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Investigation of textile permittivity under the influence of fever for designing a wearable temperature sensing antenna

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ABSTRACT

This paper aims to monitor human fever using wearable sensors as a non-invasive and real-time method. Our purpose is based on the use of textile sensors that can be integrated with the person's clothes. The origin of antenna sensor measurement presented here is based on changes in fabric relative permittivity related to variations in body temperature in the range from 35 °C to 41 °C. The structure is such that a microstrip patch antenna is implemented on the textile in the X frequency band. In the first step of designing the sensor, the measurement setup is designed to extract ε_r and tan δ characteristics of various commercial fabrics using a Keysight N1501A-101 high temperature dielectric probe. After examining a few samples of different fabrics in the setup, the commercial cashmere fabric with the highest changes in relative permittivity is selected to design the antenna sensor. The rate of change in relative permittivity of this fabric is about 0.02 for a temperature step of 2 °C. The antenna sensor provides a frequency shift of 60–80 MHz per temperature step in the X frequency band. The frequency shift per 1 °C is found to be about 35 MHz, which is acceptable and can provide good temperature detection. Given that fever is one of the main symptoms of many diseases and that its early detection can prevent endangering people's lives, the proposed wearable sensor may find important applications in fever monitoring.

1. Introduction

Medical equipment is generally divided into two categories: invasive and non-invasive. In the invasive category, the equipment for measuring the desired parameter requires sampling of the body or entry into the main limb. The main disadvantage of the invasive equipment includes the possibility of transmitting viruses and bacteria between patients. One of the medical devices that can transmit the disease is the thermometer, according to literature (John., 2018). With the spread of COVID-19, it has become vital to prevent virus transmission among individuals, making it necessary to perform thermometry during the treatment continuously. Accordingly, the use of non-invasive thermometers with continuous measurement capabilities has become more important than ever (Garzotto et al., 2021). One of the non-invasive methods used for human temperature monitoring applications is wearable sensors (Yu et al., 2020). Here, a wearable sensor is employed as a textile antenna sensor integrated with the person's clothes (Le and Yun., 2021; Piper et al., 2021; Paracha et al., 2019). Furthermore, by proposing the wearable sensor as an antenna implemented on the textile, one can provide the conditions for continuous monitoring of the person's body temperature. Other advantages of this method are the lightweight, flexibility, low price, and internet of things-based ability to send information wirelessly (Yang and Liu., 2020) .

Heron of Alexandria invented the first thermometer. Since then, many methods have been proposed for measuring body temperature over successive centuries. Based on recent reports, a relationship has been found between the temperature and textile antennas. Labiano and Alomainy. (2019) and Hearle and Morton., (2008) indicate that temperature changes affect the relative permittivity of textiles (REPOTs). A relatively linear relationship between temperature and REPOT provides the possibility of offering a passive structure to measure body temperature. Labiano and Alomainy. (2020) and Lin et al. (2015) used a non-conductive textile substrate to measure human body temperature. In this paper, we aim to complement the earlier methods for measuring human body temperature with respect to the changes it causes in REPOT. To this end, in the first step, a suitable setup is provided to measure the effects of temperature on REPOT. Next, by investigating various types of conventional commercial fabrics using this setup, we extract the range and rate of REPOT changes as a function of temperature corresponding to human fever. This enables us to select the most suitable textile with the maximum rate of change for the design and implementation of the antenna. In the second step, the desired printed antenna is implemented on the textile substrate of the previous step, followed by measuring the change in antenna characteristics with

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Table 1
Measurement REPOTs results over temperature sweep at 12 GHz.

Fabric Type	Temperature (°C) 35	37	39	41
(a) Linen	$\varepsilon_r = 1.6261$ $\tan\delta = 0.1284$	$\varepsilon_r = 1.6263$ $\tan\delta = 0.1284$	$\varepsilon_r = 1.6265$ $\tan\delta = 0.1284$	$\varepsilon_r = 1.6269$ $\tan\delta = 0.1284$
(b) Cashmere	$\varepsilon_r = 1.4207$ $\tan\delta = 0.1287$	$\varepsilon_r = 1.4419$ $\tan\delta = 0.1265$	$\varepsilon_r = 1.4590$ $\tan\delta = 0.1243$	$\varepsilon_r = 1.4823$ $\tan\delta = 0.1219$
(c) Crepe	$\varepsilon_r = 1.2446$ $\tan\delta = 0.0323$	$\varepsilon_r = 1.2466$ $\tan\delta = 0.0322$	$\varepsilon_r = 1.2469$ $\tan\delta = 0.0322$	$\varepsilon_r = 1.2469$ $\tan\delta = 0.0322$
(d) Cotton	$\varepsilon_r = 1.4851$ $\tan\delta = 0.0697$	$\varepsilon_r = 1.4875$ $\tan\delta = 0.0696$	$\varepsilon_r = 1.4895$ $\tan\delta = 0.0695$	$\varepsilon_r = 1.4919$ $\tan\delta = 0.0694$

Table 2
Dielectric properties of human tissues at 12 GHz.

Tissue	ε_r	*tan δ*	σ (s/m)
Dry skin	29.327	0.52797	10.337
Fat	4.4570	0.24462	0.7278
Muscle	40.101	0.50616	10.355

respect to temperature.

Significant research has investigated wearable techniques for measuring human body temperature, including thermopiles, thermistors, and field-effect transistor methods where the temperature is identified. The main challenge of these methods can be mentioned as the comparatively slow speed of response, the need for linearization of measurement circuits, and simultaneous reaction to pressure and temperature changes (Tamura et al., 2018; Su et al., 2020). Whereas, in the temperature measurement method using REPOT, the antenna resonant frequency is sensitive to even slight variations in the substrate permittivity caused by the narrow range of temperature changes in the human body. On the other hand, due to the hollow property, the relative permittivity of fabrics is related to the body's smallest thermal coefficients and reactions to it. Furthermore, one of the positive aspects of temperature detection using REPOT is the simplicity of the resonant method as a detection signal (Labiano and Alomainy., 2020; Lin et al., 2015).

The outline of this paper is as follows: In the experimental section, we present the proposed setup to measure REPOT. Moreover, the measurement results are given for some conventional commercial fabric samples. In results and discussion section, an antenna sensor is presented based on the textile selected in the previous section in order to measure body temperature. The results of the variation in the antenna specifications with respect to temperature are also given.

2. Experimental section

2.1. Setup design theory

When the human body temperature rises above 37 °C, the body tries to dissipate the excess heat in various ways. The human body loses excess heat through the skin in four ways: evaporation, radiation, convection, and conduction (see Fig. 1 (A)). About one-quarter of the body's excess heat is lost by water evaporation from the skin i.e. through sweating. Whenever the body temperature begins to change under fever, it rises at regular intervals. A temperature equal to or greater than 38 °C (at the rest condition) is considered a fever. The fever temperature and its rate of increase can vary depending on the kind of disease (El-Radhi et al., 2018).

According to the heat balance theory of the human body, the evaporation requirement for heat balance (E_{req}) is found to depend on the

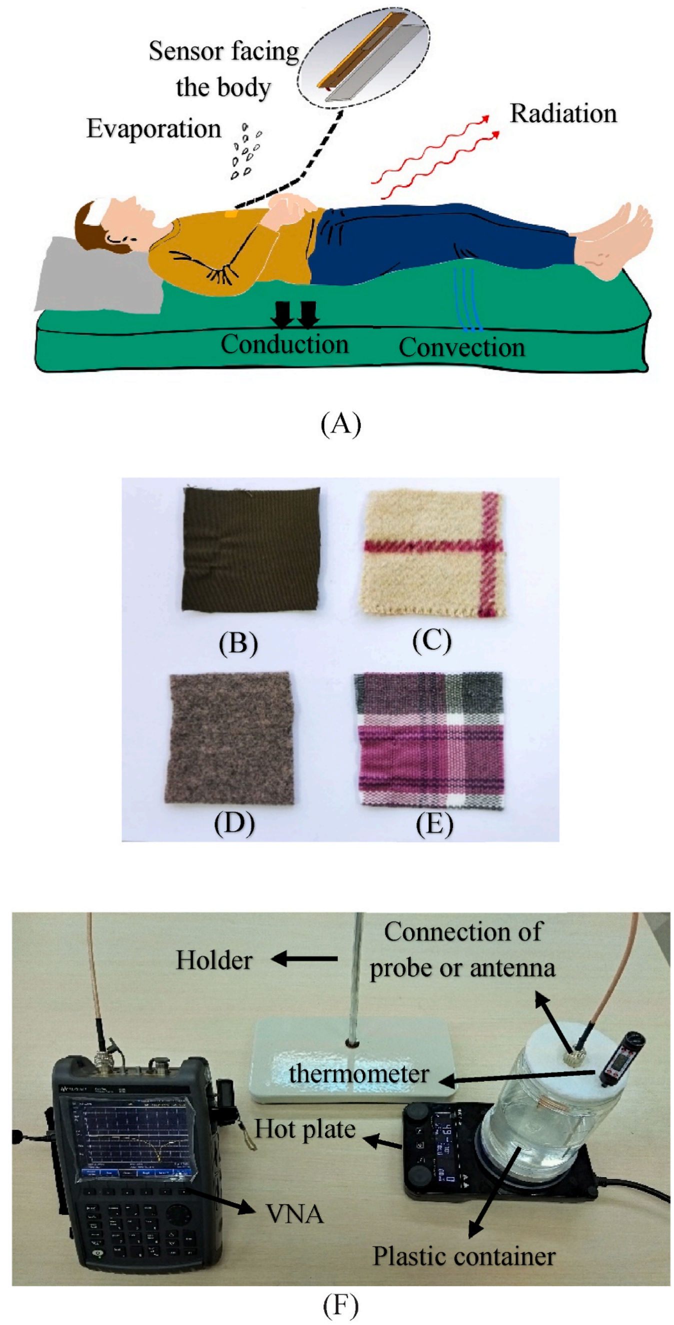

Fig. 1. (A) The different ways of losing body heat during fever. In our case, the sensor is integrated with clothes. The fabric substrate materials: (B) linen (C) cashmere (D) crepe, and (E) cotton. (F) The experimental setup designed for REPOT measurement and checking antenna performance.

maximum evaporation capacity of the environment (Baker, 2019). However, the body's metabolic energy (M) expenditure and other methods of heat loss affect the amount of sweat produced by the body as well (Chen et al., 2020). On the other hand, the temperature measurement in all the methods is carried out when the person is in a temperature balance with the environment without external activity (W). Under this condition, the person's body temperature is close to the body core temperature, being measured within the pulmonary artery. The purpose of thermometry is to determine the body core temperature (Grodzinsky and Levander., 2020). E_{req} and the parameters affecting sweat production are related by the following equation (Baker, 2019):

$$E_{\text{req}} = \text{M} - \text{W} \pm (\text{R} + \text{C} + \text{K}). \quad (1)$$

Where R is the radiant heat change, C is the convective heat change, and K is the conductive heat change. By combining the concepts of fever and E_{req}, one can state that M, R, C, and K differ from person to person. However, when the body begins to have fever, a certain amount of human body sweat evaporation (HBSE) will be observed at specific periods for each degree of temperature increase. This is because the production of more sweat does not necessarily lead to higher evaporation.

By investigating various measurements, it can be inferred that the relative permittivity of most fabrics is close to one. Due to their hollow structure, a large volume of textiles is composed of air. The greater the air volume in the textile structure, the closer their relative permittivity is to one. Now, if HBSE replaces the air at specific periods, we expect to see ΔREPOT being proportional to the temperature of the fever. In this way, the setup was designed based on the theory stated above, thus enabling us to evaluate REPOT. In fact, the purpose of this setup is to involve the role of sweat and resulting moisture in measuring the relative permittivity of the textile.

2.2. REPOT measurement setup

In this section, a REPOT measurement setup is designed for the textiles of ordinary people's daily carts. Here, four fabric materials (including linen, cotton, cashmere, and crepe) with the ability to be used as antenna sensor substrates in the next section are selected from 67 samples and evaluated by the proposed setup. Fig. 1 (B-E) shows the four fabrics studied in the present paper.

To provide the condition for the addition of HBSE to the fabrics when measuring ΔREPOT, a setup including a plastic container containing 1 L of artificial sweat was placed on a hot plate. In turn, this enabled us to apply temperature changes. The fabrics were placed inside the container without a direct connection with the sweat. Accordingly, only the moisture from the evaporation of the artificial sweat could affect the fabric. The container was completely sealed to create a temperature balance in the setup, thereby providing a water bath mode for the temperature control (Rahmat-Samii and Topsakal., 2021). The sweat was prepared by combining water with NaCl (5.0 g/L), according to EN 1811. The addition of lactic acid (1.0 g/L) and urea (1.0 g/L) was ignored (Tajin et al., 2020). Although there are several methods to measure ΔREPOT (Sankaralingam and Gupta., 2010; Declercq et al., 2008; Ouyang and Chappell., 2008; Vital et al., 2019), it is necessary for the proposed method to allow for the detection of temperature changes (Roy et al., 2017; Guido et al., 2020). In this case, a Keysight N1501A-101 high temperature dielectric probe with a Keysight vector network analyzer (VNA) was used to measure the REPOT. Fig. 1 (F) shows the complete illustration of the setup with the measuring probe and VNA.

A digital thermometer was used to continuously measure the temperature. The hot plate temperature was adjusted according to the selected temperature. The REPOT measurement was performed after the temperature stabilization. Due to an error of ±0.5 °C caused by the hot plate and thermometer, ΔREPOT was measured with a temperature step of 2 °C. The results obtained from ΔREPOT of the four fabric groups can be seen in Table I. The results show that the use of cashmere leads to the highest changes in REPOTs when compared to the other textiles. The results were recorded after being averaged for five experiments at the frequency of interest (12 GHz). These measurements showed a relative permittivity variation of about 0.02 for every 2° temperature increase from 35 °C to 41 °C for the cashmere at the frequency of 12 GHz. Also, we measured relative permittivity variation for 0.5 °C-step, and changes of about 0.005–0.008 were observed, which omitted from mentioning the values due to the lack of confidence in the measuring equipment accuracy. According to the linear relationship and the tests performed, with the provision of temperature conditions, changes can be seen in smaller steps. It is worth mentioning that, based on the different measurement results, the electrical characteristics of the textile are found to be more sensitive to temperature changes in the high frequency range (The sensitivity in the ISM frequency band is less than the amount used to monitor human body temperature). Accordingly, the X frequency band is taken into consideration in the present paper because of its acceptable relative permittivity variation, in addition to the possible fabrication of the antenna sensor. In the next step, an antenna sensor is designed using a cashmere substrate.

3. Results and discussion

3.1. Sensor design, simulation, and fabrication

The antenna sensor proposed in this section is a conventional rectangular microstrip antenna implemented on a textile substrate. Easy construction and flexibility are the features of this structure. However, the effects of bending and stretching on the antenna efficiency were ignored (Lajevardi and Kamyab., 2017; Mendes and Peixeiro., 2017). A copper tape conductive adhesive was used for implementation of the patch and ground plane with a thickness of 0.06 mm. The performance of this sensor is based on changes in the antenna resonant frequency induced by varying the relative permittivity of the substrate. Note that the relative permittivity change of the substrate is due to temperature changes. Fig. 2 (A, B) illustrates the proposed antenna structure. The measured and simulated S_{11} for a temperature range of 35 °C–41 °C with 2 °C-steps is shown in Fig. 2 (C, D). In the antenna simulation, substrate characteristics (ε_r and tan δ) at each temperature were considered based on the results in Table I for the cashmere fabric. The substrate thickness was set to h = 1.3 mm. All simulations were performed by CST Studio Suite 2021 software and the time-domain method.

As shown in Fig. 2 (C), the simulation results indicate the variation of about 300 MHz in the antenna resonant frequency for the temperature range of 35 °C–41 °C. A frequency shift of about 80–120 MHz also occurs for each 2 °C-step of the temperature change. In order to measure S_{11}, the fabricated antenna was placed in the same temperature bath presented in previous section. The measurement results of this antenna sensor are shown in Fig. 2 (D), confirming the changes in the antenna resonant frequency with respect to the temperature variation. In this case, the total shift is obtained to be 220 MHz. Moreover, a frequency shift of about 60–80 MHz is observed for each 2 °C change in temperature. This difference between the measurement and simulation results is due to several factors such as the fabrication accuracy, temperature error, and REPOT accuracy measured by the Keysight N1501A-101 high temperature dielectric probe. Overall, the 2 °C-step strategy was chosen for two reasons. Firstly, since humans are classified as homeotherms, they can maintain their body temperature within a limited range of ±2 °C even if there is a considerable change in the ambient temperature (the ideal body temperature is approximately 37 °C) (El-Radhi et al., 2018). Secondly, the effect of equipment error and measurement method on the final results can be eliminated.

To ensure the results achieved, the experiments were repeated by changing the volume of the artificial sweat in the temperature bath from 1 to 0.5 L. In this case, we obtained similar results to the previous ones. Thus, it can be stated that the HBSE amount added to the textile at fever temperature has a particular value, enabling us to detect the fever. The proposed antenna sensor has a resonant frequency shift of approximately 35 MHz for the variation in each degree of body temperature based on the measurement results obtained. The sensitivity of the wearable sensor is higher than that of other sensors reported in previous works (Labiano and Alomainy., 2020; Lin et al., 2015).

The previous sections investigate textile permittivity to its implementation by antenna structures. In the following, human body interactions with the antenna sensor, including the site of the wearable sensor on the body, the effects of body tissue on the sensor, and the Specific Absorption Rate (SAR), are examined. This investigation will help a lot in the actual use of the sensor (Fernandez et al., 2017).

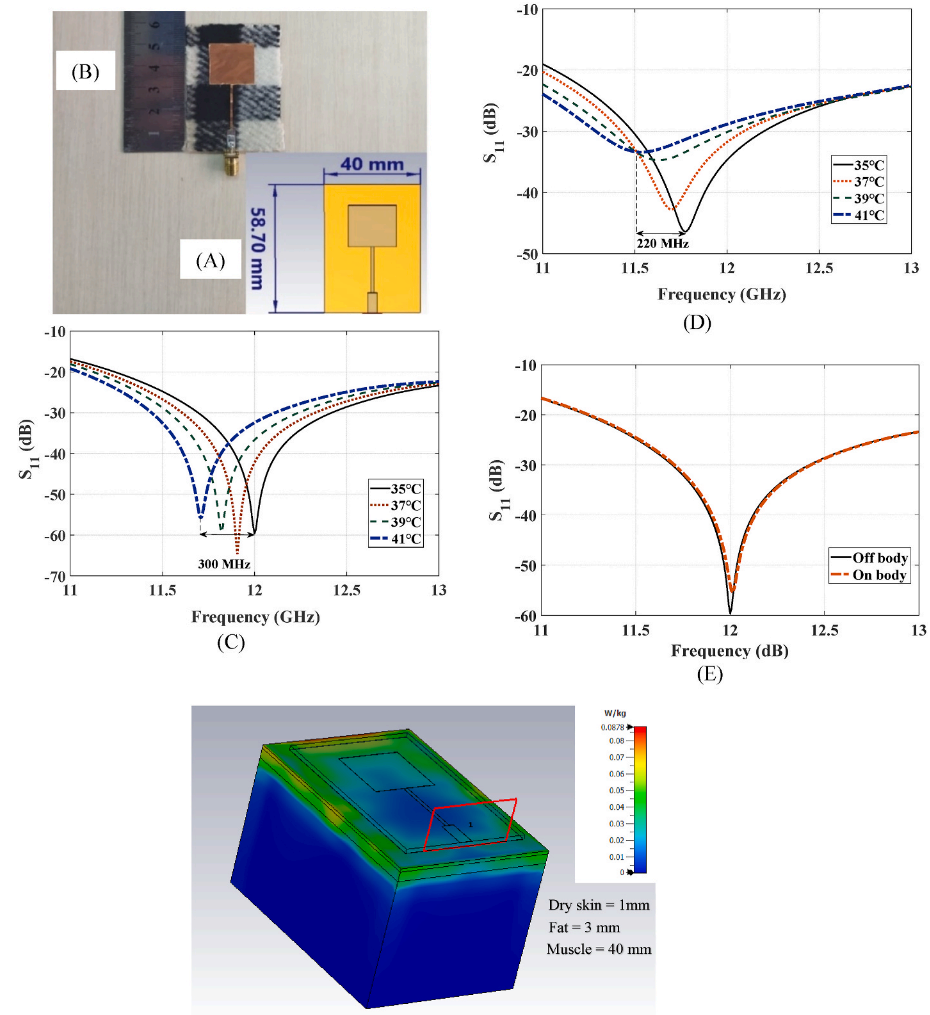

Fig. 2. The proposed rectangular microstrip patch antenna: (a) simulated structure, and (b) final prototype. (C) The simulated S_{11} for each 2 °C change in temperature. (D) The measured S_{11} for each 2 °C change in temperature. (E) The simulated S_{11} in the on-off body. (F) Simulated maximum SAR distributions in 1-g average tissue at 12 GHz.

3.2. Select site of sensor on body

From a medical-engineering view, choosing the right site to measure the actual body temperature is necessary. Measuring body temperature is highly dependent on the measurement site. Temperature sites of the human body close to the core temperature include the axilla, mouth (Sublingual), Rectal, and ear (El-Radhi et al., 2018). From a medical vision, these sites are suitable areas for thermometry. Every piece of the human body where thermometry is performed has many advantages and disadvantages. What an engineer thinks about providing a wearable thermometer includes:

- The thermometry must be non-invasive and should not enter the body.
- It is possible to measure the temperature by removing the observer (Zhou et al., 2020).
- Site after repeat thermometry does not cause damage and failure of the thermometer.

According to the items mentioned by Grodzinsky and Levander (2020), reaching a shared engineering-medical view can provide a wearable and suitable thermometer that includes:

- It can measure the core temperature and is non-invasive.
- It can be comfortable and does not cause discomfort to the patient.
- Does not cause infection at the measurement site.
- It has high repeatability and is cost-effective.
- Can be Constantly monitored temperature.

Based on the above, it can be concluded that the place that can be suitable for thermometry from a medical-engineering vision is the axilla. As a non-invasive site associated with core temperature, the axilla may be ideal for placing wearable sensors in the area. The thermometry in two sites is also proposed to reduce the thermometry error. In this regard, it can be said that this is possible by using textile wearable sensors. The axillary-axillary combination can measure temperature by simultaneously comparing data continuously. Installing a thermometer in both the right and left axilla can be an implementable issue.

3.3. Body effect on the antenna

The antenna reflection coefficient was surveyed in the on-off body. The obtained results are presented in Fig. 2 (E). Body phantom with a thickness of 44 mm was used to investigate the antenna performance (Ziskin et al., 2018). Frequency-dependent dielectric properties of tissues at 12 GHz are extracted from Institute for Applied Physics, Italian

National Research Council (Institute for Applied Physics, 2022) (see Table II). 1-mm air space was also considered between the antenna and the body phantom because there is usually a small gap between the body and the clothing for various reasons. As can be seen from Fig. 2 (E), the human body has a limited effect on antenna performance.

3.4. SAR

The SAR is calculated to ensure the health of the human body when using the proposed antenna. For this purpose, according to the data in Table II, a body phantom was defined. The power received by the antenna sensor is set to 0.5 W. The simulated SAR of the antenna sensor at 12 GHz is shown in Fig. 2 (F). It can be observed that the maximum SAR in 1-g average tissue is less than 0.0878 W/kg, meeting the IEEE C95.1–2005 standard of 1.6 W/kg (Guido and Kiourti., 2019).

4. Conclusion

In this paper, a REPOT measurement setup has been presented, while also designing an antenna sensor based on the measurement results in order to determine body temperature. The role of body sweat was also involved in the design of the proposed setup. The fabricated sensor was wearable and could be regarded as part of the person's clothes. The measurement results of the designed sensor indicated a frequency shift of about 60–80 MHz for each 2 °C change in temperature, being suitable for measuring fever.

CRediT authorship contribution statement

Sina Rahmani Charvadeh: Investigation, Conceptualization, Experiments, Design of measurement setup, Methodology, Software, Formal analysis, Implementation, Writing, Resources, Writing – original draft. **Javad Ghalibafan:** Experiments, review & editing, Formal analysis, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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