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Comparison of two thermal probe technologies for the dosimetric investigations of RF exposure systems

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Abstract— Exposure to radiofrequency waves (RF) happens everyday but little is known about the potential induced toxicity. It is therefore essential to carry out studies with rigorous experimental protocols and accurate dosimetry. To do this, we can characterize the dosimetric characteristics, namely the specific absorption rate (SAR) of the emitted RF waves and the induced thermal increment by monitoring the temperature over time. Different types of thermal probes may be used for such a study. We were interested in comparing two types of probes that can be used in conditions suitable for *in vitro* measurements, in a traditional biological consumable, 96-well plate. Such particular conditions require extreme precision in the positioning of the probe, its sensitivity and its measurement accuracy. We have chosen to compare a microscale thermocouple, an inexpensive but often criticized technology as it is metallic and therefore capable of interfering with the electromagnetic field, with a much more expensive fiber optic probe. We have highlighted the advantages and disadvantages of each in the context of this specific type of measurement.

Keywords—radiofrequencies, electromagnetic fields, dosimetry, specific absorption rate, thermal measurements

I. INTRODUCTION

The study of the toxicity of radiofrequency waves on living organisms is nowadays an important topic within the scientific community. This is even more critical with the appearance of new communication standards and the exponential expansion of their use. Studies targeting the assessment of the impact of electromagnetic waves on living organisms can be carried out at different levels, from an epidemiological point of view [1], or using *in vivo* [2] or even *in vitro* [3] models. In our case, we focused on the *in vitro* model. We have developed devices to study the effect of RF waves in common biological consumables, 96-well plates in this case. It is then necessary to develop techniques for dosimetric characterization of the radiation of RF waves under these particular conditions. The electromagnetic power radiated in the well and absorbed by its contents is a key data for a biological test. Several dosimetry measurement techniques exist based either on the measurement of the electric field or by thermal measurement. We chose to focus on this last technique and more particularly to compare two types of temperature sensors allowing the characterization and

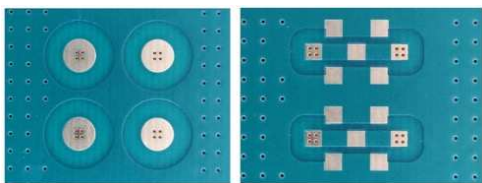


Fig. 1. Photographs of two RF applicator doublets placed side by side: on the left the radiating part, on the right the SMA connexion part.

the calibration of the power and therefore Specific Absorption Rate (SAR) of our microwave range device, compatible with 96-well cell culture plates. A similar approach [4] has been carried out in the past with a different exposure system based on large 12-well plates and a millimeterwave range horn antenna as the radiating element.

Therefore, this paper first introduces the RF applicator configuration that is used in our study as well as our full RF exposure setup. Section III provides a reminder on SAR equations and the methodology applied to extract this indicator from thermal measurements. Finally, the last section gives the experimental results obtained with two temperature probes technologies, an optical fiber ended with a crystal which is temperature dependent, and a metallic thermocouple.

II. RF APPLICATORS CONFIGURATION AND TEST SETUP

A. Configuration of the near-field RF applicator

An RF applicator adapted to the biological constraints of *in vitro* study and to high-throughput biological analysis methods has been developed. For this, we have chosen to use standard 96-well plates conventionally used by biologists and have developed an RF applicator adapted to this type of biological container. This allows us to have many conditions on a single plate. Biological controls can also be integrated on the same study plate. Figure 1 presents photographs of the top and back sides of 4 RF applicators on a Printed Circuit Board (PCB). To minimize the number of RF cables, 2 RF applicators are connected to a single SMA connector, which bonding may be easily distinguished by the 5 central gold squares.

Our RF applicators radiate in the near field allowing to study the effects of the waves on a cell layer located at the bottom of the well. Details on the dimensions of this applicator were published in [5]. The purpose of this device is to evaluate the potential toxicity of radiofrequency waves on cells. To do so, an exposure system is defined.

B. Test setup for *in vitro* RF exposure of cells

Our complete test bench, which is presented in Figure 2, is composed as follows: a signal generator in CW mode at the beginning of the chain generates the RF signal. An RF amplifier is placed at its output and allows to reach the power level required for our measurements. An isolator is then added at the output of this amplifier in order to avoid any reflected wave towards the amplifier and the generator. Finally, the RF applicator platform is placed after this isolator

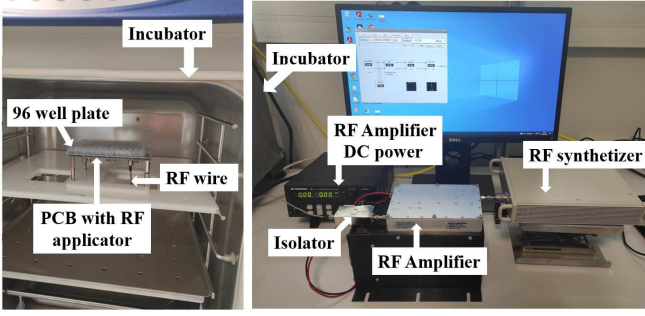


Fig. 2. Photograph of the RF exposure test bench with on the left the RF applicators platform placed in an incubator and on the right the RF generation chain

in a biological incubator to allow cell testing under environmental conditions suitable for cell development.

For this study, only two RF applicators are considered. Other RF applicators are not connected.

Next section is dedicated to the dosimetric study.

III. DOSIMETRY INDICATORS AND EXTRACTING METHODOLOGY

The electromagnetic power absorbed by an object is defined by the SAR. It is possible to get the SAR value from the thermal heating induced by the application of RF waves on the exposed material [6-8].

SAR, when time tends to zero, is expressed as:

$$SAR = \frac{\sigma \cdot E^2}{\rho} = c \frac{dT}{dt} \quad (1)$$

where σ is the electrical conductivity (S/m), ρ is the volumic mass (kg/m^3), E and c correspond to the electrical field (V/m) and the mass heat capacity ($\text{J}/(\text{kg}\cdot\text{K})$) respectively, and T is the temperature (K).

Subsequently, heat exchanges occur until a temperature equilibrium is reached, leading to the definition of a thermal increment, which corresponds to the variation between the temperature reached in steady state and the initial temperature before any RF exposure.

Fig. 3 presents the synoptic of the experimental setup defined for thermal measurements and SAR extraction. Usually, optical fiber with crystal probes are preferred for temperature measurements with RF fields application to avoid interferences with the electromagnetic signal. The corresponding conditioner and probes are however expensive and present limitations in sensitivity. We have therefore compared the performances of such a probe with a simple and much cheaper temperature probe based on a thermocouple. The RF generation chain used for temperature measurements during RF exposure remains unchanged. Due to the double RF applicator configuration, we were able to evaluate temperature modifications with the two measurement techniques simultaneously. The optical fiber-based probe is applied in one well, whereas the thermocouple is located in the second well. Details on the two technologies are given in the next section.

As far as SAR extraction is concerned, a theoretical model is defined, while considering the thermal exchanges over the long term. An example of thermal measurement versus time is shown in the next section. Due to the exponential

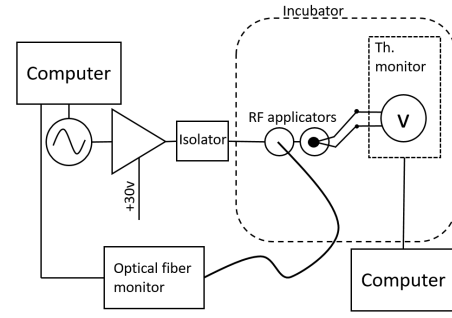


Fig. 3. Schematic of the RF test bench synoptic for temperature measurements during RF exposure

configuration of the thermal increase with RF power applied, Equation (2) is introduced.

$$T(t) = T_0 + (T_\infty - T_0)(1 - \exp(-t/\tau)) \quad (2)$$

Where T_0 is the initial temperature prior to RF exposure, T_∞ is the reached steady temperature when RF signal applied.

A regression on the Matlab software is then performed using the following model:

$$A \cdot \exp(B \cdot x) + C \cdot \exp(D \cdot x), \quad (3)$$

Which is already available in the mathematical software. Applied to Equation 1, and considering when t tends to zero, we obtain the new SAR equation 4.

$$SAR = c \frac{dT}{dt} = c(A \cdot B + C \cdot D) \quad (4)$$

Next section is dedicated to the application of the SAR extraction method on experimental data.

IV. EXPERIMENTAL DOSIMETRY STUDY WITH TWO DIFFERENT TEMPERATURE PROBES : COMPARISON STUDY

A. Experimental conditions and protocol

Two types of temperature probes for SAR evaluation have been evaluated. One corresponds to a thermocouple (TC) from RadioSpare presenting a diameter of 0.075 mm, in association to an acquisition instrument from National Instruments, the NI CDAQ 9181, and a homemade LABView program. The second thermal probe is an optic fiber (OF) from OPSENS, the OTG-M420, together with a specific signal conditioner and software.

We must carry out our tests under the same conditions as when evaluating the RF toxicity on cells. For this, we use a 96-well plate in an incubator at 37°C, with 5% CO_2 and a humidity rate above 90%. The measurements are carried out with culture medium, Dulbecco's Modified Eagle Medium – DMEM, with phenol red and antibiotics. 100 μL of DMEM are added in each illuminated well, as well as their bordering neighbors. From an RF perspective, the input power applied on the applicator doublet is 27dBm (0.5W) at a frequency of 2.3 GHz. Our temperature sensors perform an acquisition each 500ms. The well-plate is then placed on the RF applicator platform within the incubator. The thermal probes are positioned in the desired wells with a 3D printed support

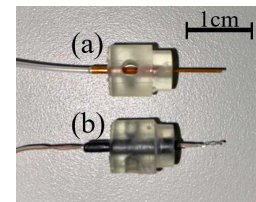


Fig. 4. Photographs of the two temperature probes (Optical Fiber- OF- and Thermocouple -TC) equipped with a specific well-plate plug support.

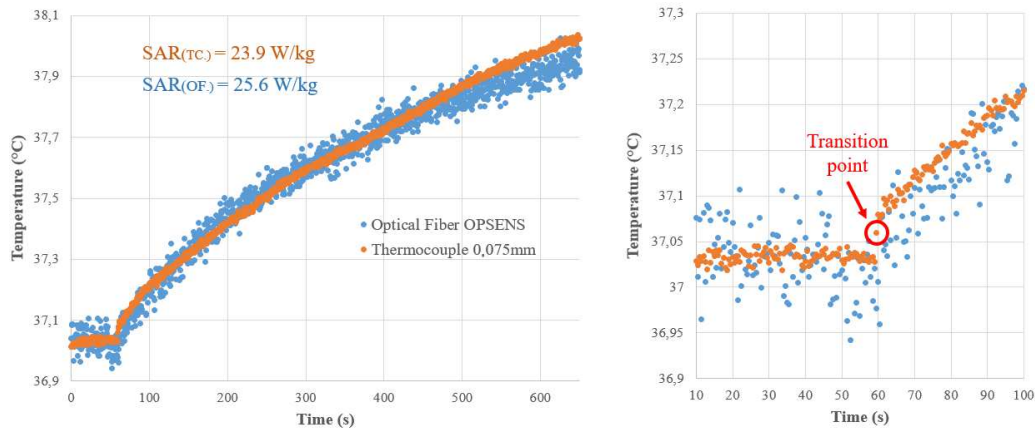


Fig. 5. Thermal measurements versus time for the two thermal probes. Left side: complete curves. Right side: focus on temperature during the first 100 seconds

system, as shown in Figure 4. This system allows the probe to be held in the center and at the bottom of the well, where we want to perform the measurement. The incubator is closed and set at 37°C. Once the DMEM is temperature-stabilized, thermal experiments vs time can be performed with both probes. The initial temperature is measured for one minute. RF signal is then applied for 10 minutes. Figure 5 presents a typical temperature profiles obtained for each probe vs time. The orange curve corresponds to the response of the TC, whereas the blue dots are obtained with the OF probe. Such data are then analyzed with the developed Matlab program, to finally extract the SAR value. During this calculation, the mass heat capacity of DMEM is considered equivalent to that of water ($4180 \text{ J.kg}^{-1}.\text{K}^{-1}$).

B. Experimental results

Thermal measurements obtained with the two probes are very similar. The trend of the curves associated with the thermal phenomenon does not depend on the type of sensor used, nor on the maximum temperature value. However, a much noisier signal (by 1 order of magnitude) is observed for the OF probe. The noise estimation is of 0.2°C for the OF instead of 0.025°C for the TC. Therefore, by zooming in on the triggering time of the RF signal, a rapid rise in temperature exactly after 60 seconds time is noticeable with the TC, whereas this triggering is more difficult to define with the OF probe due to measurement noise. The rapid and significant detection of temperature increase with the TC represents an important advantage in the observation and characterization of sudden and fast events and for very short periods. This is particularly the case in the SAR evaluation, which is defined by the slope of temperature profile once RF signal is applied. The SAR value obtained with the OF technique is slightly higher than the one obtained with the TC. However, while considering several measurements, the standard deviation is much lower for TC than with the OF, leading to more repeatable measurements.

V. CONCLUSIONS

This paper provides a comparison of two thermal probe technologies for the dosimetric investigations of RF exposure systems. From an experimental point of view, the use of the TC presents several advantages over OF. Due to its small size, it can quickly respond to thermal changes. It is also very accurate and allows us to carry out measurements at low SAR, therefore small thermal rises, ability which is impossible to reach with OF. The cost of OF is much higher than that of TC,

(about €300 against €10) which can be a determining factor if one is willing to use many sensors simultaneously. This observation may also be done for the OPSSENS acquisition module (about €3500 with the two-channels model against €300 for the 8-channel NI instrument). Regarding the implementation of thermal measurements, OF are much more practical. They are robust compared to the very thin and easily broken TC. In addition, positioning through the 3D plugs does not require any particular preparation and their rigidity allows a facilitated positioning. The program provided with the OPSSENS acquisition module is relatively user friendly and has many options for data acquisition, which is enough for our measurements. However, for specific experiments, being able to develop a suitable LabVIEW program can be an advantage. Finally, the thermal profiles and the SAR values being similar for the two sensors, we can hypothesize that the influence of the presence of the sensors in the well for the measurement of the SAR is either negligible or similar between the two sensors in this RF exposure configuration.

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