Reliability of a Re-usable Wireless Epidermal Temperature Sensor in Real Conditions

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***Abstract*—Body temperature is among most important biometric indicators that are normally checked in both domestic and hospital environments. The way to collect such parameter could be dramatically improved thanks to the Epidermal Electronics technology enabling plaster-like devices suitable to on-skin temperature sensing and capable of wireless communication with an electromagnetic reading module. The practical applicability of an eco-friendly battery-less epidermal thermometer, compatible with the UHF RFID standard, is here discussed by the help of experimentation with some volunteers. Comfortable reading procedures can be applied for both the operator and the patient. Experiments revealed a non negligible sensitivity of the temperature measurement versus the mutual distance between the reader and the sensor, that must be removed by a proper threshold filtering. Finally, the analysis of the sensor response for different placement position over the body, demonstrates that the axilla and chest loci provide only 0.6°C deviation from a reference tympanic measurement and are well accepted by the user which does not complain about the presence of the sensor.**

***Index Terms*—Radiofrequency Identification, Epidermal Electronics, Wearable temperature sensor.**

I. Introduction

Body temperature is one of the most effective vital signals and it is normally checked in both hospital and domestic environments. In clinical practice, the temperature is periodically (2-3 times a day) collected by nursing staff and manually registered on the the patients' medical chart. This procedure, beside increasing the nurse workload, reduces the likelihood of collecting blood cultures during the fever spikes, that is essential for the diagnosis and antibiotic treatment of severe infections (infectious diseases, sepsis and endocarditis).

By taking advantage of the relevant progress of wearable electronics technology, the potential application of wireless body-worn temperature monitoring devices is going to revolutionize the way such kind of vital information is collected and, above all, how it is stored and then processed. A plaster-like thermometer, permanently attached over the patient's skin, provided with an unique identification capability and a wireless interaction with a reader device could sensibly speed up the action of temperature measurement. Furthermore, it will enable a direct and transparent digitalization of the procedure as the collected temperature, and the corresponding time-stamp, are immediately stored into the electronic medical chart of the patient, thus greatly reducing the manual effort by the nursing staff.

The technology driver enabling this new procedure is the *Epidermal Electronics*, originally pioneered by the works of Rogers [1] and profitably extended in the last five years by several research centers worldwide. In particular, the authors have recently introduced [2] an epidermal thermometer, suitable to application over the skin, based on the Radiofrequency Identification (RFID). The electronic components and the antenna were deployed onto a thin bio-compatible substrate. The thermometer error was demonstrated to be less than 0.2 °C and the time constant was τ< 5 s. Moreover, the device is fully passive, i.e. no local energy source (battery) is required as the onboard electronics is driven by a power harvesting module taking energy from the interrogation device.

This work aims at boosting the usability of such an epidermal RFID thermometer [2] in real conditions, by turning such device into a useful and meaningful tool. At this purpose, the paper now investigates the clinical applicability of the epidermal temperature sensor concerning: *i*) the eco-compatibility, i.e. the possibility to reuse part of the sensor for multiple applications, thus reducing fabrication costs and pollution; *ii*) the stability of the measurement with respect to the data acquisition modality (e.g. the way the RFID reader is put close to the body for data retrieval); *iii*) the precision of the measurement with respect to a state of the art clinical thermometer like the auricular device; *iv*) the sensitivity of the temperature measurement with respect to the body part of placement.

II. Re-usable and sterile Epidermal RFID Thermometer

The RFID epidermal thermometer described in [2] was improved in order to account for low-cost biocompatible materials commonly used in clinical practice and the possibility to retrieve the sensor module at the end of the monitoring session for future reuse.

The sensor includes a meandered loop antenna connected to the EM4325 IC transponder with on-chip temperature sensing capability. The plaster thermometer was prototyped by attaching a flexible adhesive-backed copper foil on PET sheet (135 μm thickness, ε = 1.9, σ = 0.015 S/m at 870 MHz) and carving the meandered loop out of the Cu-Pet layered sheet through a digital plotter. The IC was then soldered onto the terminals of the matching shorter dipole. The loop was enclosed between two layers of a medical-grade adhesive dressings (Fixomull$^{®}$ stretch, 220 μm thickness) to comfortably attach the tag over the epidermis. An intermediate medical gauze was placed between the antenna (Whitetex Merilin®, 200 μm thickness) and the upper dressing to prevent the adhesion of the copper traces to the adhesive film.

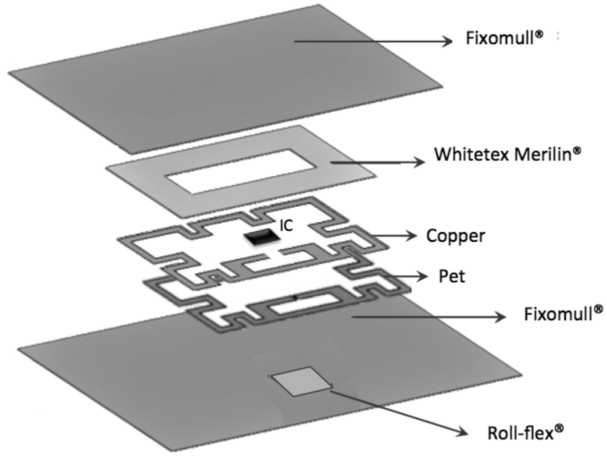


Figure 1. Sketch of the various layers of the reusable epidermal RFID thermometer.

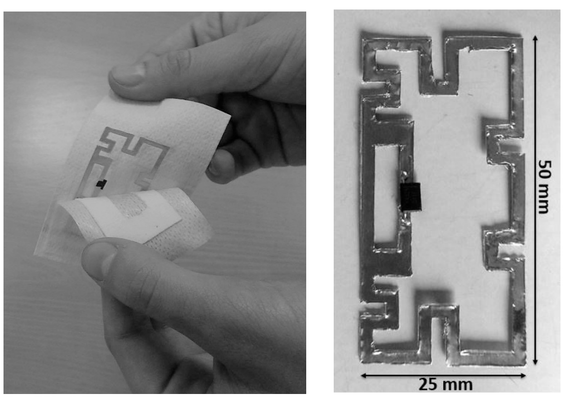


Figure 2. Sterile battery-less epidermal thermometer made of disposable dressings and a reusable inner transponder**.**

A hole was carved out of the dressing underneath the IC to ensure the direct contact between the temperature sensors and the skin, so that the thermal resistance of the substrate doesn't affect the local sampling of the temperature. The IC was then insulated by a small patch of ultra-thin biocompatible film (Rollflex film from Master-AID®, 22 μm thickness) for hygiene reasons. This layer has been proved not to delay the thermal time response of the tag [2]. The layered structure of the epidermal thermometer is schematized in Fig.1. The resulting modular device (size$50 \times 25 \times 0.8$ mm) features two detachable components (Fig.2): a reusable inner part that hosts electronics elements (the antenna, the IC and the optional battery) and disposable dressings that encapsulate the sensor and fix it to the skin surface.

The resulting temperature sensor was then thermally calibrated in controlled ambient conditions and the estimated calibration offset was written into the microchip memory for an autonomous use.

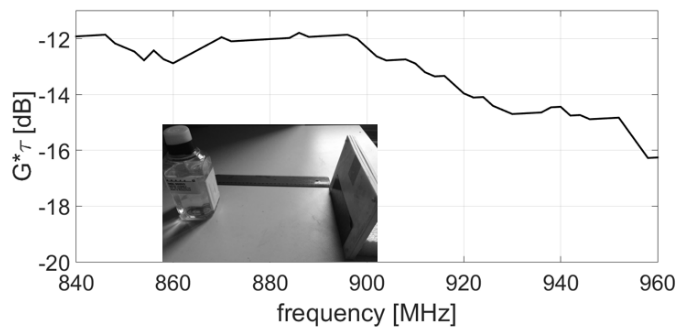


Figure 3. Measured realized gain of the passive epidermal thermometer placed over a liquid phantom..

A. Communication performance

The electromagnetic performance of the wireless thermometer in the UHF RFID frequency range (840-960 MHz) was characterized through the measurement of the realized gain [3], a performance parameter that is proportional to the second power of the maximum read distance, when the sensor was attached over a bottle-like reference liquid phantom whose electromagnetic parameters resemble the dielectric properties of the human tissues (MSL900V2 from Speag®, $\varepsilon_r = 55.1$, $\sigma = 0.015$ S/m). The measured response of the device (Fig.3) resulted quite broadband (3 dB bandwidth of 100 MHz) due to the high loss of the human tissues. The maximum value of realized gain was -12 dBi which corresponds to an estimated read distance up to 70cm in case of high-power (3.2 W EIRP) fixed measurement readers. These numbers are compatible with the unsupervised continuous temperature monitoring of bedridden patients through the reader's antenna being integrated within the bed. In the actual experimental campaign, instead, we decided to use a low power hand-held reader, described later on, that is the natural evolution of the current manual procedure for temperature measurement.

III. Sensitivity of the retrieved temperature on the reading procedure

The reliability of collected temperature data with variable reading conditions is here investigated. The considered reader was the handheld short-range CAENRFID qIDmini emitting just 150 mW power that is less than a mobile phone. The reader is battery-driven and is provided with a Bluetooth interface for communication with a PC, a tablet or even a smartphone. The reading procedure requires the operator to hold the reader and get close to the epidermal temperature sensor, as shown in Fig.4.

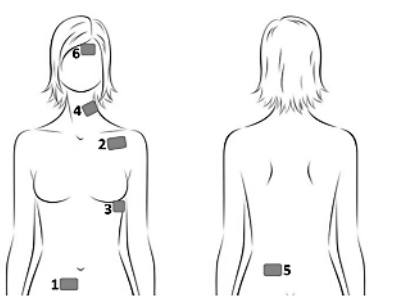
The communication performance of the epidermal thermometer was preliminary evaluated for different placements over the body surface. In humans, body temperature is not uniformly distributed and can be divided into the temperatures of the core (T_c) and shell (T_s). T_c refers to the temperatures of the abdominal, thoracic and cranial cavities, whereas T_s refers to the temperatures of the skin, subcutaneous tissue

Figure 4. Epidermal plaster on the human chest wirelessly read by an handheld reader.

and muscles. T_c is regulated by the brain, whereas T_s may be influenced more by skin blood flow and environmental conditions. We selected some central sites (see the picture in Table I) whose temperature profile is expected to correlate with the core one: abdomen (2-4 cm below the navel) [4]-[6], chest [2] (on the third intercostal below the middle of clavicle), near the axilla (in line with the chest) where the temperature is historically measured [7], on the neck (in correspondence of the carotid artery) [4], [5], on the lower back, and on the forehead (close to temporal artery) [8].

The measurements were performed on a female volunteer[1] (24 years, height 1.68 m, weight 56 kg), dressed in a shirt and a sweatshirt.

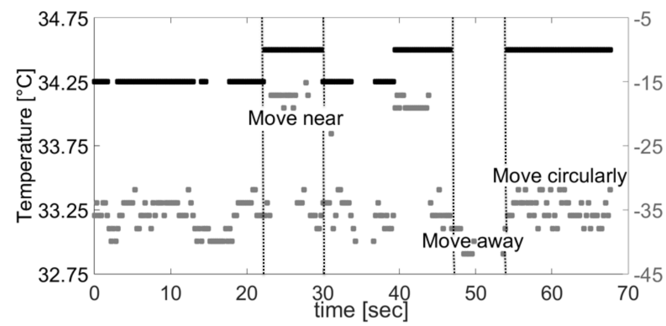
Table I
MAXIMUM READING DISTANCE OF THE EPIDERMAL THERMOMETER PLACED IN SEVERAL POSITIONS OVER THE BODY WHEN A LOW-POWER HAND-HELD READER WAS USED TO READ THE SENSORS.



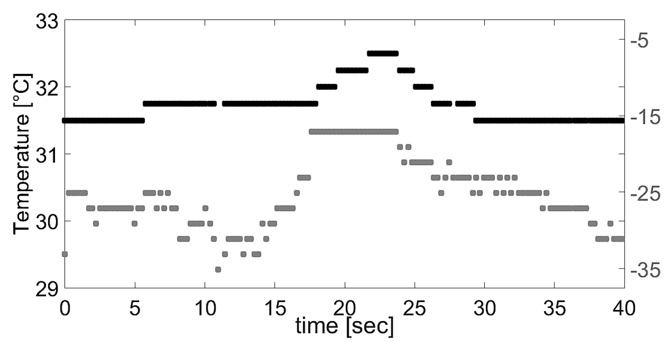
Body location	$\mathbf{d}_{max}$ [cm]
1	3-3.5
2	2.5-3
3	2.5-3
4	2-2.5
5	3.5-4
6	4-4.5

With reference to the Table I slight differences can be observed among the various body placements, as expected from the inhomogeneous composition of the underlying biological tissues. Nevertheless, in all the considered cases, a robust wireless link was established with the skin sensor without the need of contacting the patient. Accordingly, the medical personnel could execute non-invasive temperature checks without disturbing the patient, even during his resting time.

As it is expected that the nurse will randomly "scans" the patients, e.g. making the electromagnetic interrogation at different distance from the sensor, it is of fundamental interest to quantify the reliability of temperature sampling. Fig.5.a shows the temperature signals recorded from tag placed on the low back, when the reader was moved away from the tag, close to it and then circularly at a fixed distance. The same diagrams also display the *backscattered power* (P_{BS}), originated from the reflection by the tag of the interrogation power coming from the reader. This parameter is higher as the reader is closer to the sensor and hence provides an indirect indication of the reading modality.



(a)



(b)

Figure 5. (a) Temperature (black line) and backscattered (P_{BS}) signals (gray line) recorded during reader's random motion. Mean sampling time: 0.26±0.18 s. (b) Detail of temperature proximity artifact

A critical situation occurs when the reader is very close (<1 cm) to the tag, so that the temperature undergoes an anomalous increase up to more than 1 °C (see Fig.5.b). This effect is probably due to the higher strength of the electromagnetic power that impinges the sensor thus producing a secondary heating source (beside the metabolic one) through the strong induced currents over the sensor's antenna. To avoid interpreting such temperature variations as a false positive febrile state, this proximity outliers have to be removed. At this purpose a simple threshold filtering can be applied taking benefit of the measured backscattered power so that

[1]All the engaged volunteers were properly informed about the purpose of the study and signed an informed consent before the participation.

$$T(t) = \begin{cases} T(t) & if\, P_{BS}(t) \leq P_0 \\ null & otherwise \end{cases} \quad (1)$$

where $P_0 = -33$ dBm is a power threshold derived experimentally.

IV. Comparison with a benchmark tympanic thermometer

The epidermal thermometer data are finally compared with the measurements made by the actual golden standard of clinical practice, e.g. the tympanic thermometer. The considered model was the Braun ThermoScan®Pro 4000, having a resolution of 0.1 °C and a mean accuracy of ±0.2 °C within the temperature range of $36-39$ °C. The experimental session was performed in a room with a rather stable ambient temperature (24.8±0.5 °C) and involved a female volunteer (24 years old, 1.66 m height, 50 kg weight) sitting on a chair and wearing six RFID plasters positioned as in Table I. Fifteen temperature samples were thus collected by the hand-held reader for each body position at one-minute intervals. Auricular temperature was simultaneously measured at both ears and then manually stored. The variance computed over the temperature data recorded through the epidermal sensor were in the same order (hundredths of a degree) as the auricular values (II).

Table II
Variance of N.15 temperature measurements by the epidermal sensor and the ThermoScan tympanic thermometer.

Position of the sensor	variance (°C)
Abdomen	0.012
Chest	0.014
Axilla	0.032
Neck	0.010
Back	0.013
Forehead	0.001
ThermoScan (left)	0.015
ThermoScan (right)	0.011

The comparison between the epidermal thermometer data and the reference temperatures is shown in Fig.6. As expected, the difference is variable, in the range 0.6 °C<ΔT<2. °C, with the specific placement of the sensor over the body. The thorax and the axilla turned out to be the loci with skin temperature closest to the central one and for these cases a correction offset of 0.6 °C looks appropriate. These two sites are moreover well-accepted by the user who didn't complain about the sensors presence.

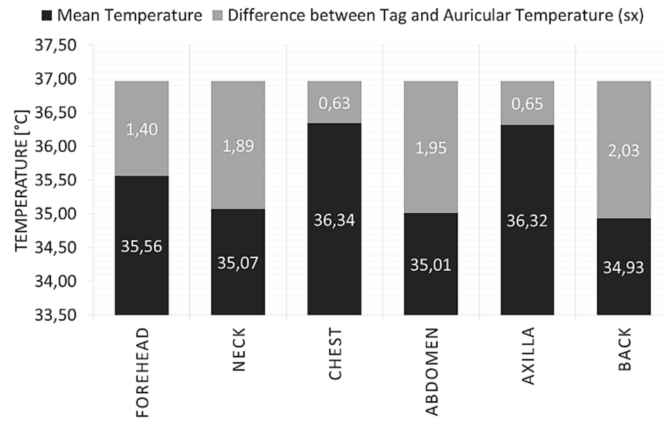


Figure 6. Mean skin temperature recorded by the epidermal thermometer over different body positions (Fig.I) and difference with respect to the tympanic temperature.

V. Conclusions

We have analyzed some of the issues determining the practical applicability of an epidermal thermometer based on the radiofrequency identification in real contexts. While the reading procedure is comfortable for both the operator and the patient side, and in particular looks much less invasive than the traditional tympanic measurement, the assessment of the collected data still requires some further detailed study. In particular, it is of prominent importance to clarify the sensitivity of the compensation offsets, for skin-to-core temperature translation, with respect to the patient variability and to the local conditions (temperature of the rooms, specific dressing).

Currently we are setting up a formal clinical trial upon the Tor Vergata University Hospital of Roma, in the Rheumatology Unit and then in the Infectious Diseases Unit, involving a large number of patients in dynamic febrile conditions. The trial is now ongoing and some preliminary results will be presented during the conference.

Acknowledgment

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