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***Abstract*— This paper shows that the manufacturing process presented in our previous work which was used for building time-stable and remotely reproducible breast and head phantoms, opens up new avenues for mimicking any types of biological tissues in the frequency range of [500 MHz – 3 GHz]. Moreover, the numerical version of the phantom (STL format file) enables us to test its conformity, as well as experimental configurations. The study is placed in the framework of the European project EMERALD.**

***Index Terms*— microwave imaging, cancer detection, stroke monitoring, dielectric characterization, UWB biological phantoms.**

I. INTRODUCTION

During the last decades, microwave imaging has attracted remarkable attention for biomedical applications mainly due to the significant contrast between the dielectric properties of normal and abnormal tissues. Compared to the other conventional imaging modalities, such as X–ray mammography, microwave imaging is an attractive approach in several aspects, namely its non–ionizing nature, low cost, and compactness of the equipment associated with its hardware system. This is the reason why, at the present time, there are dozens of research teams around the world working on bio-medical applications of microwave imaging. This is evidenced by the emergence of several COST and particularly, MiMed [1]. The latter gave rise to several projects; among them, the European project "EMERALD" (ElectroMagnetic Imaging for a novel genERation of medicAL Devices [2]) has started. EMERALD is a multidisciplinary project involving 27 partners across the Europe. It offers a unique opportunity for interactions between clinicians, researchers and instrumentation developers.

Newly designed devices require multiple tests under a controlled environment before moving to human clinical test. This paper is mainly concerned with the conception, development, and realization of the biological phantoms dedicated to test the devices developed in the project and particularly is well suited to a remote teamwork of electrical engineers, taking into account the European context. To be more specific, we show that the method proposed in the previous work [3] seems to be suitable for the production of liquid mixtures mimicking any a priori type of biological tissue over a wide range of frequencies.

This study will benefit from a complementary knowledge of research teams all around the world through partnerships, in the wave propagation domain, electromagnetic modeling [4-5], dielectric characterization [6] as well as the field of inverse problems [7-9]. This work will also include a close collaboration with clinicians involved in the EMERALD project, particularly those from Lariboisière and La Salpêtrière Hospitals [10-11].

This communication first reviews the manufacturing method of the biological phantoms and underlines the interest of using it in the frame of a project such as EMERALD. Then, discussions as well as numerical results show that liquid mixtures based on Triton X-100 and salted water solutions, are suitable to mimic any kind of biological tissues used in the frequency range of the EMERALD's project. Finally an example of simulations performed with the Microwave Studio Software, from the STL format file of a head phantom, shows the interest of developing phantoms whose shapes are provided from STL format files.

II. TRITON X-100 AND SALTED WATER SOLUTIONS

Used in the framework on the EMERALD project, the manufacturing process has to be easily reproducible by an electrical engineer in a non-specific environment (no hood), and without drastic precautions. Following our previous works, the phantoms such as the breast [12] and head [13] are composed of 3D printed cavities mostly of 1.5 mm thickness, filled up with liquid binary mixtures of Triton X-100 (TX-100, a non-ionic surfactant) and salted water. Those liquid mixtures are adjustable in time therefore their use in the manufacturing process, provide stable phantoms over time.

A. An Easy and Safe Experimental Protocol

The liquid mixtures can be prepared easily and quickly. In order to realize the samples, we proceed by mass addition according to the following process:

- Tare the balance with an empty beaker.
- Add successively the masses of NaCl and deionized water and tare the balance between each step.

- Stir the solution with a magnetic bar - when the salt is dissolved, tare the balance.
- Add the mass of TritonX-100. Note that, the TritonX100 is very viscous at room temperature, then it must be heated first separately in a 45 ° C water bath.
- Place the beaker in a water bath and stir the solution with a magnetic bar. The bath water must cover all the mixture. Note that the 40-60% solutions of TritonX-100, depending on their salt concentration, can be gelled at room temperature. It is therefore necessary to increase the temperature to obtain homogeneous mixtures in any case.
- Once the solution is homogeneous, pour it into an airtight container and keep the sample in room temperature and safe from light.

B. Concentrations of TX-100 and NaCl deduced from a binary fluid mixture law

The dielectric properties of the liquid mixtures have to be close to those provided by the 4-pole Cole-Cole models and are accessible for each tissue on the IFAC website [14]. We are looking for a liquid mixture, which contains water and salt, since the dielectric properties of the biological tissues are related to their water and salt contents. The Debye model for salted water has been developed in literature [15]. Hence in the way of looking for a second fluid, for which a Debye model is known, a binary fluid mixture law can be used to compute the dielectric properties of the mixture on wide band frequency range and for a given concentration of the salt and the second fluid. Then, the latter can be adjusted by fitting the binary and the Cole-Cole models for each tissue over a wide frequency range. This can be done, by minimizing a cost function, which represents the mean square error between the dielectric properties of the mixture and biological tissue while the 4-pole Cole-Cole model is known for them [16]. The process is based on the Gauss Newton method [17].

The similarity of dielectric properties between pure TX-100 and fatty tissues and also being water miscible, makes TX-100 as an appropriate candidate for the second fluid. A Debye model has been developed for it before [18]. Furthermore thank to the viscosity of the pure TX-100, the mixture of TX-100 and salted water is stable over time. We have the capability of mimicking a wide range of biological tissues, based on the low dielectric properties values of pure TX-100.

Several binary laws have been tested; among them the Böttcher law [19] represents the best results according to the measured dielectric properties of the liquid mixtures mimicking the breast [12] and head tissues [20].

Table 1 displays the results, obtained by using the Böttcher law, for 10 new biological tissues at the frequency of 1.5 GHz and the temperature of 25°C. As one can see, the predicted dielectric properties from the Böttcher law and the expected ones from Cole-Cole model are in a good agreement for all the tissues. Those numerical results have to be validated experimentally. Next step will consist starting from those numerical values, to adjust experimentally the concentrations of TX-100 and salt, according to the measured values of the samples. Adding salt increases the conductivity while the addition of TX-100 mainly decreases the dielectric constant. It can be noticed that at room temperature all the mixtures are liquids, except those for which the TX-100 volume percentage is in the range of 40-60 %, which corresponds to the nerve and the lung tissues.

TABLE I. BOTCHER LAW RESULTS FOR 10 NEW BIOLOGICAL TISSUES

@ 25°C, 1.5 GHz	**Mixture**		**Böttcher**		**Cole-Cole**	
Tissue	TX-100 vol %	NaCl g/L	ε_r	σ S/m	ε_r	σ S/m
Stomach	12	7	63.7	1.5	63.8	1.5
Spleen	20	7	55.1	1.5	54.7	1.6
Liver	30	5	45.1	1.0	44.9	1.1
Small Intestine	16	14	57.0	2.5	56.8	2.5
Gall-bladder	16	7	58.6	1.5	58.5	1.5
Kidney	19	8	56.0	1.6	55.4	1.7
Colon	19	6	56.1	1.3	55.9	1.4
Heart	17	7	57.6	1.4	57.2	1.6
Nerf	44	4	31.5	0.7	31.3	0.7
Lung Inflated	56	4	21.3	0.6	21.2	0.6

III. 3D-PRINTED STRUCTURES AND SIMULATION

Examples of 3D-printed structures have been already developed in the frame of our previous works [12, 13]. They come from STL format files obtained from MRI scans [21, 22], and are composed of several separated cavities to mimic the shape of the different tissue types. The anthropomorphic GeePs-L2S head phantom named JPS [13], composed of 3 cavities (brain, CSF and muscle) is compared here with the predefined human heads models of the Microwave Studio software named SAM and GUSTAV. The phantoms are supposed to be illuminated by a plane wave operating in free space at 1 GHz, since the range 1.5-4 GHz is a “forbidden band” for brain stroke monitoring [9]. Fig. 1 displays the amplitude of the electrical field inside the heads. Regarding the comparison of the electrical field amplitudes in different head models, by considering the relation of the heterogeneity of the electrical field and the dielectric properties of the head tissues, suggested phantom seems to be a good compromise of complexity.

The advantage of the head phantom, with respect to the two others, is that it is printable and thus could be used in microwave imaging devices, such as those developed in the EMERALD project. Furthermore, the obtained experimental data can also be used to test the inversion algorithms developed in the framework of the project.

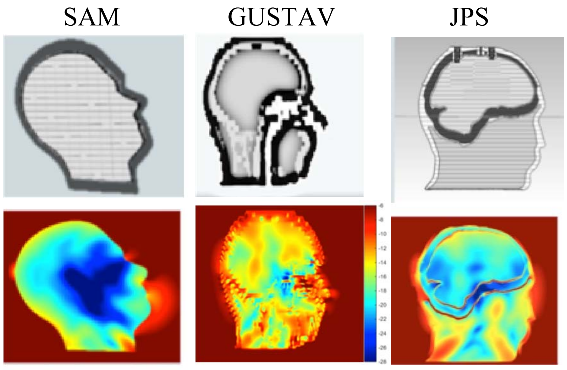

Fig. 1. The total electric field distributions obtained for the 2 predefined human heads models and the phantom proposed here, when the latter is located in the air and illuminated by a plane wave at 1 GHz.

IV. CONCLUSION

We have shown numerically that the method proposed in our previous work should be generalized to the manufacture of any biological phantom used in the frequency range of [500 MHz - 3 GHz]. Those numerical results need to be validated experimentally, as has already been done for the breast and head tissues. The manufacturing process is simple, easily reproducible by an electrical engineer in a non-specific environment (no hood), without drastic precautions, and therefore suitable to a framework of the EMERALD project. This process provides remotely reproducible phantoms, with realistic shapes and time-stable dielectric properties. The STL format files of the phantoms could be used to perform electromagnetic simulations to test the inversion algorithms and the devices developed in the project, under a controlled environment.

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