19th IMEKO TC10 Conference
“MACRO meets NANO in Measurement for Diagnostics, Optimization and Control”
Delft, The Netherlands, September 21–22, 2023

Skin monitoring and diagnostics: towards a wearable low-cost system

Raissa Schiavoni [(1)], Antonio Masciullo [(1)], Andrea Cataldo [(1)]

[1]*Universiy of Salento - Department of Engineering for Innovation, 73100 Lecce, Italy, raissa.schiavoni@unisalento.it*

***Abstract* – Wearable technology in healthcare refers to medical devices for real-time monitoring of a wide variety of biomedical parameters of the human body. The Health 4.0 scenario has led to the rapid development of these systems in all fields of medicine. However, a wearable non-invasive device for skin health monitoring for skin hydration control or cancer prevention is still an open challenge. In this regard, this paper addresses the design and the implementation of a low-cost portable system for skin diagnostics purposes which is based-on microwave reflectometry technique. For this purpose, a specific sensing element (SE), connected to a miniaturized vector network analyzer (m-VNA) has been designed and assessed for the optimal detection of the variation of the dielectric properties of the skin. The proposed system has been validated, first, through full wave simulations, then, directly on human skin, demonstrating a good potential for achieving a fully wearable system for skin monitoring and diagnostics.**

***Keywords* – skin diagnostics; skin hydration; skin cancer; microwave reflectometry; dielectric permittivity; open-ended coaxial probe**

I. INTRODUCTION

The development and the advancement of wearable monitoring technologies have delivered a wealth of results in the health sector [1,2], allowing the real-time monitoring of many physiological parameters [3-5] in a non-invasive or minimally invasive manner. Numerous recent efforts have led to an increased efficiency of sensing capability and measurement accuracy of wearable sensors [6]. However, there are still many challenges in the skin monitoring field [7], which is of great importance since the skin behaves like a barrier [8] between the organism and the outside, defending the human body from the intrusion of bacteria and pathogens and retaining the nutrients and water. For these reasons, it is necessary to preserve and monitoring the health of the skin, that can often incur the development of various diseases, which can be either dermatological or cancerous. In this regard, the skin hydration level control and the monitoring of suspicious lesions over time are crucial. As a matter of fact, most of dermatological diseases (such as atopic dermatitis, ichthyosis, psoriasis and eczema) [9-12] cause dehydration of the skin, a dangerous and sometimes painful condition. In addition, a severe dehydration can go beyond the skin and cause symptoms such as vertigo, disorientation and metabolic disorders [13]. On the other hand, some individuals, such as workers exposed to ultraviolet rays [14], harmful chemicals, or having a genetic predisposition [15], are at major risk to develop a skin cancer. In this case it is useful to provide prevention by conducting a quick check on any skin abnormalities that might appear on the skin. In this context, it is worth remembering that, at present, the diagnosis of cancer is typically made by the dermatologist simply through a visual examination of the skin, making the evaluation highly dependent on the experience of the doctor. However, a definite diagnosis can be carried out only after a biopsy, which is an invasive procedure.

For all these reasons, in many situations, a portable and wearable device capable to monitor in real-time the skin hydration status or to perform periodic checks for prevention purposes becomes fundamental. In addition, the possibility to generate an alert and to tele-transmit the data to the doctor can be useful. However, most of the state-of-the-art skin monitoring systems are not wearable and are unsuitable for real-time use. Other kinds of technology are very expensive (e.g., Confocal Raman [16], Near-IR [17] or Terahertz Spectroscopy [18]) while other methods based on bioimpedance or capacitance measurements [19, 20] are characterized by low measurement accuracy. On such basis, the aim of this work is the development of a low-cost, wearable skin monitoring system suitable for skin hydration monitoring but also for future applications in skin cancer prevention. Previous works demonstrated the feasibility of microwave-based systems for these applicative scenarios [21,22]. In fact, both scenarios involve a sudden change in the dielectric properties of the skin depending on the ongoing chemical-physical process. This phenomenon can be detected through the microwave reflectometry, a technique that exploits the interaction between an electromagnetic (EM) field and the tissue under test. For this reason, a thorough design of the sensing element (SE) to be in contact with the skin has been carried out. This allowed the optimization of the related sensitivity for discriminating the dielectric variations of skin tissues even in areas of a few millimeters.

The present work is organized as follows. Section II describes the basic theoretical background behind the proposed system and the used experimental setup. Section III addresses the design of the SE and numerical analysis. Section IV describes the experimental tests performed directly on human skin. Finally, conclusions and future work are outlined in Section V.

II. MATERIALS AND METHODS

Microwave reflectometry (MR) is a powerful tool for several monitoring and diagnostic applications [23-26]. The basic concept is to propagate an EM test signal and to analyze the reflected one [27-31] which contains useful information on the chemical and physical composition of the tissue. In fact, the reflected signal is strictly correlated to the frequency-dependent complex dielectric permittivity $\varepsilon^*(f)$ [32].

$$\varepsilon^*(f) = \varepsilon'(f) + \varepsilon''(f) \quad (1)$$

where $\varepsilon'(f)$ and $\varepsilon''(f)$ are the real and the imaginary part of the complex permittivity, respectively. To do this, it is enough to measure the reflection scattering parameter $S_{11}(f)$ at the SE when it is placed in contact with the skin. The $S_{11}(f)$, which depends on the dielectric properties, can be measured through vector network analyzers (VNAs). These instruments are generally bulky and expensive. In order to overcome this issue and for the purpose of the present application, it is adopted a low-cost, compact and portable VNA. In particular, in this work, a nano VNA developed by HCXQS and operating in the frequency range [50 kHz – 3 GHz] has been adopted.

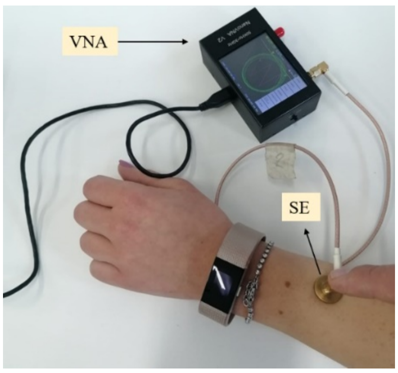

Fig. 1. Picture of the reflectometry-based measuring system: the VNA and the designed coaxial SE.

For the sake of a performance assessment, comparative measurements were carried out between this miniaturized VNA and a very accurate and expensive VNA thus confirming a good measurement accuracy ensuring a deviation in the order of 2%. The instrument is currently controlled by USB port for PC interfacing but, it can be easily adapted for a remote control and data tele-transmission. This option, together with the small size of the PCB of the electronic equipment, will make the setup fully wearable in the near future. As for the designed SE, in order to guarantee a non-invasiveness for the in-vivo measurements and sensitivity in the skin layer only, a specific open-ended coaxial probe has been chosen and customized.

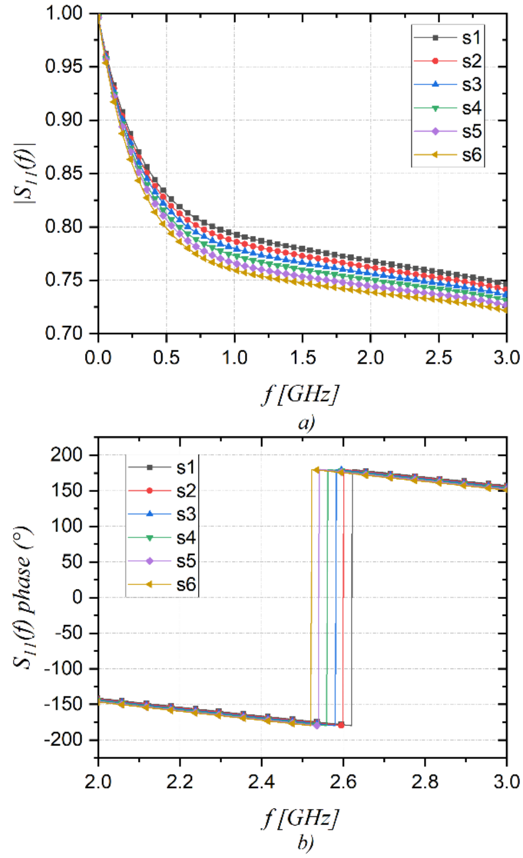

Fig. 2. Simulation results for the $S_{11}(f)$ of the SE for 6 skin different states (different dielectric permittivity). The s1 curve corresponds to the dry condition, while from s2 to s6 the dielectric properties increase of the 2% each time. Magnitude (a) and phase (b).

III. DESIGN OF THE SENSING ELEMENT AND NUMERICAL ANALYSIS

In previous work [21] the proposed SE was a planar three-wire transmission line characterized by comfort and high measurement accuracy but not suitable for monitoring small areas. For this reason, in this work, an enhanced version of the system is presented. As explained above, the general configuration of open-ended coaxial probe has been customized in order to ensure simultaneously non-invasiveness, portability, penetration depth only in the skin layer and capability of discriminating the dielectric properties of the tissue.

To this purpose, full wave simulations have been carried out through the CST Microwave Studio® software modeling the SE in contact with a three-layer structure composed by skin, fat and muscle. The dielectric parameters of the different tissues are reported in Gabriel & Gabriel's database [33]. It is worth noting that coaxial probe measurements are possible because of the fringing fields between outer and inner conductors of the SE placed on the tissue. More in detail, the fringing fields interact with tissues, causing changes in the scattering parameter measured by the VNA. In order to improve the sensitivity in terms of the fringing field effect and to make the discrimination of the dielectric properties more sensible to the corresponding variation of the $S_{11}(f)$, a flange around the coaxial probe has been added in the design phase. Subsequently, a specific fine tuning of the parameters of interest, such as inner and outer diameter of the SE, size of flange and input power level, has been carried out in order to identify the optimal configuration of the SE.

Finally, a set of full wave simulations has been carried out varying the dielectric permittivity of the skin layer. More in detail, starting from the dry skin condition (s1), the subsequent simulation data conditions (corresponding to s2, s3…, s6) have been obtained by an incremental increasing of 2% in the dielectric permittivity values of the skin. Figure 2 shows the corresponding variations in terms of the response of the reflection coefficient S_{11} in magnitude and phase, respectively. In this way, the ability of the designed SE to discriminate small dielectric properties variations of the skin has been assessed.

IV. EXPERIMENTAL RESULTS

After the design phase and the sensitivity analysis, the SE was realized and tested in-vivo on human skin, in particular on the forearm of a volunteer subject. Measurements were performed considering three different conditions, so as to cover a different variety of dielectric properties, such as more or less hydrated skin. More in detail, the first measurement was performed in the dry skin condition. Then, a moisturizing lotion was applied on the skin to increase the dielectric permittivity, which can be directly associated to the hydration condition and, consequently, a second measurement was performed. The third measurement was performed in conditions of wet skin, through the application of a water-impregnated swab. The results corresponding to these three real situations, are summarized in Figure 3, showing the good capability of the system in terms of dielectric discrimination among dielectric properties associated to different skin conditions. In fact, as is well known, as the hydration level increases, the dielectric permittivity increases due to the very high value of water's relative dielectric permittivity (≈80), and this corresponds to a decrease in the magnitude of the reflection coefficient $S_{11}(f)$.

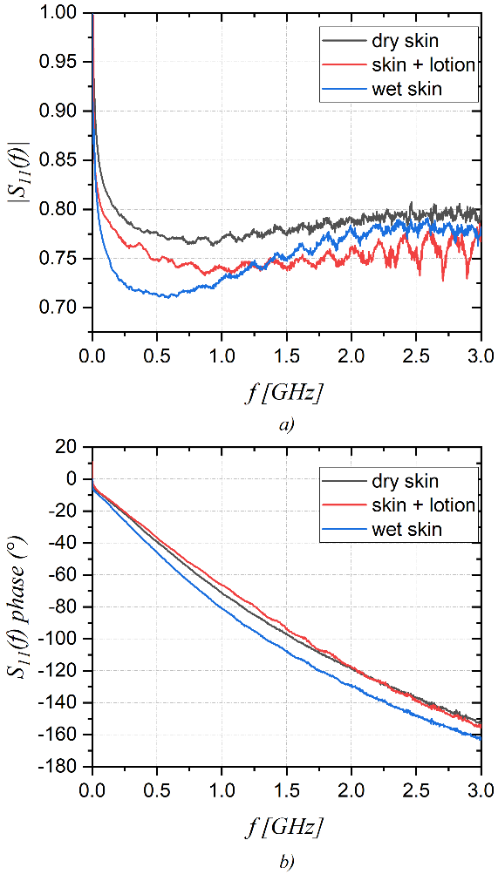

Fig. 3. Comparison of measurement results for the $S_{11}(f)$ of the SE for the three tested conditions: dry skin, skin with moisture lotion and wet skin: magnitude (a) and phase (b).

This phenomenon is evident both in the case of wet skin and skin with a moisture lotion. Furthermore, for the sake of assessing the capability in discriminating potential skin abnormalities, such as skin tumors, ulterior tests will be executed on patients with skin lesions through the supervision of the medical personnel. As a matter of fact, skin tumors have significant differences compared with healthy tissue, and this results in a dielectric contrast between normal and cancerous skin tissues at microwave frequencies [34, 35]. This aspect suggests the potential of the system also for skin cancer early diagnostics.

V. CONCLUSIONS AND OUTLOOK

In this paper, the design, realization and implementation of a portable low-cost skin hydration sensing system based-on microwave reflectometry has been presented. First, a numerical analysis was performed in order to identify the optimal configuration of the SE which is characterized by non-invasiveness, high sensitivity in detecting dielectric variations of the superficial skin area and applicability for both cancer prevention and skin hydration monitoring. Subsequently, experimental tests were carried out in-vivo directly on human skin, through a low-cost portable VNA, analyzing different skin conditions associated to different dielectric properties. Results show the possibility of implementing a fully wearable system for skin hydration monitoring purposes. Starting from these results and given the amount of potential of the proposed method, further activities will be focused on the possibility of extending the use of the system also for skin cancer detection. In addition, efforts will be dedicated also to the full wearability of the device, to the implementation of data tele-transmission and to the fully assessment of the method on a large-scale campaign on voluntary subjects.

REFERENCES

[1] **Tortorella, G. L.; Fogliatto, F. S.; Vergara, A. M. C.; Vassolo, r.; Sawhney, R.**: Healthcare 4.0: trends, challenges and research directions, *Production Planning & Control*, 31:15, 2020, 1245-1260

[2] **Arpaia, P.; De Benedetto, E.; Duraccio, L.**: Design, implementation, and metrological characterization of a wearable, integrated AR-BCI hands-free system for health 4.0 monitoring, *Measurement*, 2021, 177, 109280.

[3] **Starliper, F. Mohammadzadeh, T. Songkakul, M. Hernandez, A. Bozkurt, E. Lobaton**: Activity-aware wearable system for power-efficient prediction of physiological responses, *Sensors*, 2019, 19, 441.

[4] **Corchia, L.; Monti, G.; De Benedetto, E.; Cataldo, A.; Angrisani, L.; Arpaia, P.; Tarricone, L**: Fully-textile, wearable chipless tags for identification and tracking applications. *Sensors*, 2020, 20, 429.

[5] **Wang, T.W.; Chen, W. X.; Chu, H. W.; Lin, S.F.:** Single-channel bioimpedance measurement for wearable continuous blood pressure monitoring, *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–9.

[6] **Seneviratne, S. Hu, Y.; Nguyen, T.; Lan, G.**: A Survey of Wearable Devices and Challenges, *IEEE Communications Surveys & Tutorials*, 2017, vol. 19, no. 4, pp. 2573-2620

[7] **Wilson, H, Avsar, P, Patton, D, Budri, AMV, Moore, Z.**: Skin hydration measurement and the prediction of the early development of pressure ulcers among at risk adults: A systematic review, *Int Wound J*, 2023; 20(3): 880- 891.

[8] **Rosso, J.D.; Zeichner, J.; Alexis, A.; Cohen, D.; Berson, D.:** Understanding the Epidermal Barrier in Healthy and Compromised Skin: Clinically Relevant Information for the Dermatology Practitioner, *Proceedings of an Expert Panel Roundtable Meeting. J Clin Aesthet Dermatol*. 2016 Apr;9(4 Suppl 1):S2-S8. Epub 2016 Apr 1. PMID: 28936279; PMCID: PMC5608132.R.

[9] **Werner, Y.; Lindberg, M.;** Transepidermal water loss in dry and clinically normal skin in patients with atopic dermatitis, *Acta Derm. Venereol*., 1985, 65, 102–105.

[10] **Oji, V.; Traupe, H.:** Ichthyosis: Clinical manifestations and practical treatment options, *Am. J. Clin. Dermatol.* 2009, 10, 351–364.

[11] **Roberson, E.D.; Bowcock, A.M.;** Psoriasis genetics: Breaking the barrier, *Trends Genet*, 2010, 26, 415–423.

[12] **Blichmann, C.; Serup, J.:** Hydration studies on scaly hand eczema, Contact Dermat., 1987, 16, 155–159.

[13] **Grandjean, A.C.; Grandjean, R.N.:** Dehydration and Cognitive Performance, Journal of the American College of Nutrition, 2007, 26:sup5, 549S-554S

[14] **Narayanan, D.L., Saladi, R.N.Fox, J.L.:** Review: Ultraviolet radiation and skin cancer. *International Journal of Dermatology*, 2010, 49: 978-986.

[15] **Halpern, A.C.; Altman, J.F.:** Genetic predisposition to skin cancer, *Current Opinion in Oncology*, 11(2):p 132, March 1999.

[16] **Caspers, P.J.; Bruining, H.A.; Puppels, G.J.; Lucassen G.W.; Carter, E.A.:** In vivo confocal Raman microspectroscopy of the skin: Noninvasive determination of molecular concentration profiles, *J. Investig. Dermatol.,* 2001, 116, 434–442.

[17] **Attas, E.M.; Sowa, M.G.; Posthumus, T.B.; Schattka, B.J.; Mantsch H.H.; Zhang, S.L.:** Near-IR spectroscopic imaging for skin hydration: The long and the short of it, *Biopolym. Orig. Res. Biomol.,* 2002, 67, 96–106.

[18] **Kadlec, F.; Berta, M.; Kužel, P.; Lopot, F.; Polakoviˇc, V.:** Assessing skin hydration status in haemodialysis patients using terahertz spectroscopy: A pilot/feasibility study, *Phys. Med. Biol.,* 2008, 53, 7063

[19] **Yao, S.; Myers, A.; Malhotra, A.; Lin, F.; Bozkurt, A.; Muth, J.F., Zhu, Y.:** A wearable hydration sensor with conformal nanowire electrodes, *Adv. Healthc. Mater.,* 2017, 6, 1601159.

[20] **Alanen, E.; Nuutinen, J.; Nicklén, K.; Lahtinen, T.; Mönkkönen, J.:** Measurement of hydration in the stratum corneum with the MoistureMeter and comparison with the Corneometer, *Skin Res. Technol.,* 2004, 10, 32–37.

[21] **Cataldo, A.; De Benedetto, E.; Schiavoni, R.; Monti, G.; Tedesco, A.; Masciullo, A.; Piuzzi, E.; Tarricone, L.:** Portable Microwave Reflectometry System for Skin Sensing, *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-8, 2022, Art no. 4003308.

[22] **Schiavoni, R.; Maietta, G.; Filieri, E.; Masciullo, A.; Cataldo, A.:** Microwave Reflectometry Sensing System for Low-Cost in-vivo Skin Cancer Diagnostics, *IEEE Access,* vol. 11, pp. 13918-13928, 2023.

[23] **Schiavoni, R.; Monti, G.; Piuzzi, E.; Tarricone, L.; Tedesco, A.; De Benedetto, E.; Cataldo, A.:** Feasibility of a Wearable Reflectometric System for Sensing Skin Hydration, *Sensors,* 2020, 20, 2833.

[24] **Cataldo, A.; Farhat, I.; Farrugia, L.; Persico, R.; Schiavoni, R.**: A Method for Extracting Debye Parameters as a Tool for Monitoring Watered and Contaminated Soils, *Sensors*, 2022, 22, 7805.

[25] **Pittella, E.; Schiavoni, R.; Monti, G.; Masciullo, A.; Scarpetta, M.; Cataldo, A.; Piuzzi, E.**: Split Ring Resonator Network and Diffused Sensing Element Embedded in a Concrete Beam for Structural Health Monitoring, *Sensors,* 2022, 22, 6398.

[26] **Schiavoni, R.; Monti G.; Tedesco, A.; Tarricone, L.; Piuzzi, E.; De Benedetto, E.; Masciullo, A.; Cataldo, A.:** Microwave Wearable System for Sensing Skin Hydration, *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC),* Glasgow, United Kingdom, 2021, pp. 1-6.

[27] **Cataldo, A.; Schiavoni, R.; Masciullo, A.; Cannazza, G.; Micelli, F.; De Benedetto, E.**: Combined Punctual and Diffused Monitoring of Concrete Structures Based on Dielectric Measurements, *Sensors*, 2021, 21, 4872.

[28] **Piuzzi, E.; Cannazza, G.; Cataldo, A.; De Benedetto, E.; Giorgi, L.; Frezza, F.; Leucci, G.; Pisa, S.; Pittella, E.; Prontera, S.; Timpani, F.**: A comparative assessment of microwave-based methods for moisture content characterization in stone materials, *Measurement*, 2017, 98, pp. 1-8. ISSN 0263-2241

[29] **Cataldo, A.; Cannazza, G.; De Benedetto, E.; Giaquinto, N.**: Experimental Validation of a Tdr-Based System for

Measuring Leak Distances in Buried Metal Pipes, *Progress In Electromagnetics Research*, 2012, 132. 71-90.

[30] **Cataldo, A.; Monti, G.; De Benedetto, E.; Cannazza, G.; Tarricone, L.; Catarinucci, L.:** Assessment of a TD-Based Method for Characterization of Antennas, *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 5, pp. 1412-1419, May 2009

[31] **Piuzzi, E.; Cataldo, A.; Cannazza, G.; De Benedetto, E.:** An Improved Reflectometric Method for Soil Moisture Measurement Exploiting an Innovative Triple-Short Calibration, *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 10, pp. 2747-2754, Oct. 2010

[32] **Cataldo, A.; Cannazza, G.; De Benedetto, E.; Tarricone, L.; Cipressa, M.:** Metrological assessment of TDR performance for moisture evaluation in granular materials, *Measurement*, 2009, 42. 254-263.

[33] **Gabriel, C.:** Compilation of the dielectric properties of body tissues at rf and microwave frequencies, 1996.

[34] **Zakharov, P.; Dewarrat, F.; Caduff, A.; Talary, M.:** The effect of blood content on the optical and dielectric skin properties, *Physiological Measurement*, vol. 32, p. 131–149, 2010

[35] **Gniadecka, M.; Philipsen, P.; Sigurdsson, S.; Wessel, N.O.; Christensen, S.D.; Hercogova, J.; Rossen, K.; Thomsen, H.; Gniadecki, R.; Hansen, L.; Wulf, H.:** Melanoma diagnosis by raman spectroscopy and neural networks: Structure alterations in proteins and lipids in intact cancer tissue, *J. Invest. Dermatol.*, 2004, vol. 122, p. 443–449