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# Experimental Phantom for Contrast Enhanced Microwave Breast Cancer Detection Based on 3D-Printing Technology

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**Abstract**—Rapid-prototyping techniques have been used in the past few years to create experimental phantoms for microwave breast cancer detection. After a literature review on existing phantom designs this paper introduces an advanced experimental model which allows for contrast enhanced microwave imaging within a hemispherical multistatic antenna arrangement. The proposed phantom is based on 3D printing technology and consists of geometric inclusions of different sizes which can be filled with tissue-mimicking liquids of varying dielectric contrast. This work is a step forward towards the development of standard breast phantoms that are already available for other modalities for medical diagnostics such as breast ultrasound, MRI etc.

**Index Terms**—Microwave-based breast cancer detection, experimental breast phantom, rapid prototyping, 3D-printing.

## I. INTRODUCTION

Breast cancer is still one of the most dangerous types of cancer for women worldwide [1]. In order to increase the survival rate, early and reliable detection is required in order to initiate moderate ways of breast cancer treatment. A promising alternative to conventional diagnostic methods, such as X-Ray, ultrasound or MRI, is given by microwave imaging [2]. This method uses non-ionizing electromagnetic waves in the frequency range between 500 MHz up to 20 GHz, to determine the dielectric contrast between healthy and malignant tissue [3]. Further advantages are, among others, that microwave imaging is more comfortable for the patient compared to X-ray mammography, since no compression of the breast is needed and devices can be produced in a cost-efficient way. A number of prototype systems have been developed in the past which are tested by tissue-mimicking phantoms (TMM) to evaluate their performance. Based on the well-known clinical large scale study in [3], different TMMs have been developed and tested.

The first goal of this paper is to summarize several quality criteria of TMM in Section II. After that, Section III discusses several ways to create microwave phantoms for biomedical applications. Finally, we propose a new phantom design in Section IV that enables contrast enhanced microwave imaging within a multistatic hemispherical array. This approach not only enables the analysis of different sizes for the inclusion,

but also different materials with varying dielectric contrast. The latter is an important property to evaluate the performance of image reconstruction algorithms.

## II. CHARACTERISTICS OF A HIGH QUALITY MICROWAVE BREAST PHANTOM

There are several quality criteria that describe an appropriate breast TMM-phantom.

- 1) Mechanical properties: Since the breast phantom shall be used to imitate a breast during examination, their size and shape need to be similar to one of a real patient. They should further be anatomical correct regarding flexibility, but also be durable enough to be able to contain/regain their shape after compression [4].
- 2) Dielectric properties: The dielectric properties of TMM can be described by their relative permittivity and conductivity. While the permittivity is mainly influenced by the relative water content [2], the conductivity depends on the presence of ionized molecules. Therefore, the permittivity and conductivity of adipose tissue is relatively low, because it consists mainly of fat, while malignant tissue has a higher water content and hence higher dielectric properties. Both, permittivity and conductivity, change as a function of frequency [3].
- 3) Heterogeneity: The human breast consists of different tissue types, including skin layer, fatty and adipose tissue, glandular structures, muscles, transitional tissue and may also contain malignant tissue, all with different dielectric properties [5], [6]. An ideal breast phantom for testing and valuating microwave based imaging systems should therefore be made of a material that represents the different tissue types in a spatially distributed way by using different ratios of the components to achieve the heterogeneity of a real breast.
- 4) Time-stability: Preclinical studies demand repeated testing over a long period of time. Hence, materials that contain their dielectric properties despite an elongated shelf-life should be used [7]. This reduces costs, saves time and secures reproducibility of data.

- 5) Conservation: To improve the stability over time some materials require conservation like storage in hermetically sealed containers and/or keeping them in a refrigerated environment [8]. Ideally, the TMM should abstain from special conservation, since this can be inconvenient among other things due to the fact that a cooled phantom needs to warm up before measurement or because corresponding facilities or containers are not at hand.
- 6) Expenditure in manufacturing: The phantoms should be easy to manufacture in a typical laboratory environment without depending on expensive machinery [5]. Complicated production steps may lead to defective phantoms and thus to inaccurate data.
- 7) Cost-efficiency: Low costs as well as easy available materials and equipment are elementary.

### III. TYPES OF TISSUE-MIMICKING PHANTOMS

In the last few years several breast tissue-mimicking phantoms have been developed and constructed using different materials. In this section different kinds of TMMs, grouped based on their main substance, are introduced and their properties, as well as their specific characteristics are described. More detailed reviews about TMMs are given in the papers by O'Halloran et al. [7] and Lazebnik et al. [9].

#### A. Water-based

The relative permittivity and effective conductivity are primarily related to the amount of water content in the tissue. Hence, a reasonable projection for biomedical imaging was to develop low-cost tissue mimicking materials featuring water. Most water-based tissue-mimicking phantoms consist mainly of saline mixed with glycerin or polyethylene and a gelling agent, such as TX150 and T151 [9], [10], [11]. Because these TMM are based on water, heterogeneous models are hard to build. In one the most recent practices of this kind of material Klemm et al. [10] measured the dielectric properties over frequencies reaching from 3 GHz to 10 GHz. Those applications do not require realistic skin layers in perspective of mechanical and dielectric properties. Thus rigid plastic shells were used to contain the fragile water-based TMMs, that prevent the phantom from compression [5]. Another disadvantage is that water-based breast phantoms suffer from evaporation and solvent diffusion, what leads to an undesirable change of the dielectric properties. Keeping them in hermetically shut containers, away from air exposure elongates their service life up to several weeks [9].

#### B. Oil-in-gelatine

Another type of TMM material is based on oil-in-gelatine. These are the most commonly utilized phantoms and can be realized via compositions of oil, water and a gelling agent or a formaldehyde emulsion [12], as well as other reagents like NaCl or propylene-glycol. In the majority of cases the oil was a mixture of equivalent amounts of kerosene and safflower oil [13]. By varying the content of oil in the mixture, different

high- and low-water content TMM materials can be generated, which can be used to build complex breast phantoms, with the aid of molds. These models displayed very good dielectric properties over the tested area ranging from 500 MHz to 20 GHz [9], were flexible and did not require shells like the water-based phantoms. Like for the water-based TMM most of the materials are affordable, as well. However, in this kind of material evaporation is still a problem, appropriate conservation, in a refrigerator and air-tight, lead to shelf life ranging from 5 days [12] to 9 weeks [9]. Other disadvantages are that the manufacturing process is more complex, than the ones for other TMMs and the phantoms may be stable without a shell but are not very durable.

#### C. Triton X100

Polyethylene-glycol-mono-phenylether, also known as Triton X100, is a non-ionic detergent usually used for cell lysis and to make proteins soluble for biochemical applications. Furthermore, the surfactant has been utilized as a head tissue-mimicking material in narrow-band frequencies [14]. Solutions of Triton X100 with different percentages of deionized water have been created and characterized in the frequency range up to 12 GHz. The obtained relative permittivity and effective conductivity values were in good agreement with the dielectric properties of real human breast tissue. The conductivity was even enhanced by Joachimowicz et al. [15] via adding NaCl to the mixture. Phantoms consisting of this TMM are very stable in time, at least one year without particular conservation, as well as they are over temperature. Since Triton X100 solutions are liquid at room-temperature, molds are required. Heterogeneous phantoms can be build, with complex molds featuring separated cavities that can be filled with different solutions [14], [15]. Compared to other TMMs Triton X100 is rather expensive.

#### D. 3-D printed

Due to the achievements in the field of 3-D rapid prototyping technologies, that were made over the last few years, it became possible to print very extensive plastic objects, based on precise numerical models. In 2012, Burfeindt et al. [16] used MRI-derived data to build a phantom that featured several cavities, representing glandular structures among adipose tissue. Those excavations were filled with a mixture of deionized water and Triton X100 surfactant to gain an appropriate dielectric contrast between the fatty tissue-mimicking plastic and fibroid-glandular tissue [16]. Since MRI images from a real patient were the basis of the computer model, the resulting breast phantom was anatomical very accurate, especially in perspective of the inner structures. However plastic is too rigid to match the mechanical properties and heterogeneity can only be achieved in combination with other TMMs. The plastic model was characterized over the frequency range of 500 MHz to 3.50 GHz and displayed a effective conductivity and a dielectric constant lower than the values recorded by Lazebnik et al. [3], [16].

Under normal circumstances carbon behaves as a semi-conducting material, but in combination with an insulating matrix it becomes a dielectric, because it induces space charge polarizations at contact surfaces of two materials [5]. Several materials may function as insulating matrices, among them silicon and urethane rubber which both display the flexibility of biological tissue. In 2014, Garrett and Fear [4] found that the latter is more suited, since the phantoms are more durable and easier to manufacture. Further they tested two different carbon powders, namely carbon black and graphite, as conductive filler, with the result that different tissue types are represented best with varying combinations of both varieties. To obtain materials that display high permittivity, the content of carbon black or graphite respective, needs to be high as well [4]. But increased percentages of carbon are correlated with an inferior mixing ability. Hence, Santorelli et al. [17] used the same approach to build a heterogeneous breast model, but added small amounts of acetone as thinning agent to enhance miscibility and hence the permittivity. On the other hand, this TMM provides limited ability for contrast enhanced microwave imaging applications.

All of the models were characterized over the frequency range of 1 GHz to 10 GHz and showed adequate, yet improvable, dielectric properties. Further the phantoms had good time stability, Garrett and Fear [4] reported a deviation of the dielectric properties of 5% after a period of eight month, while no conservation was required.

#### IV. BREAST PHANTOM DESIGN

The discussion above has shown that several ways exist to create experimental phantoms for microwave breast imaging applications. In this paper, we propose a phantom design, shown in Fig. 1, which aims at contrast enhanced microwave imaging. Contrast enhanced microwave imaging is currently being discussed in the literature as a method to enhance the sensitivity of microwave diagnostics. This can be achieved either by the injection of nano-particles [18] or bacterial microbots [19]. The proposed phantom is based on three components: The first part is a hemispherical shape which fits to Bristol's prototype for microwave breast imaging as shown in Fig. 2. This shape is filled with a homogeneous TMM liquid. A holder is placed on top of it which has four vertical bars and multiple options to arrange the third component. This last component is a hollow structure that can be filled with a TMM liquid which has a different permittivity compared to the surrounding TMM material. One opening of that structure is in vertical direction so that air bubbles disappear automatically. This structure can be combined with a pump system as presented in [20]. Three different version of the third component have been manufactured, each with a different diameter of the inclusion. This enables, in addition to a different dielectric contrast, the analysis of different sizes of the artificial tumor.

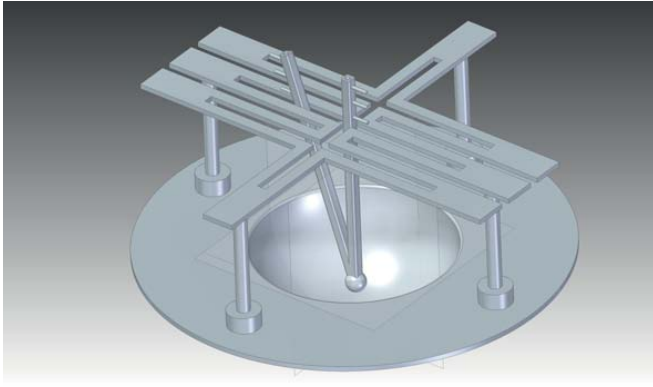
This paper has reviewed several techniques to manufacture experimental phantoms for microwave breast imaging applications. Moreover, we have presented an experimental phantom for microwave breast cancer detection which is based on rapid prototyping techniques. This design enables both, the simulation of contrast enhanced microwave imaging and the simulation of inclusions of different size. The proposed experimental phantom will be used in the future for experimental investigations to evaluate the performance of image reconstruction techniques.

#### ACKNOWLEDGMENT

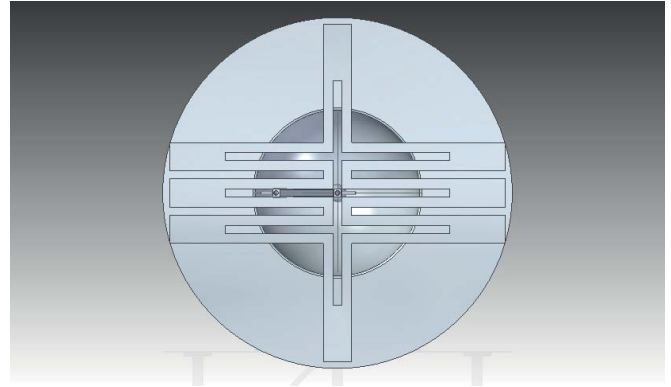
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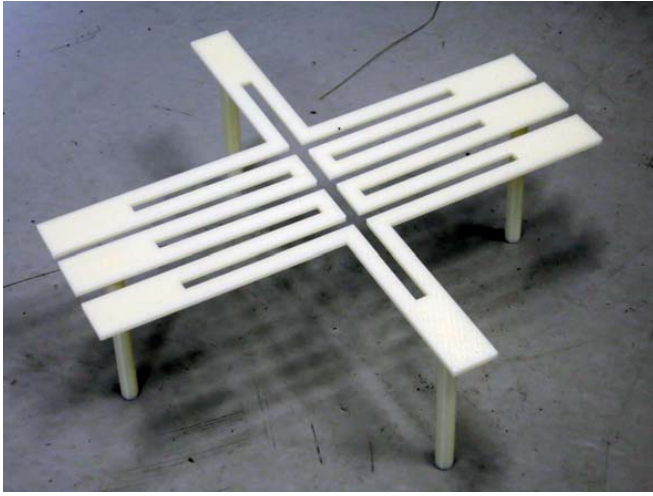
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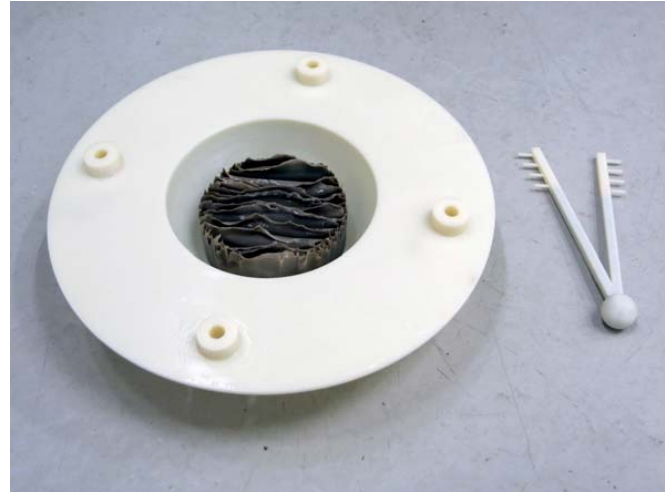
(a)



(b)



(c)



(d)

Fig. 1: (a,b) Drawing of the breast phantom for contrast-enhanced microwave breast imaging in isometric and top view. (c,d) Realized experimental breast phantom.

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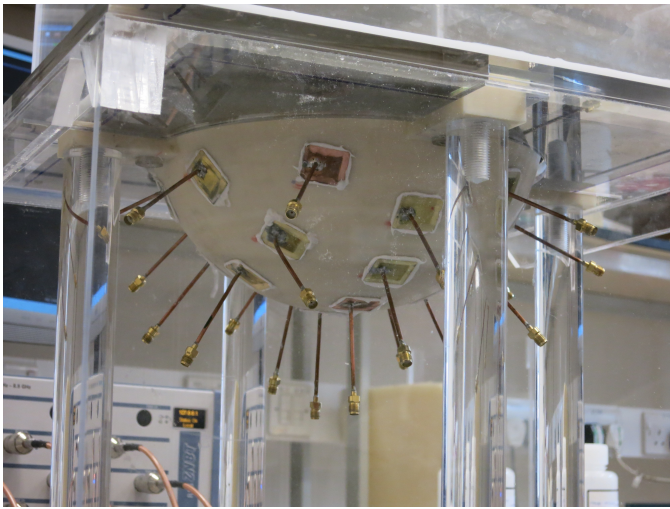


Fig. 2: Experimental prototype system for microwave breast imaging at the University of Bristol.