt is developed with the NTC temperature sensor and conductive textile wires embedded in soft bamboo fabrics with a happy frog appearance. The prototype is implemented to demonstrate the performance of neonatal temperature monitoring and the possibilities for aesthetic features. The proposed design is suitable for the integration into a monitoring platform, for example, a neonatal smart jacket.

Sensor testing and user testing were carried out to validate the function of the prototype. Experimental results from the testing on neonates at NICU of Máxima Medical Center (MMC), Veldhoven, the Netherlands, showed that the device is safe to use at NICU; comparing to the standard patient monitor the prototype belt achieves accurate temperature monitoring and the monitoring errors are within 0.1 degrees Celsius.

For future development of the temperature monitoring solution, the connection between conductive textile wires and the temperature sensor could be improved with more advanced binding or soldering techniques. With further development of pervasive computing and wearable sensors, smart textiles which can achieve at least the same measurement accuracy will be considered for more patient comfort and more compatibility of integration into fabrics.

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