Non-Invasive Microwave Thermometry of Multilayer Human Tissues

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***Abstract*—In this paper, radiometry measurements of human tissue layer phantom temperature are presented. A skin-fat-muscle phantom allows independent heating/cooling of the lowest muscle layer. A narrowband probe is designed specifically for that tissue stack-up and a sensitive radiometer is used to measure total radiometric power in the 1.4-GHz quiet band. The knowledge of the volume power loss density from the probe, obtained from full-wave simulations, is used to determine the tissue weighting functions, which in turn allows for estimating black-body power radiated from a specific buried layer. Measured data using a Dicke radiometer shows that the radiometer tracks the internal tissue temperature.**

***Index Terms*—wearable sensors, radiometry, near-field radiator, thermometry, complex permittivity, black-body.**

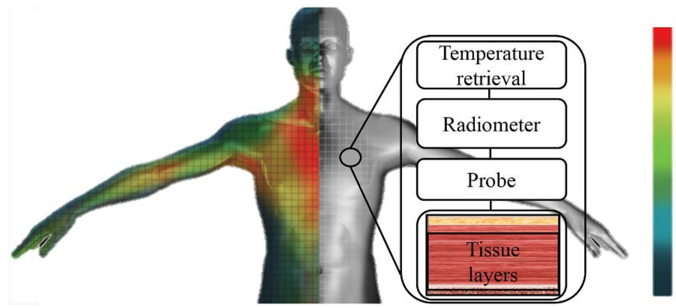

Fig. 1. Illustration of wearable internal (core) temperature measurement using a probe and radiometer positioned on the skin. The goal of the work in this paper is to demonstrate a calibratable microwave thermometer capable of tracking temperature at several centimeters of depth in the body.

TABLE I
DIELECTRIC PROPERTIES OF HUMAN TISSUES AND SOME TISSUE PHANTOMS AT 1.4 GHZ [11] AND [12]

Tissue	$\sigma(S/m)$	Permittivity	tan δ
Skin	1.035	39.661	0.335
Fat	0.064	5.395	0.154
Muscle	1.142	54.112	0.270
Salmon	1.510	52.500	0.370
Rogers 6010	0.002	10.200	0.0023
Saline (Salinity=9ppt)	1.570	78.000	0.260

I. INTRODUCTION

Tracking the core body temperature is important in a number of applications such as diagnostics in patients with sleep disorders, athletes during heavy exercise, soldiers under heavy training, and fire fighters and astronauts under challenging ambient conditions for preventing hyperthermia and heat stroke.

There are several ways to track internal body temperature currently, but most are invasive, such as rectal probes, or large and expensive, such as MRI. Heat flux thermometers are compact but have limited depth resolution [1]. An alternative passive method based on microwave radiometry was attempted by several groups [2], [3], [4], [5], [6], [7], [8]. In [2], a non-wearable broadband radiometer, susceptible to RF interference (RFI), was used to measure temperature in a controlled environment. In [3] a cavity-backed slot probe was used with 10% temperature accuracy. Systems reported in [4], [5] are large and not wearable.

The goal of the research presented here is to demonstrate a solution for a wearable calibrated microwave thermometer and probe, as illustrated in Figure 1. A probe placed on the skin feeding a radiometer is designed specifically for that tissue stack-up for measuring total radiometric power. The knowledge of the volume power loss density from the probe, obtained from full-wave simulations, is used to estimate black-body power radiated from a specific buried layer.

II. PRINCIPLE OF OPERATION

All objects at non-zero temperature radiate power across the entire electromagnetic spectrum dictated by the Planck's law [9]. In the microwave frequency region, the Planck distribution of the power spectral density is directly proportional to the temperature ($P = kTB$) where k is the Boltzmann constant. The black-body curve peaks in the infrared region for the human body ($T = 310\,\mathrm{K}$), but the penetration depth of human tissue (e.g. breast) at IR is at most 2 mm [10]. At lower microwave frequencies, e.g. 1 GHz, the penetration depth of a plane wave incident on the skin is 3.2 cm, but the power radiated by the tissues is much lower than at IR, requiring a highly sensitive receiver.

The diagram of the experimental setup for estimating temperature of a buried tissue layer is shown in Figure 2(a). A near-field antenna probe at a physical temperature T_p is placed on the skin surface on top of a layer of skin at physical temperature T_1, a layer of fat at temperature T_2, and a layer of muscle at T_3, with properties listed in Table I. The Dicke radiometer measures the total radiometric power. The weighting functions of each layer (W_1, W_2, W_3) depend on frequency, physical temperature, layer thickness and complex permittivity and near-field probe spatial field pattern.

The absorbed power in each layer is, by reciprocity, equivalent to radiated power from that layer. Therefore, a calculation of the absorbed power at every point in the body can be used to predict the radiated power from the same point. Since the absorbed power decreases with depth, by reciprocity, deeper tissues will radiate less power. This in turn has implications on optimal probe design, as detailed in the next section.

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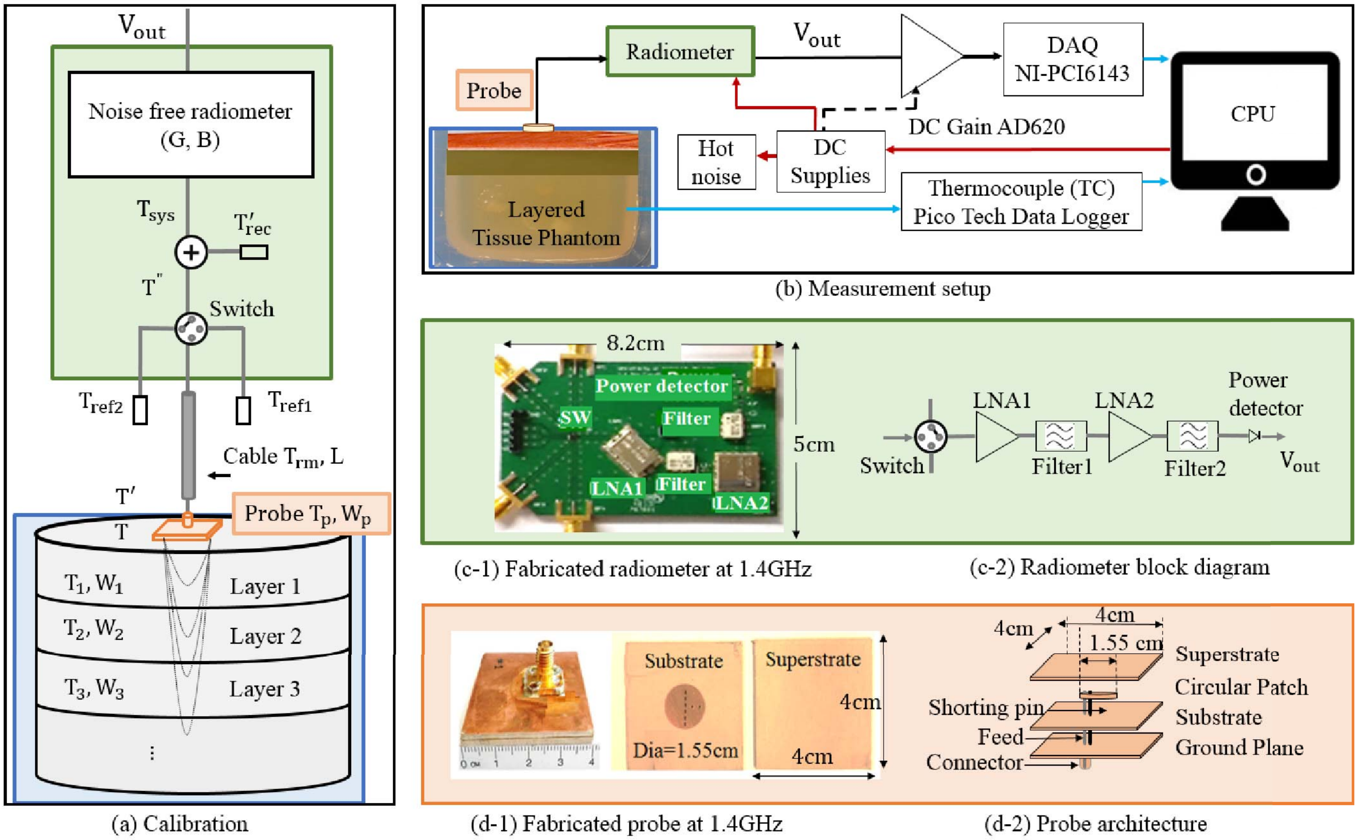

Fig. 2. (a) Diagram of experimental setup for estimating temperature of a buried tissue layer. A near-field antenna probe at a physical temperature T_p is placed on the skin surface on top of various tissue layers (1,2,3,...) at physical temperatures $T_1, T_2, T_3, \ldots$. The Dicke radiometer measures the total radiometric power. The weighting functions of each layer ($W_1, W_2, W_3 \ldots$) are used in the estimation of each layer temperature. (b) Measurement and data collection setup diagram. (c) Radiometer architecture. (d) Probe details.

III. Probe and Simulation

The frequency chosen for the probe and radiometer is the 1.4–1.427 GHz quiet band allocated to radio astronomy in order to minimize received power that is not radiated by the tissues. The design of the probe includes a ground plane which has two functions: to help with shielding from RFI and to provide an RF ground for both the probe and radiometer. A circular patch probe is designed specifically for a tissue stack of skin, fat and muscle [13]. The first two layers are 2 mm and 5 mm thick, respectively, while the muscle layer is assumed to be much thicker than the penetration depth at 1.4 GHz. Figure 2(d) shows a photograph of the probe which includes a high-permittivity ($\epsilon_r = 10$, Rogers 6010, 1.27 mm) superstrate for better matching to the tissues. The probe is fabricated on a 1.27 mm substrate and coaxially fed. A shorting pin is used as loading to reduce the overall size to a diameter of 1.55 cm. The size of the ground plane and superstrate is 4 cm×4 cm.

The measured return loss of the probe, calibrated to the SMA feed connector, is shown in Figure 3 for two cases: when placed on a human cheek and when placed on a phantom stack, consisting of a 2-mm layer of smoked salmon (skin) on top of a 5-mm thick Rogers 6010 substrate (fat) and a thin bag of saline solution (muscle). The match is better than 15 dB at the design frequency with good signal rejection in the crowded cellular bands in the 1.8-2.14 GHz and the 2.4 GHz ISM band.

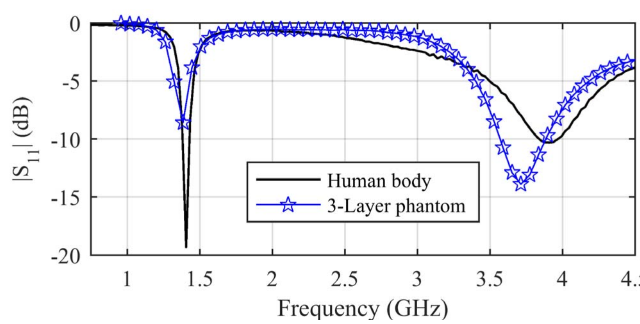

Fig. 3. Probe matching to human body (cheek) and a three-layer phantom consisting of salmon, Rogers 6010 and saline.

Human tissue layers have high dielectric contrast and typically the probe absorb most of the power from the skin layer. In order to receive power from a lower (buried) tissue layer, during the design process, volume density of losses was simulated at all points in the tissue stack to maximize the absorbed power density in the buried muscle layer. Absorbed and received power densities are reciprocal. Figure 4 shows the

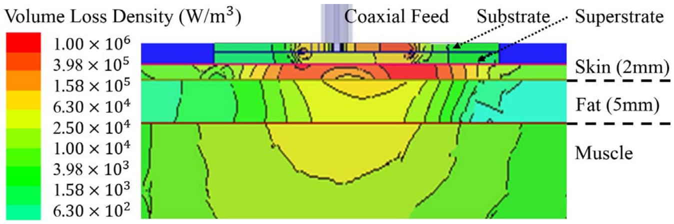

Fig. 4. Volume loss density pattern of the probe placed on the stack of skin (2 mm), fat (5 mm), and muscle.

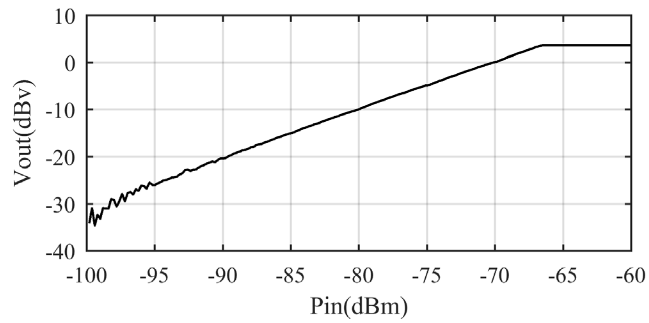

Fig. 5. Power response of the radiometer from Fig.2(b) measured at 1.4 GHz.

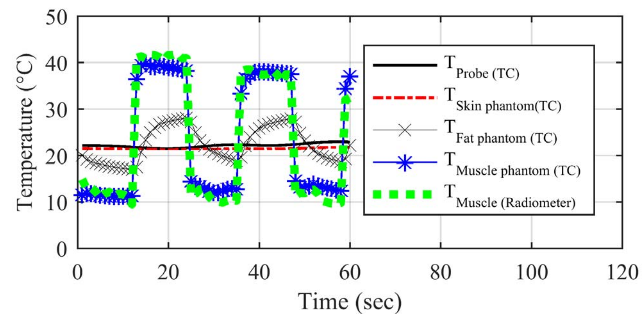

Fig. 6. Calibrated sub-layer temperature estimation of skin-fat-muscle stack compared to thermocouple (TC) measurements of the different layers.

simulation for the circular patch probe for 1 W of input power at 1.4 GHz, where it can be seen that a large fraction of the power is absorbed in the fat layer, although it has the lowest loss. This is due to the large mis-match in the real part of the permittivity between fat and the neighboring skin and muscle (refer to Table I). The high real part of the relative permittivity of the top layer (skin) results in probe size reduction.

IV. Measurement Results

A compact version of the Dicke radiometer presented in [14], is implemented from off-the-shelf components, as shown in Figure 2(c) [8]. The calculated black-body power at the input of the probe at the normal body temperature of 310 K is about -100 dBm. Taking into account the measured responsivity of the diode detector, a gain of at least 45 dB is required. The measured response of the radiometer at 1.4 GHz is shown in Figure 5, and the measured noise figure is 1.58 dB at 1.4 GHz. The output voltage is linearly related to temperature, so calibration can be done with the two known noise temperatures, e.g., Agilent 346A hot noise source and 50 Ω cold noise source.

Measurements are performed with a well-controlled phantom as shown in Figure 2(b), where the lowest layer is muscle, simulated with a bag of saline which could be heated and cooled. The temperature is independently monitored with a thermocouple. The output of the detector is sampled by a National Instruments data acquisition board (NI-PCI6143).

Once the raw data is measured by the radiometer, a model is needed for the tissue stack-up to estimate the temperature. This can be done using weighting functions obtained from full-wave near-field electromagnetic simulations. The total measured temperature T', related to the measured power as $P = kT'B$, is obtained from the following expression:

$$T' = \sum_{i=1}^{\infty} W_i(f) T_i$$

where W_i is the weighting function and T_i the unknown temperature of the i-th layer. Each weighting function defines the contribution from a layer of tissue to the overall probe radiometric temperature. The weighting function of each layer is a function of frequency, tissue electrical properties $(epsilon_r, \sigma)$ and layer temperature, as well as the loaded probe near field profile. The W_i values are found by calculating the power absorption rate, which is the dissipated power in a certain layer, normalized to the total dissipated power in all layers [6] and [2]. These weighting functions can be obtained by full-wave electromagnetic simulations, e.g. using finite-element methods, such as Ansys HFSS, or finite-difference time-domain methods, such as Zurich Med Tech Sim4Life [15]. For the results in this paper, HFSS was used to calculate the skin, fat and muscle weighting function at 1.4 GHz. For 2 mm thick layer of salmon (skin), 1.58 mm layer of Duriod (fat), and thick layer of saline (muscle), with properties given in Table I.

Figure 6 shows the buried layer temperature detection as a hot saline bag is replaced by a cold one periodically. The probe, salmon (skin), substrate (fat) and saline (muscle) temperatures are measured by 4 thermocouples while the calibrated estimated radiometric measurement is shown in green dots. As a second example (Figure 7), the raw uncalibrated data from a measurement on a human cheek are shown together with thermocouple measurements inside the mouth, for different temperatures of water. Both examples show that while there is also thermal conduction through the layers, the radiometer instantaneously track the internal temperature.

V. Acknowledgments

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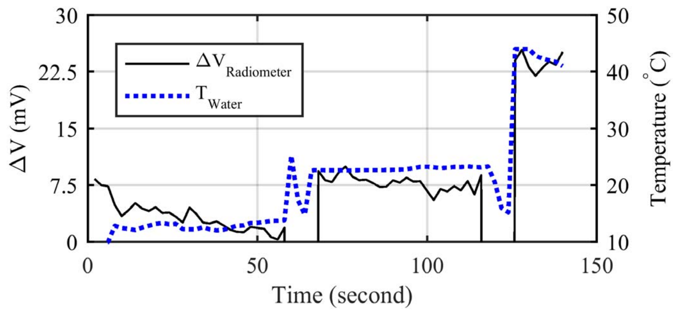

Fig. 7. Uncalibrated measurement of voltage at the radiometer output as a function of time when cold, room-temperature, and warm water are hold in the mouth with the radiometer probe placed on the cheek.

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