Evolution of the Complex Permittivity of Biological Tissue at Microwaves Ranges: Correlation Study with Burn Depth

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***Abstract*—The evolution of the muscle tissue's complex permittivity represents a growing interest in terms of characterization in medicine and biology. The influence of a burned part on the permittivity is not very developed. In this work, an estimation of the complex permittivity of biological tissues is performed as a function of the depth of burn tissues. The sensor, an open-ended coaxial probe, is placed directly against each sample. The evolution of the complex permittivity is studied for two measurements conditions (in the air and in a physiological solution). A correlation study is attempted with the depth of burn tissue.**

I. Introduction

In medicine, practitioners need to burn parts of organs for therapeutics purposes. For example, cardiac arrhythmia substrates may be cured by intra-cardiac procedures which consist in burning specific endocardial sites [1]. The depth of the cardiac lesions is related to arrhythmia recurrences. To date, it can't be assessed accurately during the procedures [2]. Indeed, electrophysiologists have no informations about the burn in progress into the body. They seek to create transmural lesions that will prevent the recurrence of arrhythmia. The clinical accuracy of the determination of burn depth has to be less than 0.5 mm.

Using a coaxial probe, our work consists in the estimation of the complex permittivity of the muscle tissue (in vitro) with the burn depth. To simplify the experimental conditions, a biological model composed of muscle fibers (beef meat) is used to reproduce the human heart. In fact, their dielectric properties are pretty similar in the frequency range of interest [3]. Several studies, still led in air, are focused on the post-mortem ageing of biological tissues [4], and the orientation of the fibers [5]. A research laboratory has obtained the dielectric properties of bovine liver in a thermostatic bath according to the burn temperature at 2.45 GHz [6].

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However, no action, to our knowledge, has focused on the evolution in the air and in a physiological solution of the complex permittivity of muscle tissue according to the depth of burn tissue. In this study, the determination of these parameters is performed with a coaxial probe in contact with the sample.

II. Principles of Measurements and Devices

The measurement is based on the microwave characterization of materials with a technique often-called open-ended [7]. It consists in the analysis of the complex reflection coefficient Γ, defined as the ratio between the reflected wave and the incident wave, which propagates through the material in contact with the coaxial probe. In (1), the real part of the reflection coefficient is represented by Γ' and the imaginary part by Γ''.

$$\Gamma = \Gamma' + j\Gamma'' \qquad (1)$$

Data acquisition is performed using a vector network analyzer (ZVB20, Rohde & Schwarz). It gives directly both informations. Before measurements, an open-short-load calibration is necessary to avoid the electronical noise and measurements errors. In this study, the coaxial probe has a female SMA connector and the diameter of his flange is approximately 9.5 mm. During measurements, the probe is placed directly on the sample as shown in fig. 1. The pressure applied through the probe on the sample is set by a "z-axis controller" (Physik instrumente Inc, M-501). The displacement accuracy of this device is less than 0.1 micrometer. The pressure is identical for each sample which is set on a support during measurements and burnings. A radiofrequency generator EP-shuttle (Biosense Webster Inc) is used to produce burns on the sample. Before the measurement, the beef meat is immersed in a physiological solution at 20°C during 20 minutes to lose a maximum of blood which would remain otherwise inside the meat. This step is important because the evolution of the meat in the solution gives a significant change on the acquired signal.

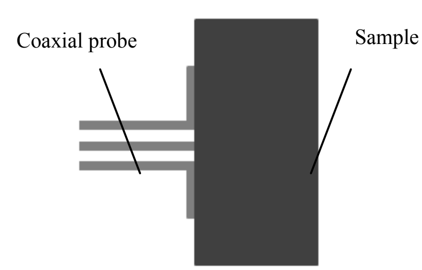

Figure 1. Schema of an open ended probe in contact with a sample [7].

The interaction between the wave and the sample depends on the complex dielectric permittivity ε of it (2).

$$\varepsilon = \varepsilon' - i\varepsilon'' = \varepsilon' - i\sigma/\omega\varepsilon_0 \quad (2)$$

Where $\omega = 2\pi f$ (with f the frequency), ε_0 is the vacuum permittivity (ε_0 = 8.85 x 10^{-12} $F.m^{-1}$), and σ is the conductivity. ε' is the real part of the complex permittivity and traduces the storage of the energy while ε'' is the imaginary part of the complex permittivity and traduces the loss of the energy by conduction. The evolution of the permittivity as a function of the frequency for biological tissues is presented in fig. 2. Several dielectric relaxations exist for biological tissues [8]. These are connected to different mechanisms. The relaxation α is associated with a phenomenon of ion diffusion at the surface of the cell membranes. The relaxation β is linked to the mechanism of a capacitive load of the cell membranes. In this study, we focused particularly on the relaxations γ and δ, reflecting respectively the relaxation of free water molecules and water molecules in the vicinity of macromolecules. These relaxations are around a few Gigahertz. They are important for this study because when the burn is done, the quantity of water into the tissue is modified.

The complex permittivity of the sample is extracted from the measured reflection coefficients, through a Labview based system. The system computer, which calculates the real and the imaginary part of the complex permittivity, is based on the Cole's bilinear calibration model (3-4) given by [9-10]:

$$\varepsilon(\omega) = [A(\omega)\rho(\omega) + \varepsilon_{ref}(\omega)] / [1 - B(\omega)\rho(\omega)] \quad (3)$$

Where

$$\rho(\omega) = [\Gamma_{ref}(\omega) - \Gamma(\omega)] / [[\Gamma_{ref}(\omega) + \Gamma(\omega)] \quad (4)$$

The complex permittivity of a reference fluid is represented by ε_{ref} (ω). A (ω) and B (ω) are complex calibration constants determined by two calibration fluids of known permittivity and Γ_{ref} (ω) and Γ (ω) are the complex reflection coefficients for the reference fluid and the fluid under test respectively. The radiation effects are not taken into account by this model. However, as long as the permittivity of the calibration fluids are close to that of the fluid under test, the errors due to these effects will be reduced [11].

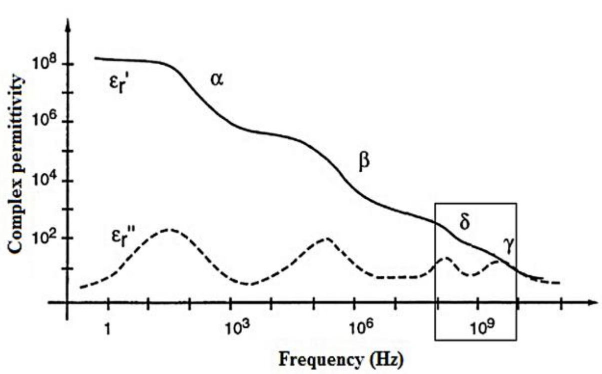

Figure 2: Evolution of complex permittivity of biological tissue as a function of frequency [8].

For these reasons, in this study, the three reference fluids are distilled water and saline solutions at 0.3 and 0.9% in weight. Their permittivities are available on [12]. These reference solutions are pretty close from the complex permittivity of the beef meat in our frequency range (1GHz to 6 GHz). To validate our software, the measurement of the effective permittivity of a bovine muscle in the air is done and compared with those given in the literature [3]. Indeed, bovine muscle is formed by different components like muscle fibers, endomysium, interstitial fluid, etc. A muscle can be considered like a composite material. Several measurements are done on a sample. The mean values and the uncertainties (U) of the effective permittivity are calculated. Results are shown in table 1. In order to clarify the data lecture, only three frequencies are presented from the entire frequency range (1GHZ, 2.45 GHz and 6 GHz). The error on the real part of the permittivity is less than 4 % and the error on the imaginary part is around 10%. Thus, the model gives some values close to the ones available in the literature.

III. RESULTS

The measurements have been done in two different conditions. On one hand, the measurements of the complex permittivity have been performed in the air. This step is required to prove the feasibility of the distinction of bovine muscle with and without burns. On the other hand, the measurements have been done in a physiological solution (distilled water with 0.9 %wt of NaCl) maintained at body temperature (37°C) to reproduce the clinical conditions. After all measurements, a transversal cut is made on the sample and the depth of the burn tissue is measured with the help of a photography (fig. 3). In order to limit the difficulty of graphics, only two burns are presented (3 mm and 6 mm).

TABLE 1: VALIDATION OF THE SOFTWARE FOR THE ESTIMATION OF THE COMPLEX PERMITTIVITY.

Frequency	**ε' (literature)**	**ε' (experimental)**		**error (%)**
		Mean	***U***	
1 GHz	57.48	59.52	4.42	3.54
2.45 GHz	54.94	55.74	3.67	1.47
6 GHz	49.03	47.91	1.02	2.27
	ε'' (literature)	**ε'' (experimental)**		**error (%)**
		Mean	***U***	
1 GHz	21.49	19.21	5.69	10.06
2.45 GHz	15.89	14.43	3.25	9.17
6 GHz	19.66	17.86	1.84	9.15

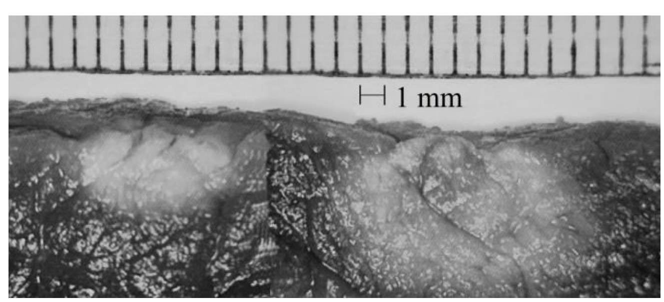

Figure 3: Transversal cut of bovine muscle with two different burn depths.

For both conditions (air and solution), five samples are used to determine the effective permittivity and for each sample, five reflection coefficients are measured. Thus, the reflection coefficients, obtained from several samples, are gathered and an average is calculated. The variation of the reflection coefficient is less than 1%. So, the measurements are repeatable and reproducible. The mean value is used in the model to estimate the complex permittivity. These permittivities are presented in fig. 4-7.

A. Measurements in the air

Firstly, the evolution of the complex permittivity as a function of the burn depth on biological tissue has been studied in the air. A decrease is observed for both parts (real and imaginary part) of the effective complex permittivity with burns on the entire frequency range. The observations are pretty similar to the literature [13-14] where burns were done on pork skins. The decrease of the real part of the complex permittivity (fig. 4) probably came from a decrease from the concentration of water contained in the tissues. In fact, during the heating process in the air, the beef meat changed its consistency, releasing fluids and becoming more compact. Concerning the imaginary part of the complex permittivity (fig. 5), the burns cause a decrease of the conductivity of the bovine muscle.

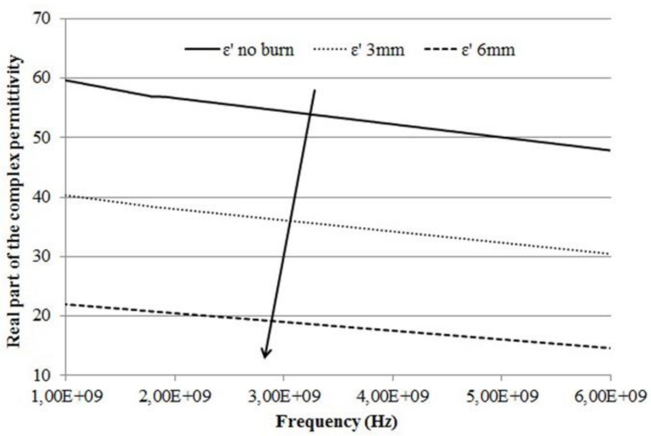

Figure 4: Evolution of the real part of the complex permittivity with depth of burn tissue (measured in the air).

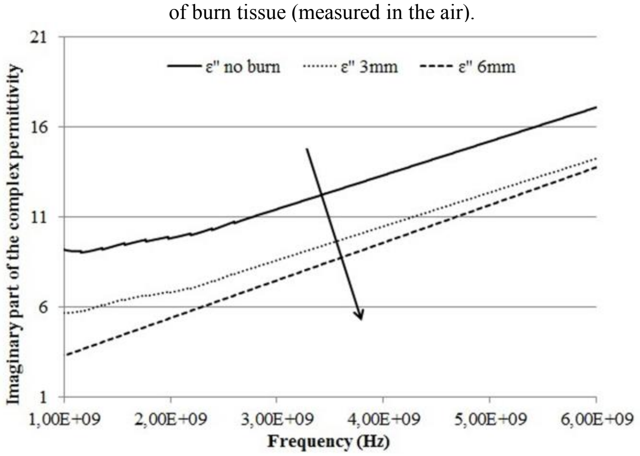

Figure 5: Evolution of the imaginary part of the complex permittivity with depth of burn tissue (measured in the air).

B. Measurements in physiological solution

The complex permittivities presented in this section are obtained with several specific conditions. These conditions, like temperature and concentration of physiological solution or pressure applied by the sensor on the sample, are possible variation sources of the permittivity. The evolutions of the real and imaginary part of the complex permittivity on the entire frequency range are respectively presented in fig. 6-7.The measurements conditions are identical for all measurements (same temperature, same contact force). In this case, an increase of the real part of the permittivity with the tissue burn depth is observed. On the contrary, a decrease of the imaginary part of the permittivity with the depth of burned tissue is presented.

C. Comparisons

A decrease of the imaginary part of the complex permittivity as a function of the tissue burn depth is presented for both conditions (in the air and in a liquid). A possible explanation is that the burn tissues are less conductive than the tissue without burn and inducing a diminution of the imaginary part. However, a difference appears for the real part. An increase of the real part of the permittivity is observed with a growing depth burn in the solution. An assumption is that the concentration of saline solution into the tissue is growing with the burn depth.

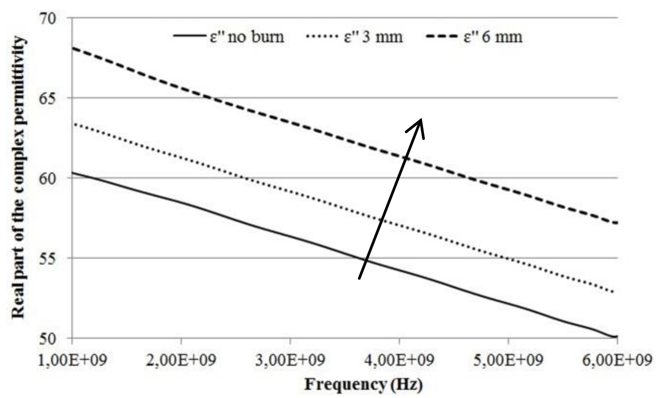

Figure 6: Evolution of the real part of the complex permittivity with depth of burn tissue (measured in the physiological solution).

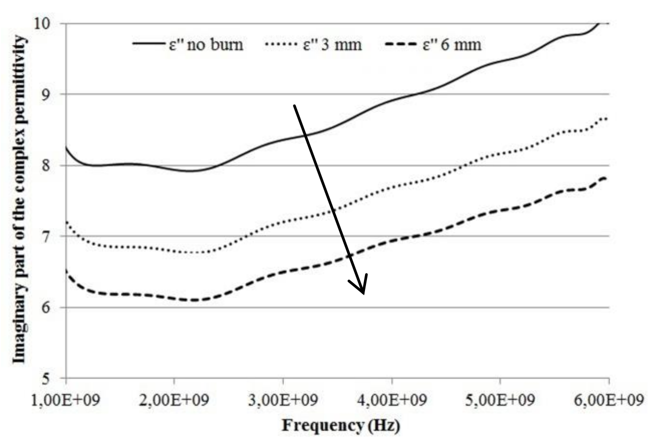

Figure 7: Evolution of the imaginary part of the complex permittivity with depth of burn tissue (measured in the physiological solution).

In both conditions, an evolution of the complex permittivity is observed with the burn depth of the tissue on the entire frequency range. So, the determination of the burn depth in liquid medium is possible from the reflection coefficient [15] as from the permittivity (fig. 8). In this figure, the relative variation of the complex permittivity is represented as a function of the depth of burn tissue for the 2.45 GHz frequency. The choice of the frequency is not of great interest because the variation on the studied frequency range (1 GHz-6 GHz) is approximately identical. However, the evolutions of the imaginary and real part are linear with the depth of burned tissue. The correlation coefficient and the equation of the linear regression are indicated on the figure. Moreover, the vertical and horizontal error bars respectively refer to the uncertainty on the estimation of the effective complex permittivity and to the uncertainty of measured burn depth.

IV. CONCLUSION

In this paper, we show that the burn depth of the tissue have an impact of the complex permittivity (real and imaginary part). The evolution of this permittivity causes a change of the reflection coefficient and the burn depth can be estimated with a good accuracy without destruction of the sample. It conducts to the possibility of the development of a sensor that will help the electrophysiologists during procedure.

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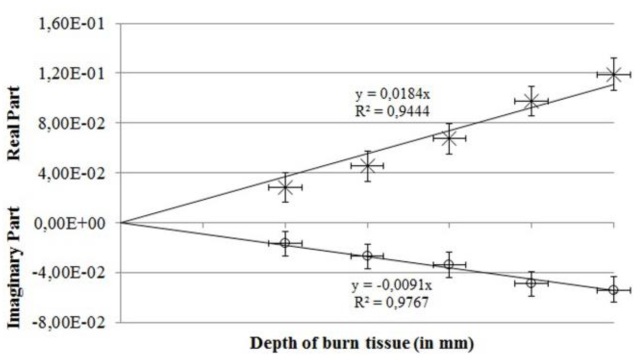

Figure 8: Relative variation of the complex permittivity (real and imaginary part) as a function of depth of burn tissue.

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