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Electrical Impedance Spectroscopy at mmWave for Bio-Sensing

Ashley Cox and Satheesh Bojja Venkatakrishnan
Florida International University, Miami, FL - 33174
(acox031@fiu.edu, sbojjave@fiu.edu)

***Abstract*— Chronic skin wounds resulting from burns, diabetes, ulcers, and other medical conditions can overwhelm the skin's regenerative capabilities, leading to persistent infections and even amputations in severe cases. Over 10 million patients with chronic wounds are treated yearly in the United States, with an estimated cost of more than US $ 40 billion in annual spending for treatment. Even with the latest advancements in IoT-based connected health, smart bandages can only aid in drug release to prevent infections. However, a smart bandage that can non-intrusively diagnose or monitor the burn wound's state does not exist. To address this shortcoming, in this work, we present a non-intrusive, affordable, real-time wound assessment device, that employs mmWave patch sensor for burn wound prognosis through electrical impedance spectroscopy.**

I. Introduction

Recent developments in wearable and flexible electronics along with the growth of the internet of things (IoT) networking, have created new frontiers in smart and connected healthcare [1-2]. The increasing cost of healthcare services has created a growing demand to monitor a patient's health in their personal environment instead of a clinical setting using IoT-based smart bandages that provide real-time monitoring and continuous assessment of wounds. Despite these advancements, chronic wound monitoring is one area of human health that has received relatively less attention from the research community. Accurate diagnosis of chronic skin wounds, particularly in the early stage, can provide efficient and targeted treatment, ultimately reducing patient suffering.

Currently, diagnosis is primarily performed based on a physician's visual assessment of the skin wound. Specifically, for burn wound diagnosis, clinical visual observation accuracy can be 64-76% for experienced surgeons and as low as ~50% for inexperienced surgeons. The complex pathophysiology of burn wounds necessitates the development of accurate wound assessment techniques and proper care. In addition to wound diagnosis, information regarding oxygenation, cytokines, inflammation, and other healing data is crucial to modify drug release and discern healing phases. Although smart bandages are programmed to aid in moisture control and release drugs to prevent infections, they fail to provide information about wound state. Consequently, there is a strong need to develop a non-intrusive and affordable chronic wound monitoring sensor(s) that can be readily integrated with existing smart bandages to provide real-time information of the wound state.

Accurate diagnosis and prognosis of a skin wound treatment commonly require measuring the wound area, maximal wound depth, wound exudate's chemical composition, and type of tissue affected. Previous approaches employ a single sensor that targets a single biomarker and lacks wireless telemetry, which is critical for remote assessment of the wound [3-4]. A popular approach for wound monitoring is through electrical impedance spectroscopy (EIS). EIS enables the measurement of the skin impedance, thereby enabling the accurate estimation of wound depth and lateral extents, all without removing the dressing, thus not disturbing the wound healing process [5]. Notably, the presented technique leverages the variation in the water content between the burnt skin and healthy skin at mmWave to estimate the severity of the burn wound. This work brings forth an innovative millimeter wave (mmWave) sensor capable of accurate wound diagnosis as well as prognosis.

II. Electrical Impedance Spectroscopy (EIS)

Electrical impedance spectroscopy involves the characterization and analysis of electrical properties of tissue over a range of frequencies to map wounds. Notably, high-frequency complex dielectric constant of materials is represented by its real (i.e., permittivity (ε')) and imaginary parts (i.e., loss factor (ε")) indicating the ability of the material to store and absorb electromagnetic energy, respectively. The effective dielectric constant of materials, made of a mixture of several different constituents can be closely estimated using effective medium theory [8], given by (1), where ρ corresponds to the fill fraction of water, and ε_1 and ε_2 is the permittivity of the healthy skin (predominantly water) and dry/burnt skin (predominantly biological matter), respectively. Hence, changes in the fill fraction ρ can significantly impact the skin's overall permittivity, thereby changing its impedance.

$$\varepsilon_{eff} = \varepsilon_2 \frac{2\rho(\varepsilon_1 - \varepsilon_2) + \varepsilon_1 + 2\varepsilon_2}{2\varepsilon_2 + \varepsilon_1 - \rho(\varepsilon_1 - \varepsilon_2)} \quad (1)$$

$$Z = Z_0 \frac{1 + S_{11}}{1 - S_{11}} \text{ and } Z = \sqrt{\frac{\mu_0}{\varepsilon_{eff}\varepsilon_0}} \quad (2)$$

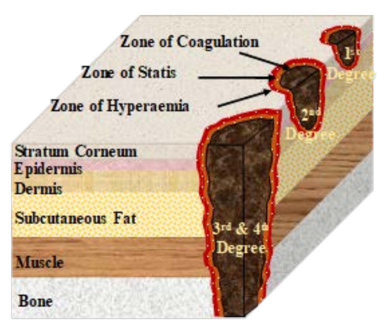

Figure 1. Effect of different burn wounds on human skin [6-7]

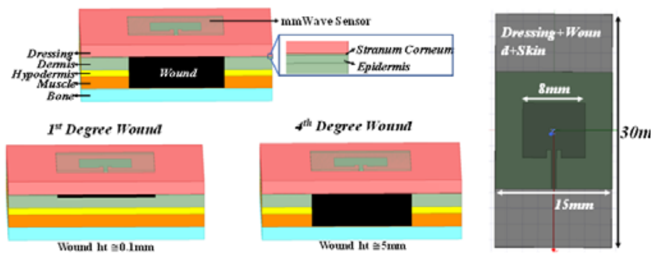

Figure 2. Simulation model for wound prognosis. (left) EM simulation setup of the sensor & modeling of different wound degrees in simulation, (right) Dimensions of the mmWave sensor

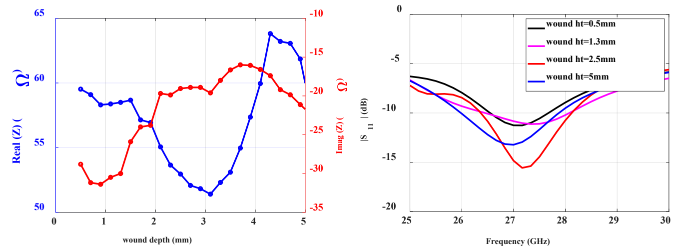

Figure 3. (Left) Variation of input resistance and reactance as the wound heals at 27 GHz, (Right) Input reflection coefficient (S11) as a function of frequency as the depth of wound reduce.

In this work, we leverage the variation of skin impedance as the wound depth varies. The schematic structure of human skin, consisting of epidermis, dermis, and subcutaneous tissue composed of fat (also referred to as hypodermis), is shown in Fig. 1 [6-7]. The electrical properties of each of these layers are given in Table 1. Based on Jackson's burn model shown in Fig. 1, the burn wound is divided into three zones: zone of coagulation, zone of stasis, and hyperemia [6]. The coagulation zone is the part in contact or close to the thermal source. The tissue in this part is dead and irreversibly injured. Usually, the burn degree is determined by the depth of the coagulation zone [6-7].

Depending on the severity of the burn wound, the skin impedance influences the patch antenna loading. Based on the impedance variation (also represented as S_{11}), the impedance profile can be computed, from which the effective complex dielectric permittivity of the burn wound can be computed, based on (1) & (2). The estimated value is then compared against the pre-calibrated datasheet to arrive at the burn wound's invasion depth.

We provide preliminary simulation results to validate our concept. A multi-layer skin model was set up in a full-wave electromagnetic simulator, as shown in Fig. 1. Each layer is modeled using typical thickness, permittivity, and loss tangent values, as shown in Table 1. The wound's healing is modeled as a reduction in the depth of the wound (as illustrated in Fig. 2.) which ultimately changes the input port's impedance.

The variation of the real and imaginary parts of the impedance as a function of wound depth at 27 GHz is shown in Fig. 3 (left). It is evident that the sensor can detect a resolution of ~0.1mm. Tracking the trajectory of the resistance and reactance aids in the prognosis of the wound. Further, to increase reliability, different frequencies within 25-30 GHz can be leveraged depending on an individual's body composition. Fig. 3 (right) shows the variation in reflection loss (S_{11}) for different invasion depths (various degrees of burn) and different operating frequencies. The results confirm that the dielectric properties of the burn wound differ significantly from the intact cover tissue.

TABLE 1: ELECTRICAL PROPERTIES OF DIFFERENT LAYERS OF SKIN [9]

Layer	Thickness	Relative Permittivity	Loss Tangent
Dressing	2mm	4	0
Stratum Corneum	0.02mm	4	0
Viable Epidermis	0.08mm	11.5	0.63
Dermis	2mm	11.5	0.63
Hypodermis	1mm	6	0.5
Muscle	2mm	24.40	0.83
Bone	2mm	7.51	0.7
Wound	Variable	2.5	0

III. Conclusion

Accurate diagnosis of chronic skin wounds, particularly in the early stage, can provide efficient and targeted treatment, ultimately reducing patient suffering. A smart bandage that can non-intrusively diagnose or monitor the burn wound's state does not exist. To overcome the obstacles associated with existing burn wound profiling, we present mmWave based electrical impedance spectroscopy to accurately estimate the profile of the burn wound. At the conference, we will present the fabricated and measured data of our mmWave patch sensor.

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