



Smart Pillow— Intelligent system to comfort newborn infants using vibration and monitoring movement of the infants via wireless sensor system

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Abstract—Premature infants are subject to numerous interventions ranging from a simple diaper change to surgery while residing in neonatal intensive care units. These neonates often suffer from pain, distress, and discomfort during the first weeks of their lives. Although pharmacological pain treatment often is available, it cannot always be applied to relieve a neonate from pain or discomfort. This paper describes a nonpharmacological solution, called Smart, which provides comfort through mediation of a parent's physiological features to the distressed neonate via an intelligent pillow system embedded with sensing and actuating functions. We present the design, the implementation, and the evaluation of the prototype. Clinical tests at Máxima Medical Center in the Netherlands show that among the nine of ten infants who showed discomfort following diaper change, a shorter recovery time to baseline skin conductance analgesimeter values could be measured when the maternal heartbeat vibration in the MIMO was switched ON and in seven of these ten a shorter crying time was measured.

Index Terms—Bonding, comforting solution, heartbeat, preterm neonates, user-centered design.

given in some of these cases, a large proportion (50%) [1], [3] of the interventions are performed without any form of pain treatment.

Simple procedures and environmental factors are also possible sources of pain and discomfort to preterm neonates. Nociception is the term used to refer to the neural processes of encoding and processing painful stimuli. In preterm neonates, this nociception system is not yet fully developed. A possible consequence of this not-fully developed nociception system is that stimuli such as sound and light, which are normally not considered painful to a human being, may be perceived as painful by the preterm neonate [4]. Injuries, but also clinical procedures, will result in more widespread sensitivity to pain [5]. The stay of a preterm infant in the incubator is negatively influenced by stress (excessive light and noise) and painful procedures [6]. Exposure to repetitive pain, stress, and discomfort in premature infants is associated with cognitive and neuro developmental impairments [7]. The consequences of untreated procedural pain in neonates can be both severe and long term. It is believed that exposing preterm neonates to pain negatively affects their ability to cope with pain and stress in later childhood [5], [8]. There is growing awareness that pain following a painful procedure should be treated appropriately and adequate soothing by parents or nurses is advocated.

Neonates show many different responses to pain and stress. These responses can be of both physiological and behavioral nature, and can be used to detect discomfort of a neonate. Physiological responses include an increased heart and respiratory rate, increased or decreased blood pressure, decreased oxygen saturation, vagal tone, and skin temperature. Behavioral responses are even more varied. Examples include vocalizations like crying and whimpering, facial expressions like grimacing with eyes squeezed shut or a stretched open mouth, and body movements like finger and toe splaying and trunk arching [5]. It is worth noting that a change in any of these responses does not always imply that the neonate is experiencing stress or discomfort.

I. INTRODUCTION

BABIES that are born after a pregnancy lasting 37 weeks or less are typically considered premature. Critically ill neonates are a special group of patients that consist of premature infants who may suffer from diseases that are mainly caused by immaturity of their organs, and full term infants, who become severely ill during or immediately after birth. Critically ill newborn infants are normally admitted to a neonatal intensive care unit (NICU) for treatment by neonatologists and specialized nurses. Survival of the preterm neonates is unfortunately reliant on many painful medical interventions. These interventions include, but are not limited to: heel punctures, venipunctures, and in- or detubations [1]. The attachment and removal of sensors required for measuring physiological signals can also be unpleasant, stressful, and painful [2]. Although pain treatment is



The past two decades have seen an increase in interest in neonatal pain treatment [8]. Christo Ananth et al. [9] discussed about an eye blinking sensor. Nowadays heart attack patients are increasing day by day. "Though it is tough to save the heart attack patients, we can increase the statistics of saving the life of patients & the life of others whom they are responsible for. The main design of this project is to track the heart attack of patients who are suffering from any attacks during driving and send them a medical need & thereby to stop the vehicle to ensure that the persons along them are safe from accident. Here, an eye blinking sensor is used to sense the blinking of the eye. spO2 sensor checks the pulse rate of the patient. Both are connected to micro controller. If eye blinking gets stopped then the signal is sent to the controller to make an alarm through the buffer. If spO2 sensor senses a variation in pulse or low oxygen content in blood, it may results in heart failure and therefore the controller stops the motor of the vehicle. Then Tarang F4 transmitter is used to send the vehicle number & the mobile number of the patient to a nearest medical station within 25 km for medical aid. The pulse rate monitored via LCD. The Tarang F4 receiver receives the signal and passes through controller and the number gets displayed in the LCD screen and an alarm is produced through a buzzer as soon the signal is received.

Nonnutritive sucking was one of the first nonpharmacological comforting techniques to be studied and refers to offering a pacifier for the neonate to suck on [12]. A sucrose solution can be provided as an extra means of comfort during more painful procedures. During facilitated tucking, the caregiver holds one hand on the baby's head and another one on the feet or body, depending on what is feasible at that moment [14]. Similar techniques are containment and swaddling [15]. The aim of all these techniques is to restrict the movement space for the neonate and to maintain it in a position similar to in utero.

One of the most successful comforting techniques is SSC, otherwise known as kangaroo mother care (KMC) [16]. One downside of this comforting technique is that the neonate needs to be taken out of the incubator, which can be stressful to the child. Some neonates are unable to receive this particular kind of care, because their medical condition does not allow them to be taken out of the incubator.

The majority of these comforting techniques have in common that a parent or nurse needs to be present to provide the desired care. The same holds for nurses, as they often have multiple neonates to care for. A comforting solution that does not require the continued presence of a parent or nurse is thus a design path worth exploring.

The Eindhoven University of Technology (TU/e) has started a ten-year project on perinatology research in cooperation with the M'axima Medical Center (MMC) in the Netherlands. The goal of this project is to improve the wellbeing for the pregnant woman and her child before, during, and after delivery [21]–[23]. Research results that have been reported from this project area, for example, a smart jacket for neonates integrated with textile sensors [24], [25], a power supply based on contactless energy transfer [26], blood oxygen saturation monitoring for neonates using a reflectance pulse oximeter [27], [28], neonatal temperature monitoring [29], textile mat design [30], data transmission [31], [32], and a device to support cardiopulmonary resuscitation of neonates [33].

This paper presents a new concept and design for comforting preterm neonates, which aims at comforting preterm neonates by mimicking selected features of the baby's mother or father and making the features available to the baby when the parents cannot be present themselves. We were inspired by the fact that KMC is beneficial for newborn infants. Apart from the skin to skin contact and maternal scent, one of the features of KMC is the exposure to the maternal heart beat [34]. Dohenyet al. [35] reported that exposure to biological maternal sounds improves cardiorespiratory regulation in extremely preterm infants. Although the effect of a mother's heartbeat versus any other heartbeat has not been shown, it is beneficial to use a parental heartbeat. Empowering parents to play an active role in their child's incubation process is very important [36]. By letting parents donate their heartbeat to the child, they feel that they can contribute to the child's wellbeing which is an important factor in the parent child bonding process [37], [38]. The concept, called Mimo, is a comforting solution through an intelligent pillow system embedded with sensing and actuating functions that provides neonates with an experience similar to being held by their parents. The following sections will present the concept in more detail, and describe the implementation and evaluation of the prototype at the MMC in the Netherlands.

II. DESIGN CONCEPT

The concept for the proposed comforting solution was based on findings from the literature and the user studies performed at NICU.

A. User Studies

An essential first step in the development of a new, nonpharmacological pain treatment is the recognition and evaluation of the *status-quo*. We apply user-centered design (UCD) during the industrial design process and based on the outcome of user research define system requirements and

make decision on technological directions. In UCD, the end-user is constantly involved in the design process. In this case, medical staff and parents can be valuable sources of information, in effect, becoming the voice of the neonates. Interviews with medical staff and observations at a NICU facility have been performed in order to gain better insight on the conditions and treatments given at a NICU.

Neonates can be comforted in two ways: by providing an active comforting treatment or by taking away sources of discomfort. Some hospitals [e.g., the Maternity District Hospital –Helena Venizeloull (GR)] have a very strict policy that focuses on the latter. The fragile neonates are taken out of the incubator only for medical treatments. The care policy focuses on limiting external stimuli to the neonates as much as possible. Noise and light levels are reduced to absolute minimum and parents can visit their babies during fixed visiting hours. Other hospitals [e.g., MMC in Veldhoven (NL) and the Maastricht University Medical Centre (NL)] are less strict and emphasize on the value CHEN *et al.*: MIMO PILLOW—AN INTELLIGENT CUSHION DESIGNED WITH MATERNAL HEART BEAT VIBRATIONS 981 of parent–child bonding as a source of active comfort. Therefore, they allow parents to visit their baby in the NICU at any given time. These hospitals also encourage the parents to take part in their child’s care, by changing diapers or bottle feeding. This kind of involvement also helps the parents who often feel that they cannot help their fragile baby during the stay at the NICU. These hospitals encourage KMC as a means of comfort and bonding. Nurses and parents from these hospitals stated that infants are the most relaxed during KMC. Although it is clear that parents can play an important role in the comfort of their child, they cannot be present at all times to provide this comfort. In all hospitals, some more than others, there are situations in which alternativemeans of comforting are required. Therefore, it seems appropriate that a new comforting solution would focus on providing a neonate with the same feeling of comfort that parents would provide, even when the parents cannot be physically present.

B. Concept

Based on the literature review, the aforementioned user studies and a brainstorm, a concept for a novel solution of comforting preterm neonates was proposed. This concept, called Mimo, is a comforting solution that provides neonates with an experience similar to being held by their parents. Since neonates show less stress signs when they are in contact with their parents and held to their chest, which seems to be one of the most pleasant experiences for a preterm neonate, Mimo aims at providing a

comforting solution with qualities similar to those of being held to a parent’s chest, available especially when the parent cannot provide the comfort himself or herself.

This concept might not only increase the general comfort level, but it can also contribute to the bonding between parent and infant. Mimo gives parents the chance to record their personal features such as heartbeat, smell, and temperature, which can be mediated to the child when it is in need of comfort. When the concept is fully realized, the child might experience a feeling as the parents were close to them, even when the parents are not physically there. One of Mimo’s basic characteristics is its ease of use, which enables parents to record their physiological features without guidance.

III. PROTOTYPE

The initial prototype of Mimo was designed to mediate the parent’s heartbeat by means of vibrations, much like a pulse. One of the basic characteristics of the concept is that Mimo should be easy to set up and use, so that parents could record their physiological data on their own, without the guidance of a nurse for example. Then, the nurse needs only to switch ON and activateMimo when comforting is needed. Moreover, theMimo prototype features a pillow-like device to convey the heartbeat, which can replace the regular pillows that are used in incubators, thus, sustaining the neonate’s nvironment and avoiding extra special equipment that would load the incubator. This prototype was designed to be comfortable and ergonomic for a premature neonate, but also washable and clinically safe to meet hospital standards. Options for reproducing heartbeats both in terms of sensing and output/actuation have already been explored [17].



Fig. 1. Prototype with the Mimo recorder (left) and the smart pillow (right).

However, we strived to develop a system that would be very easy to use without the need for medical personnel assisting in the process.

The photoplethysmogram (PPG) sensor is noninvasive and easy to use by the parents. Moreover, the main objective of our research is to develop a device that would provide comfort both to the child and the parents by empowering parents to make

active contribution even when they are not present to their baby. Therefore, we designed the system to measure PPG signals and play heart beat vibrations to comfort the baby. A study on an intelligent baby carriage with a PPG system and heart beat vibration feedback has been reported in [39] with preliminary experimental evaluation of only one child. In our study, we run clinical tests to investigate the effectiveness of Mimo.

The Mimo prototype (see Fig.1) consists of two parts:

- 1) A recording unit (Mimo recorder), for registration of the parent's heartbeat.
- 2) A pillow-like object (Smart pillow), for transmitting the parent's heartbeat to the neonate.

A. Mimo Recorder

The Mimo recorder is a white cubical box that allows parents Of preterm neonates to make a recording of their heartbeat. A heartbeat hotoplethysmograph (PPG) sensor as well as a connection cable are attached to the side of the box. The front of the box features a number of LEDs displaying the status of the recording process and a button to initiate the recording process.

1) *Sensor*: The heartbeat sensor that is used in the prototype is a PPG sensor, which is an optical sensor that measures a person's pulse. An infra-red LED on one side of the sensor shines through the finger onto a photosensitive sensor at the other side of the finger. The amount of blood that flows through the finger influences the amount of light that reaches the sensor, hence, providing information about the person's pulse. Although there are other ways to record a heartbeat (such as electrocardiogram sensors), the PPG sensor provides a quick and easy way to record a heartbeat for this application.

2) *Electronics*: An overview of the circuitry inside the Mimo recorder can be found in Fig. 2. The heart of the Mimo recorder is an Arduino Uno microcomputer, powered by a 9-V battery. The Arduino handles almost the complete recording process, ranging from sensing and storage to transmission of the heartbeat to the pillow. It was deliberately chosen to use a battery rather than a fixed power supply, to provide maximum flexibility to parents in their choice of a recording location.

3) *User Interface*: The user interface of the Mimo recorder as designed to be as simple as possible, so that parents can perform the complete recording process themselves. Four LEDs provide feedback to the parents about the status of the heartbeat recording. One light shows whether the device is switched ON, another light indicates whether the sensor is properly attached, and the two remaining

lights indicate whether the recording has not started yet (lights OFF), is currently in progress (lights blinking) or has finished (lights ON).

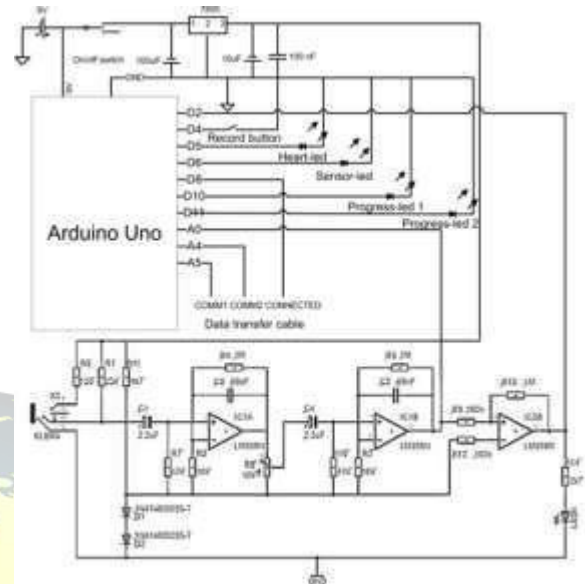


Fig. 2. Circuit diagram of the electronics in the Mimo recorder.

In order to record their heartbeat, parents first need to attach the sensor to their finger or earlobe. Once the sensor indicator confirms that the sensor has been properly attached, the parent can press the recording button and wait for the status lights to light steady. Then the pillow can be connected to the recording unit and the heartbeat will be transferred to the Smart pillow

B. Smart Pillow

The Smart pillow is the part of the prototype that stays with the neonate. It is a boomerang-shaped pillow that is filled with polymer beads and contains a pouch that accommodates the electronics. The polymer beads that are used for the filling act as support and ensure both softness for the neonate as well as stability that allow the pillow to be shaped around the neonate's body. The form of the pillow was determined through an iterative design process— Inspired by the design of the -Frederick T. Frogg pillow by Philips [40], and matured through discussions with medical staff. The materials were chosen on the basis of their suitability for the NICU environment (safe, easy to clean, comfortable for the child).

1) *Electronics*: Much like the Mimo recorder, the Smart pillow is controlled by an Arduino Mini microcomputer. This Arduino version is much smaller and flatter than the one used in the Mimo

recorder, such that it is hardly felt from the outside

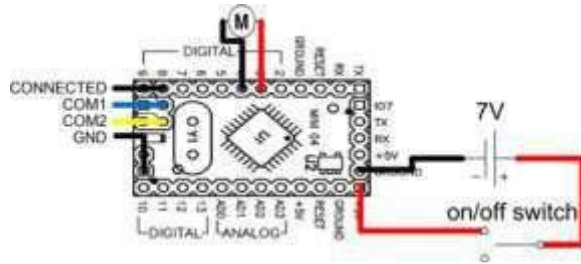


Fig. 3. Circuit diagram of the electronics in the smart pillow.



Fig. 4. (a) Mother records her heart beat at NICU using the Mimo recorder.

(b) Baby with the Mimo pillow during the test.

of the pillow. Other efforts to ensure that electronics are not felt by the neonate have been made by using a specialized flat model racing battery as power supply, a tiny vibration motor to mediate the heartbeat vibrations, and by using a tiny control to switch ON or OFF the electronics. A detailed overview of the electronic circuit is provided in Fig. 3.

2) *User Interface*: The heartbeat data that has been recorded with the Mimo recorder can be transferred to the Smart pillow by connecting the connection cables of both devices. Once the heartbeat data has been transferred to the pillow, it is immediately ready for use. The recorded heartbeat data is stored in the microcomputer in the Smart pillow and is played back continuously, as long as the device is switched ON.

IV. CLINICAL TESTS AND EVALUATION

To test the viability of the design, clinical tests were carried out at M'axima Medical Center in the Netherlands. The objective is to assess the effects of the Mimo system on newborn infants following a discomforting procedure. We hypothesized that sensing of the maternal heart beat by the infant could offer additional consolation and hence reduce the crying time following a discomforting procedure. An

analysis of risks was performed before applying the prototype to the NICU. The safety of the Mimo rototype system was analyzed by clinical physicists and the ethical commission of the MMC approved the experiments.

A. Method

First, the heartbeats of the neonates' mothers were recorded with the Mimo recorder. The signal was uploaded to the Mimo pillow and after switching on the rhythmic vibrations can be felt at the surface of the pillow. The Smart pillow was placed on the chest of the infants after their diaper change before their feeding, a moment of discomfort where most baby's cry. Fig. 4 shows that a mother records her heart beat at NICU using the Mimo recorder and a baby with the Smart pillow during one test. To rule out any effects of consolation by the pillow without heart beat vibrations, we tested the pillow both with the vibrations switched ON and the vibrations switched OFF during two subsequential diaper changes.

We conducted a pilot study in late preterm infants that were admitted at the medium care ward of M'axima Medical Center. Patients were randomly assigned to 1) comforting with the pillow with vibrations switched ON, followed by comforting with the vibrations switched OFF and 2) comforting with the vibrations switched OFF, followed by comforting with the pillow with vibrations switched ON. The change in comfort level following placement of the pillow on the infants chest was assessed by video recording of the facial expressions to measure crying time and by the measurement of recovery time to baseline values using the skin conductance analgesimeter (SCA) [41]. The mean baseline SCA value was measured for each baby when he or she was in a calm condition before the diaper change. During the diaper change, the SCA values increased due to the discomfort of neonates. The recovery time was calculated by measuring the duration of time after the diaper change for the SCA values returning to the baseline SCA value. The observer (AvM) was unaware of the vibrations in the Mimo pillow being switched ON or OFF.

B. Results

19 infants with a gestational age between 32 + 7 and 36 + 6 weeks enrolled in the study. Nine infants did not show any sign of discomfort after the diaper change and obviously did not show any change in study parameters following placement of the Mimo pillow on the chest of the infants. The results of the other ten infants that cried after the diaper change are shown in Table I.

In this study, we show that nine of ten infants that showed discomfort following diaper change, a shorter recovery time to baseline SCA values could be measured when the maternal eartheat vibration in the



Mimo was switched ON. In seven of these ten, a shorter crying time was measured. Differences Between mimo-OFF and mimo-ON have been tested by the Wilcoxon Rank Sum test yielding a p-value of 0.037 in recovery time and 0.086 in crying time, respectively. The results indicate that preterm infants can benefit from the Mimo pillow during and following stressful procedures. The device seems to be a simple, effective, and safe intervention for pain in newborn infants.

V. DISCUSSION

The sSmart pillow concept consists of two parts: a recording unit and a technologically enhanced pillow. The recording unit is used to record physiological data (such as heartbeat, breathing rhythm, parental smell, and body temperature) from a parent. This data can then be transferred to the pillow, which includes technology that enables it to replay the recorded data to the neonate. The current prototype achieves a part of the functions of the original concept, as it focuses only on the recording and playback of a parent's heartbeat. In the future study, the complete functions for more sensing and actuating modalities (e.g., breathing rhythm, parental smell, and body temperature) will be developed. Further developments also include miniaturization of circuits and electronics and a flash disk or wireless module (e.g., bluetooth) to store/transfer the mother heart beat data to the pillow.

The parent-child bonding is loose for the NICU patients because of the separation of neonates from their parents. The use of Mimo is expected to comfort the neonates on one hand and in the meanwhile to comfort parents and help them feel much closer to their babies. We carried out preliminary interviews with parents at MMC and online by demonstrating them the use of Mimo. The feedback from parents show that Mimo plays a positive role in comforting parents and attaining parental role by helping them feel much closer to their babies and feel that they are always there to support their babies.

More clinical tests will be carried out in the future study to compare Mimo with other neonatal pain treatments (e.g., sucking or swaddling) and compare the effectiveness of parental heart beat with any other heart beat in order to further investigate the analgesic effect of the heartbeat of mother.

The crying time was assessed by observation on the babies' facial expression. Because the participants are premature infants and their facial expression is not as well developed as the facial expression of a term infant, the physiological measure of recovery time to baseline SCA value is more reliable than observation. More physiological data, such as ECG,

EEG, and heart rate variability, and behavioral data of the neonates could be measured for the purpose of multimodal assessment and statistical analysis.

Furthermore, the current design is only a prototype for tests and demonstration purposes. To develop the solution to a ready-to-market product, strict product design process and clinical safety evaluation of the reliability of the complete system are needed.

VI. CONCLUSION

This paper presents the design, implementation, and evaluation of a new nonpharmacological comforting solution for preterm neonates. The concept, named Mimo, aims at comforting a neonate by providing the baby with a feeling similar to that of being close to a parent. An intelligent pillow system was proposed and implemented with embedding sensing and actuating functions for the transfer of maternal heart beat into the pillow and playing the pulsation to the neonate. The prototype was tested on premature babies at MMC in the Netherlands. Among the nine of ten infants who showed discomfort following diaper change, a shorter recovery time to baseline SCA values could be measured when the maternal heartbeat vibration in the Mimo was switched ON and in seven of these ten a shorter crying time was measured. Thus, this device has potential to be a simple, effective, and safe intervention for comforting newborn infants.

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