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Anthropomorphic Multi-tissue Head Phantom for Microwave Imaging Devices Testing

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***Abstract*—This paper describes the realization of a versatile anthropomorphic multi-tissue head phantom for testing microwave imaging devices, employing mixtures featuring readily available, not harmful, and stable components. Considering that the evaluation of devices, such as medical ones, might require the variation of the characteristics of the tissues for their assessment, the manufacturing approaches the issue using both unalterable and adjustable components. For the former, we reproduce skin, fat, bone, grey matter, white matter, cerebellum, and ventricles using flexible and solid compounds made with proper proportions of urethane rubber, graphite powder, and salt. While for the latter, water, triton X-100, and salt are used to generate a liquid mixture to mimic cerebrospinal fluid. The anatomical structures of the tissues are faithfully rendered using 3D-printed molds and assembled without additional intermediate plastic layers. The materials' dielectric properties are measured via an open-ended coaxial probe method, investigating the frequency range of 0.5-2 GHz. The final prototype fits the nominal dielectric values in the literature, presenting stability and replicability, demonstrating its validity as a multi-purpose test object.**

***Index Terms*—biomedical application, dielectric properties, head model, microwave devices, propagation.**

I. Introduction

Microwave-based technologies have proven their high potential in sensing and imaging medical applications, taking advantage of the sensitivity of organic tissues and pathological conditions in the microwave band. Breast cancer screening and brain stroke diagnosis and monitoring are notable examples of ongoing research and pre-clinical trials [1]–[4]. A significant matter in developing a microwave scanner, both in the industry both in academia, is the product testing step, generally performed on anthropomorphic physical models. An ideal testing phantom offers the reliability of dielectric properties, stability in time, availability, and manageability of materials.

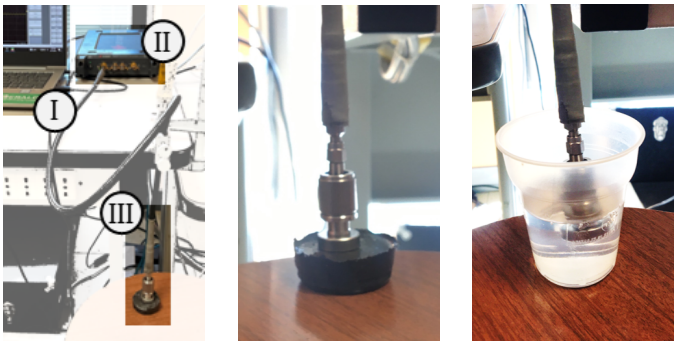
In the last two decades, extensive work has been done in tissue-mimicking chemical mixtures, leading to several solutions for narrowband and broadband applications, both in a solid state, e.g. gelatine-based materials [5]–[8] and carbon powder-urethan rubber compounds [9], and in liquid one [10]–[12]. Yet, liquid alternatives usually use plastic containers with single or multiple cavities, which introduce unwanted, non-realistic, and compound features that distort the tested electric fields, scaling with the number of layers [4], [10], [13]. Hence, an alternative in complex models, such as the head, is exploiting the ease of use of gelatine mixtures [14]–[16]. However, as observed in [17], it is challenging to preserve them over time. In this context, new solid materials options have been attempted, though selecting the components to achieve the target dielectric properties is not trivial. Graphite, carbon black, and urethane rubber or silicone composites are typically combined to emulate human tissues, as in [1], [18], which propose two refined breast models, and in [19], where a head phantom is realized.

In line with [19], here we present the realization of an anthropomorphic multi-tissue head phantom intended to test microwave imaging devices operating from 0.5 to 2 GHz [2], [16], [20]. The phantom is realized with custom low-complexity recipes, including non-toxic and readily available materials. All the head tissues are faithfully reproduced using 3-D printed molds, and the designed assembling allows to avoid plastic layers. In particular, cerebrospinal fluid (CSF) is a removable and customizable liquid mixture filling a cavity between the solid tissue layers.

II. Phantom Realization

A. Tissue-mimicking Recipes

Two types of mixtures are studied to emulate different head tissues by systematically analyzing the permittivity and conductivity while the compounds are varied. Then, employing the open-ended coaxial probe method, the properties are obtained. Figure 1 depicts the utilized experimental setup, highlighting the vector network analyzer (VNA) Keysight N5227A, the dielectric probe Agilent 85070D, and two kinds of samples used to characterize the materials (see Fig. 1(b-c)). Here, it is worth noticing that the measuring surface of the solid samples



(a) (b) (c)

Fig. 1. Experimental setup. (a): **I**-laptop; **II**-vector network analyzer; **III**-coaxial probe. (b): Sample of Gr-UR. c: Tr-W-S.

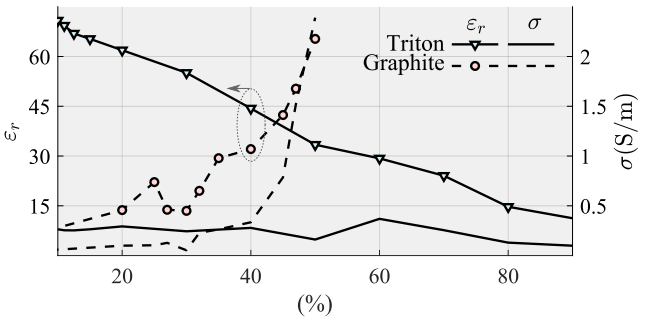


Fig. 2. Variation of permittivity and conductivity values at 1 GHz using different mixture compositions. The (%) indicates the percentage in weight of triton-X and graphite in the mixtures Tr-W and Gr-UR, respectively.

is flat and soft, allowing adequate contact with the probe and, thus, the use of this technique.

One of the mixtures is composed of urethane rubber (UR), a solid and flexible material, and graphite powder (Gr), used to increase the permittivity. The second one is a liquid compound containing triton X-100 (Tr), water (W), and salt (S), suitable for emulating the CSF. Then, from herein, we dub the mixtures as UR-Gr and Tr-W, which are optimized to work at the 0.5-2 GHz band, taking as variables the percentage of the mixture compounds. For instance, Fig. 2 shows the UR-Gr and Tr-W properties obtained at 1 GHz, where Gr varies between 10-50% in weight and Tr between 10-90% in their respective mixtures, reaching the permittivity span of all nominal values taken from the database [21]. Moreover, salt is used as the third ingredient for minor adjustments to the formulas.

The final recipes are then derived based on the interpolated curves and reported in Table I. Moreover, the permittivity values are provided as the average and standard deviation estimated on several measurements. In fact, to verify the measurement's stability and the manufacturing process's repeatability, the samples are measured several times, even after days, and the same recipes are repeated in multiple samples.

TABLE I
TISSUE-MIMICKING MIXTURES COMPOSITION (%) & PROPERTIES AT 1 GHZ

Tissue	UR*	Gr*	Tr*	Salt	Water	ε_r	σ(S/m)
Cerebel.*	53†	47	–	–	–	48.24±2.92	1.32±0.09
Ventricle	50†	50	–	–	–	66.31±4.15	2.67±0.99
White	62	38	–	–	–	39.73±6.99	0.76±0.22
Gray	57	43	–	–	–	50.27±2.92	1.06±0.09
CSF	–	–	8.9	1.4	89.7	67.89±0.53	2.24±0.08
Fat	68†	8	–	24	–	5.82±1.15	0.045±0.01
Bone	80	20	–	–	–	14.02±1.42	0.13±0.01
Skin	55	45	–	–	–	40.27±6.99	0.82±0.22

†Reoflex, the values without dagger use Ecoflex [22].
*Urethane rubber (UR), Graphene (Gr), Triton X-100 (Tr), Cerebellum (Cerebel).

B. Phantom Manufacturing

Phantom manufacturing consists of molding the designed tissues and building and assembling the whole head structure.

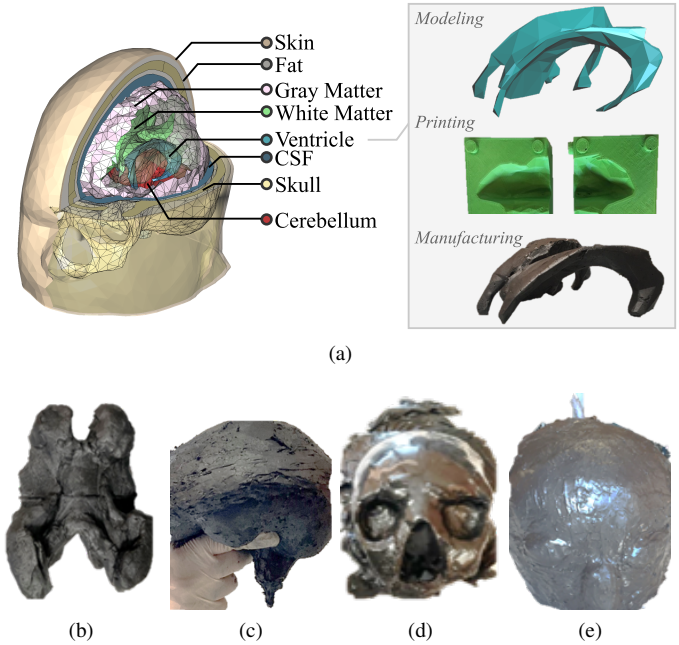


Fig. 3. Phantom manufacturing workflow. (a): Digital model on the left; ventricle model, its mask, and physical model on the right. (b-e): Examples of tissues, from left to right, white matter, CSF's container, skull, and the complete integrated head phantom, respectively.

For the former, we cast multi-piece 3-D printable molds using as a starting point a collection of computer-aided designs (CAD) of the human head taken from the visible human project library and based on computerized tomography and magnetic resonance images of human bodies' cryosections [23], [24]. Each piece is printed employing either polylactic acid (PLA) or acrylonitrile-butadiene-styrene (ABS) filaments, then the components are molded using their respective mixtures. Figure 3 (a) illustrates the sectioned digital model of the head, exampling the process with the ventricle.

For the assembling, we start separately manufacturing the ventricles, cerebellum, and white matter, which are positioned and immersed within the gray matter. Then, the whole brain structure, i.e., ventricles, cerebellum, and white and gray matter, is encapsulated in an external multi-layer made of fat, bone (skull), and skin, keeping an air gap in the CSF area. This region acts as the CSF container that can be filled through a hole in the top of the head. Figure 3 (b-e) show different steps during the phantom production.

III. Experimental Results

This section reports the dielectric properties measured on samples of each emulated tissue, valued within 0.5-2 GHz. Figure 4 summarizes the results, comparing them with the nominal tissue values available in the literature (dashed lines) [21]. It is noted that the nominal reference for the ventricle is equal to the CSF's one and thus is neglected in the plot. Considering the reduced degree of freedom of the mixtures, it was impossible to perfectly match the estimated values with the nominal ones over the whole band, though with a good

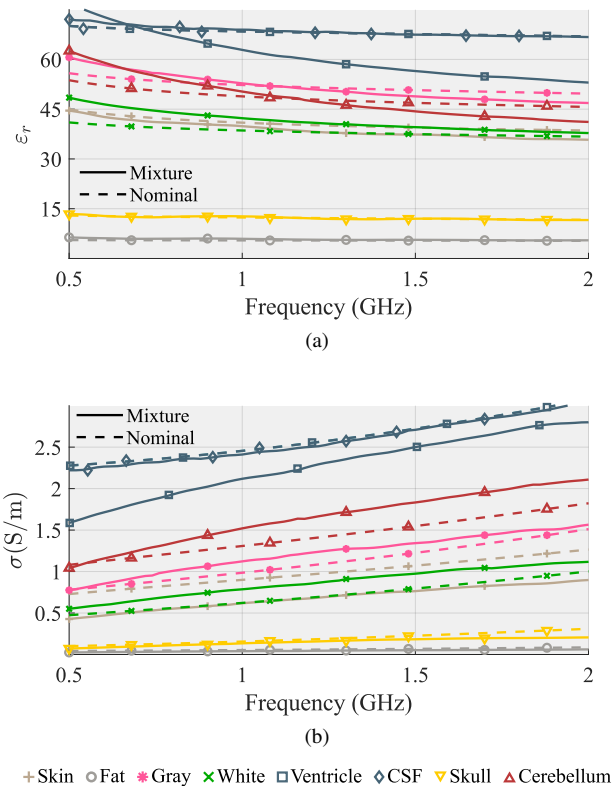


Fig. 4. Comparison of nominal values from database [21], against tissue-mimicked ones, for all studied tissues, respectively. (a): Permittivity. (b): Conductivity.

agreement. To find a trade-off, we opt for a user-based criterion prioritizing the values at 1 GHz, a common working frequency for brain imaging microwave devices [25], [26]. Moreover, only liquid Tr-W mixture allows to modulate separately the values of the dielectric constant and the conductivity, the latter increasing with a higher percentage of salt dissolved in water.

IV. Conclusion and Perspectives

This contribution introduced the design procedure and realization of a complete multi-tissue human head phantom suitable for microwave imaging devices testing, showing customizable features and adaptability, thus to multi-propose assessment scenarios employing two kinds of mimicking mixtures. First, we use an on-testing-adaptable liquid made of water, triton X-100, and salt to emulate the CSF. Second, solid compounds of urethane rubber and graphite powder (available and safe materials) represent a stable anatomical structure. All tissues agree with the nominal dielectric properties available in the literature. The next step is to use the designed phantom in lab testing and validation of microwave imaging devices, such as [4].

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