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Review Article

General design criteria for neonatal temperature monitoring sensor using "smart material" conducting polymer development: A review

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ARTICLE INFO	ABSTRACT
	Surface thermistors are currently being used in patient monitoring, including temperature monitoring among neonates. However, these thermistors are reported as being mechanically rigid. This review article aims to provide researchers with a guide to better design a flexible neonatal temperature monitoring sensor. A literature search was conducted to obtain available literature on temperature sensors with specific attention to designing flexible temperature sensors. The achievement of a flexible-type thermistor for neonates requires a basic understanding of the thermistor. Also, the conducting polymer material being used and the rationale for their placement. The updated technology in thermistors should be made flexible for the ease of neonates during monitoring. Careful considerations for the design and conduct of flexible temperature sensor research, as outlined in this review, would help to enhance the quality and comparability of future research studies. Considerations for efficient neonatal temperature monitoring and protection include accuracy, sensor size, weight, material, and sensor placement. Flexible sensors could be the alternative to conventional bulky and stiff temperature sensors.

1. INTRODUCTION

Neonatal monitoring means monitoring vital physiological parameters [1] of premature infants, full-term infants critically ill, and a combination thereof [2]. Generally, continuous monitoring of neonates' vital signs and parameters is essential in neonatal intensive care units (NICUs) [3]. Special care and attention to the neonate's vital signs are crucial, including body temperature, heart rate, breathing rate, body temperature, respiration, blood oxygen saturation, and blood pressure, as premature infants are exposed to the risk of developing adverse conditions. Thus, it must sustain individuals' vital signs and physiological parameters [4,5]. Their organs are not mature enough to allow expected postnatal survival [6].

Effective neonatal care in the NICUs prevents possible clinical implications such as apnea, hypoglycaemia, sepsis or sepsis-like infection, seizure,

arterial hypotonia, bradycardia, and hypoxia [7,8]. Other complications include difficulty breathing, increased glucose utilisation, post-delivery acidosis, and many more [9].

Body temperature status is one of the necessary indicators for neonates [10], especially pre-term neonates. Continuous monitoring of body temperature helps with the early identification of temperature instability [11]. Deviation from an average body temperature indicates that there is a pathological condition [9]. It is essential to accurately measure the body temperature of neonates as thermoregulation can influence their survival [11]. As the survival rate of neonates has increased significantly in the last decades, the quality of life of neonatal intensive care unit (NICUs) infants has also become an important issue [12].

The maturation of temperature sensing technology has been anticipated for over 1,000 years ago. Around 400 B.C, physicians placed their hands on the patient's forehead and utilised their sense of touch to estimate their body temperature [13]. Later, in the 17th century, a simple thermometer was devised, the first objective biomedical sensing device. Since then, temperature sensors have become essential in healthcare services and realise the importance of scientific developments and advances in biomedical technologies.

In recent years, a wide range of temperature monitoring and sensors for patient monitoring have been developed. The neonatal health monitoring technology development includes a diversity of wearable devices [7] [10], such as smart jackets [10] and intelligent fabric. For example, Chen et al., 2010 introduced a wearable device incorporating a negative temperature coefficient (NTC) type of temperature sensor, a thermistor, to their bright infant jacket.

The traditional method of neonatal temperature monitoring is by direct supervision of the healthcare personnel using a thermometer [14]. This method is sometimes difficult to identify fundamental temperature changes, which may be of concern. In addition, the response time of the thermometer is inadequate, and it took at least 9 seconds for a constant thermometer reading from room temperature to 50 °C [15]. Another issue is that the glass mercury thermometer is due to the potential hazard with mercury [9]. Furthermore, continuous monitoring of the neonates cannot provide due to the measurement mechanism that requires the healthcare provider to take the temperature measurement repeatedly. The measure of core body temperature through rectal using the thermometer has been reported, but it did not provide continuous monitoring. Furthermore, the rectal measurement method is invasive and potentially risks rectal injury [11] due to repeated rectal temperature measurements.

To overcome the problem, later, the use of surface temperature sensors is introduced. Any device that senses temperature information is termed a temperature sensor, with a recordable, usually electrical or optical [13]. Temperature sensors achieve continuous temperature monitoring. Thus, the neonate's body temperature information can be closely monitored. The skin temperature sensor is preferable for temperature monitoring as it is non-invasive and reflects the core body temperature [11]. Continuous temperature measurements can also be retrieved using an embedded temperature in an oesophageal tube [16] as soon as the baby is delivered.

Thermocouples, RTDs (resistance temperature detectors), and thermistors are commonly researched temperature sensors. The intrinsic principles associated with these sensors have their advantages and disadvantages, shown in Table 1, Table 2 and Table 3. The applications of these types of sensors in the medical field are demonstrated in Figure 1.

Table 1. Thermocouple.

Characteristics	It consists of two wires of different metals connected at two points. The varying voltage between these two points reflects proportional changes in temperature.
Advantages	Inexpensive, durable, and able to operate across the broadest temperature range (from -200 °C to 1750 °C).
Disadvantages	One of the most challenging sensors to operate with low accuracy and small output voltage requires precise amplification. Also, susceptibility to external noise over long wires

Table 2. Resistance temperature detectors (RTDs).

Characteristics	Measures temperature by correlating the resistance of the RTD element with temperature
Advantages	Offer a wide range of temperature measurements (smaller than thermocouples) and provide accurate and repeatable measurements
Disadvantages	Expensive, slower response time and require an excitation

Table 3. Thermistors.

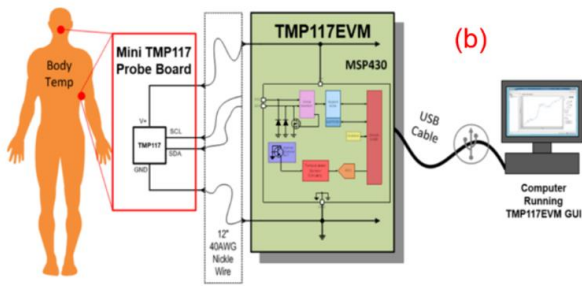| Characteristics	A thermally sensitive resistor
Advantages	Durable, small and exhibits a large, predictable, and precise change in resistance correlated to variations in temperature
Disadvantages	Nonlinear outputs

Figure 1. (a) Thermocouples for a catheter to measure temperature [17]. (b) Body temperature measurement system using RTDs [18]. (c) An infant is attached to the thermistor probe using a reflective foil [19].

This paper aims to review thermistor-type temperature sensors for neonatal monitoring. A thermistor is a thermal resistive type of temperature sensor. The thermistor is a temperature-dependent resistor with steep rising or falling resistance characteristics [20]. It displays significant changes in resistance in proportion to small changes in temperature. The relationship between the thermistor resistance R_t and absolute temperature T (K) is in equation (1) [21]. Note that β and T_0 are in Kelvin. The temperature coefficient is not constant but varies with temperature changes [22].

$$R_t = R_0 e^{\left[\frac{\beta(T_0 - T)}{TT_0}\right]} \qquad (1)$$

where:

β = material constants

T_0 = standard reference of temperature

There are two types of thermistors. One with steep rising resistance characteristics is described as having a Positive Temperature Coefficient (PTC) of resistance,

while the other with a falling resistance characteristic has a Negative Temperature Coefficient (NTC). The PTC-type thermistor is nonlinear, whereas the NTC-type thermistor follows a roughly logarithmic law with no violent changes in resistance [22]. The primary output of the thermistor is electrical in nature and hence easier to integrate into a chip for further signal processing [23]. Figure 2 depicts a typical circuit for a thermistor.
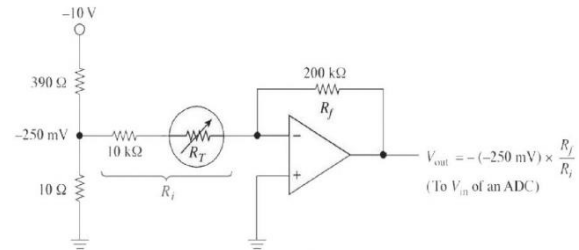

Figure 2. Circuit to convert thermistor ohm to DC voltage [24].

Most neonates' body temperature is monitored using a ceramic-based thermistor taped on the skin surface using adhesive tape [12]. However, existing devices' bulky and non-flexible nature will limit the duration of comfortable use [25] and be inconvenient to wear for a long time, restricting their applications. In addition, the sticky and adhesive tape and the presence of wires, on the other hand, will be painful when removed and discomfort for the neonates [12].

This paper focuses on a flexible skin surface thermistor type of temperature sensor. Current thermistor-based medical sensor technologies still have not attained the mechanical properties of being flexible. This study is inspired by flexible and thin-film electronics technology and the importance of neonatal temperature sensing in medical applications. Advanced flexible electronics could make continuous contact with soft and curved infant bodies. Hence, potentially initiating long-term monitoring of neonatal temperature changes.

Constructing a conductive and flexible sensor for neonatal temperature monitoring is challenging yet interesting. More specifically, a qualified, flexible sensor design must also consider several criteria, and the outward appearance should meet the aesthetic requirements [7]. A comparison is also made among different clinical thermistors regarding the sensor's responding time and accuracy. Pertinent journal papers and research articles were also reviewed to justify this review paper's emphasis on summarising thermistors design's criteria of flexible thin-film (thin-film substrate size less than 2 µm [5]) technology currently undergoing assessment. Neonatal monitoring sensors should also be non-invasive [7]. General criteria for temperature sensors or thermistors are discussed as follows.

2. GENERAL DESIGN CRITERIA FOR NEONATE'S TEMPERATURE SENSOR

This section emphasises the essential design criteria and considerations for neonatal temperature monitoring. Several criteria must be met to achieve flexible sensor requirements. The desirable provision of the adjustable temperature sensors includes high sensitivity, fast response, wide-working temperature range, and lightweight [14].

2.1 Sensor's Accuracy and Response Time

One of the major concerns in designing body temperature sensors is accuracy. Sensor accuracy represents how close the temperature is to the actual value. A suitable temperature sensor should possess high accuracy and sensitivity [26] to record the infant skins' temperature. Thin and flexible skin surface sensors must have sufficient sensitivity and accuracy due to their attachment to the non-planar skin surface with motion [26] The accuracy can be addressed by picking a temperature sensor with high measurement precision.

Another critical factor is the sensor's response time. A temperature sensor should be responsive to temperature changes with a relatively fast speed and accuracy of 0.1 °C from 37 to 39 °C and 0.2 °C both below 37 °C and above 39 °C [26]. The sensor's response speed is determined by the sensor's amount of thermal mass [18]. The sensor's size and placement will affect the response time; thus, both criteria must be taken. While the sensor's size also impacts the design, the sensor size and thickness determine the thermal response time. Therefore, the sensor's weight and size need to be small, and it should not hinder the user's movements and actions, especially in infants [7]. The small dimensions of most bead, disc, and chip thermistors used for resistance thermometry ensure a rapid response to temperature changes.

This feature is handy for temperature monitoring and control systems requiring quick feedback [27]. A comparison is made among different clinical thermistors regarding the sensor's responding time and accuracy, depicted in Table 4. There are several clinical skin probe sensors for neonatal monitoring, but not enough data from the thermistor's datasheet for reference. Other characteristics are the sensor's repeatability and stability against surrounding influences [26]. The overall design needs to be considered to achieve these requirements, such as size, thickness, and material choices. Also, the patient monitoring temperature sensors should possess an operating temperature range of (25 °C to 40 °C) [26].

Table 4. The accuracy and response time of some clinical temperature sensors.

Thermistor Types	Accuracy	Response Time	Tolerance
Body surface NTC sensor probe, Hefei Jingpu Sensor Technology	± 0.1 °C	2 seconds	-
Skin/surface probe, model 427, TE Connectivity	± 0.1 °C	extremely fast	25 to 45 °C
NovaTemp skin temperature sensor	± 0.2 °C	rapid	25 to 50 °C
PASCO skin/surface temperature probe	± 0.5 °C	-	-10 to 70 ± °C
LMT70 temperature sensor	± 0.1 °C	-	20 to 42 °C

2.2. Placement of Sensors

Package and placement can impact the response time and conduction path; both are critical for effective temperature design. In infant temperature sensing, the specific site of body temperature recording must be selected carefully to truly reflect the patient's temperature [4]. During thermoregulation, the body heat is generated mainly in the deep organs, especially the liver, brain, heart, and skeletal muscles' contractions. Hence, the active organs will either increase in temperature or decrease in weather. For example, the liver is one of the most active organs, where the temperature around the liver is relatively high [10]. Therefore, the skin temperature above the liver of infants under radiant warmer in the NICU is usually measured. Figure 3 shows a wearable sensor demonstrated on a baby doll where the thermistor is set between the infant's back and the mattress of the incubator [10].

Figure 3. The proposed wearable sensor placement[10].

The skin temperature of infants can be monitored while the sensor probe attaches to the arm [25], abdomen, flanks, chest, or back area [28]. They are usually measured by using a surface thermistor [10] or an infrared light absorption technique [29] under the direct supervision of nurses, parents, and clinicians [7]. For example, figure 4 shows a pre-term infant in an incubator where the thermistor probe is attached to the infant's back [30].

Figure 4. A baby in the neonatal intensive care unit[30].

Based on a study done by Pouy and Chehrzad, 2018, they concluded that the best measurement site for measuring skin temperature in NICUs neonates is the right hypochondrium and right axillary areas [11]. Their finding is based on the diagnostic clinical trial done on 203 premature neonates who were cared for under a radiant warmer, where the temperature probe was placed at seven different locations. In addition, a temperature sensor should not be placed above bones [10]. As for localised temperature sensing, the sensor could be placed at the infected area on the skin surface or readily available devices such as catheters for intravenous temperature monitoring.

2.3 Body Temperature Range

If body temperature information needs to be achieved using a temperature monitoring device, sensory inputs similar to the infant's normal and abnormal body temperature must provide the necessary feedback to explore further and analyse physicians. For example, a review reported that the lethal limits of body temperature range from as low as 26 °C (78.8 °F) to a high of 43 °C (109.4 °F) [31].

Usually, temperatures within this limit do not cause thermal injury to body tissues. Likewise, patients with a temperature increase too far above average may be at risk of seizures, brain damage, and other complications. Unlike adults, children and babies have a little higher temperature value in a range of 36.6 °C (97.9 °F) to 38 °C (100.4 °F). According to The World Health Organization (WHO) (1997), the range for the average temperature of

an infant is 36.5° to 37.5°C [16]. Although the core body temperature is typically maintained at around 37 °C, the skin surface temperature is slightly lower and depends on location, gender [32], and measurement time [31]. Table 5 shows the range of premature infant temperatures according to the measurement location.

Table 5. The general temperature ranges for premature infants [16].

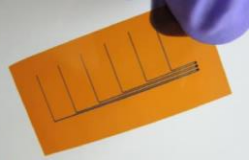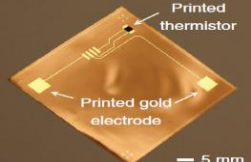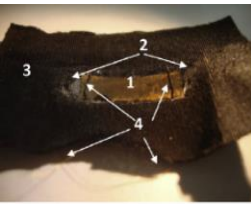| Measurement location	Temperature
Rectal	(36.5 to 37.5°C)
Skin	(36.2 to 37.2°C)
Axillary	(36.5 to 37.3° C)

2.4. Material Selection

Correct material selection is not less important in building a temperature sensor. Flexible temperature sensors and thermistor types of sensors gathered considerable interest, and efforts have been made in various kinds of material. Table 6 shows examples of flexible and wearable temperature sensors and thermistors. However, scholars in these fields have not adequately addressed flexible, mechanically robust, and sensitive sensors using PPy as sensing material and P.U. as a substrate's sensor.

2.5 Conducting Polymers (C.P.s) as Sensing Material

Conducting polymers (C.P.s) have received increasing attention over the past decades owing to their electrical properties similar to those metals and traditional semiconductors [37], labelled as "synthetic metals" in the late 1970s [37, 38]. There are at least 20 types of C.P.s available [39]. C.P.s have tremendous technological potential for the development of sensors. C.P.s are conducting polymers in which a conducting material is dispersed in a non-conductive polymer (organic polymer) [37,40]. C.P.s can conduct electricity [41]. When it is doped and is distinguished from other types of polymers due to its conjugated double bond structure [39], described by sigma (σ) and pi (π) bonds. In comparison, the σ electrons are fixed and immobile due to the formation of covalent bonds [42]. Among the listed conductive polymers, Polypyrrole (PPy), Polyaniline (PAni) and Poly (3,4-Ethlynedioxythiophene (PEDOT) are the most promising conductive polymer, arguably the most studied conductive polymer, reflected by the amount of publication surrounding its properties [39] and their applications in the Biomedical field [43].

Table 6. Thermal sensor and thermistor specification for temperature monitoring

Sensor Material	Substrate Material	Key Features	Limitation(s)	Final Product	Ref.
Graphene	Polydimethy lsiloxane (PDMS)	Flexible and stretchable	Sensitivity fluctuation under Strain		[33]
Nickel Oxide (NiO)	Polyimide film	High-sensitivity, scalable manufacturing	Not stretchable, poor material adhesion		[34]
Nickel Oxide (NiO)	Polyimide	Mechanically robust	Unknown sensitivity		[35]
Organic conductors $(BEDT\text{-}TTF)_2X_3$ (Bis[ethylenedithio] tetrathiafulvalene, X_3)	Polycarbona te (P.C.) film containing eight wt% of BEDT-TTF	Lightweight and accuracy of 0.005	Unknown sensitivity		[36]

2.6 Flexible Encapsulation Material (Substrate)

In most bio-hybrid technology, the primary thin film substrates are usually fabricated using elastomeric material to provide cell adhesion and proliferation such as Polydimethylsiloxanes (PDMS), Polymethylmethacrylate (PMMA), Polyurethane (P.U.), Polyester, Polycarbonate [44], polyimide (P.I.) and polyethene terephthalate (PET) [26]. In addition, encapsulation of the thermistor is essential as it needs to provide adequate barriers to reduce moisture intake and protect the thermistor from later processing [35]. PDMS material is the most used substrate [26], but P.U. is prevalent [45].

3. OTHER POTENTIAL BIOMEDICAL APPLICATIONS

Other than being used for neonates, the criteria can be applied to design flexible or wearable thermistors for other potential biomedical applications. Small in size, thin, flexible, and lightweight could also be helpful in telemedicine due to its ability to follow the body's contours. This sensor could also be applied to catheters making it a sensing catheter to assist surgical interventions such as measuring temperature during the cardiopulmonary bypass circuit. Also, to attach it to catheters for applications such as Pulmonary Artery Characterization (PAC), Foley catheters, and Intravenous therapy. The small size and thin thermistors could also be wearable and embedded into babies' fabric, shoe soles for diabetes patients' feet, or attached to the tracheal tube for paediatric patients. Additionally, ongoing studies in temperature monitoring with flexible and stretchable formats open up other potential areas, such as artificially electronic skins [26].

4. CONCLUSION

This article sought to provide a quick guide to the body of literature outlining the potential criteria in designing a temperature sensor, a thermistor. Careful considerations for the design and conduct of thermistor research will enhance future research studies quality and comparability, especially in thin-film and flexible temperature sensors in neonatal monitoring. The use of

skin surface thermistors for neonates has grown substantially over the years. Moreover, neonatal healthcare providers are primarily still using ceramic-based thermistors. Future directions include the current study to fabricate a conducting polymer-based flexible thermistor for neonatal monitoring. An additional circuit will be added to analyse the overall sensor's performance, thus can yield a more optimised design. However, it is still challenging to fabricate a flexible temperature sensor with a reproducible sensing response in an appropriate temperature range.

CONFLICTS OF INTEREST

No conflict of interest affects this publication.

ACKNOWLEDGEMENT

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