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CANDIDATE FOR TISSUE MIMICKING MATERIAL MADE OF AN EPOXY MATRIX LOADED WITH ALGINATE MICROSPHERES

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Abstract—We present a new composite material containing calcium alginate microspheres incorporated into an epoxy matrix. The new material is mechanically stable and does not degrade over time. Its dielectric properties are extracted by model calculations and compared to the properties of some selected human tissues. Good agreement is observed, which identifies the proposed composite material as a good candidate for the use as a phantom material. The presented material is a two component composite and it is shown how its effective properties can be predicted by using appropriate mixing formulas.

1. INTRODUCTION

During the last decades, the interest in research related to the interaction of electromagnetic radiation with biological tissues continuously increased. Such situations are present in the cases of medical imaging and therapy (ultrasound [1, 2]), magnetic resonance imaging [2, 3] or computer tomography procedures) or during the

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operation of mobile phones. Therefore, there is a high demand for materials that can mimic in particular human tissue properties and which can be used to build testing phantoms.

Materials used for building phantoms can have tissue equivalent properties at single frequency of interest or in the broad frequency range (such as in low power UWB cancer detection [4]).

Regarding mechanical properties, there are liquid [5, 6], solid [7–10] and gel based phantom materials [11–16]. When liquid mixtures are used, always appropriate containers are needed that hold the liquid. Solid materials, such as polymers loaded with carbon, exhibit high dielectric values and are thus not suitable to mimic tissues such as breast fat which the dielectric properties are relatively low.

There are materials which contain substances such as honey syrup or egg whites [17, 18]. These materials are also proposed as phantom materials because their properties at some frequencies agree with tissue properties.

The gel based materials are usually easy and cheap to manufacture. They can mimic tissues with low dielectric properties. Problems with these materials are their limited mechanical stability, durability, and inability to produce layered structures where the layers have different characteristics.

The material that we propose is composed of calcium alginate (Ca-alg) hydrogel microspheres incorporated into a hard epoxy matrix. The proposed material overcomes some shortcomings of the purely gel based materials. It is mechanically stable, easy to mold in different shapes, and its properties are stable over time. The material is composed of two components and it is possible to predict theoretically the effective permittivity and conductivity of samples with different volume fractions of inclusions.

The paper describes the procedure of the material synthesis and the characterization and presents the properties as well as the comparison of the dielectric properties with the properties of some tissues. Conclusion about the future work complete the paper.

2. MATERIAL SYNTHESIS AND CHARACTERIZATION

2.1. Material Synthesis

Alginic acids or alginates are anionic polysaccharides that are extracted from the cell walls of brown algae. Their sodium salts (Na-alg) are water-soluble. The interaction with divalent cations such as Ca^{2+} or Ba^{2+} yields hydrogels usually containing over 90% of water. Various technologies yield spherical hydrogels with diameters in the range of a few microns to few millimeters. The idea to incorporate empty and iron loaded alginate microspheres into an epoxy matrix was presented for the first time in [19]. The initial motivation for such work was related to the design of absorbing materials which exhibit low reflection and good absorption properties at microwave frequencies up to 360 GHz.

Procedures for preparing Ca-alg spheres as well as composite samples are described in detail in [19] and will briefly be repeated here.

A clear Na-alg solution (100 ml, 2 wt%) was obtained by dissolving Na-alg powder (Kelton LV, lot No. 46198 Kelco, San Diego, CA, USA) under slight warming and constant mixing for 45 minutes. The aqueous gelation bath contained 2 wt% completely dissolved $CaCl_2$. The Na-alg solution was extruded through a needle (needle diameter was 0.8 mm) into the gelation bath where gelation was completed after approximately 3 min. Ca-alg spheres with diameters in the range of 350 to 500 μm were obtained and separated from the bath by filtration.

The separated Ca-alg spheres were incorporated into an epoxy matrix. Stycast W19 (W19) and Stycast 2850 FT (S2850) from Emerson and Cuming Company were used. The two epoxies differ in their dielectric properties and viscosity. S2850 epoxy is loaded with alumina and has a higher permittivity and conductivity then W19 epoxy, however, both epoxies exhibit low losses. Figure 1 presents the comparison of the dielectric permittivity and conductivity of the two epoxies. The results presented in Figure 1 are taken from [20]. W19 epoxy is less viscous than S2850 and can thus accept a higher volume fraction of inclusions.

The composite samples were prepared in the following way. 100 g

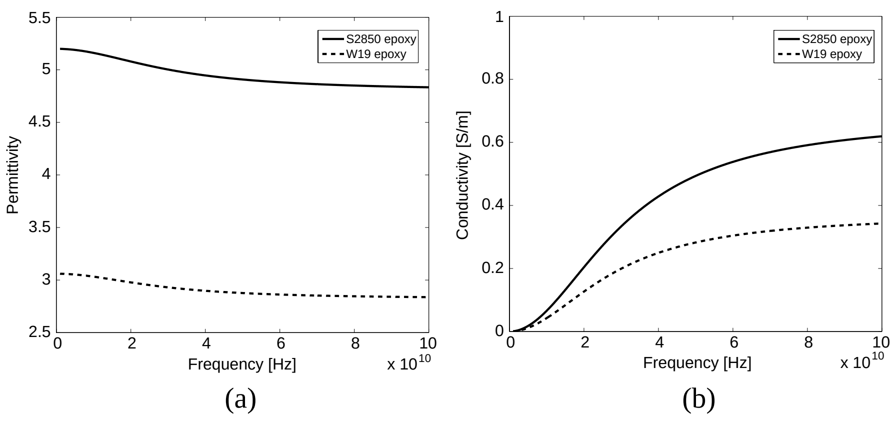

Figure 1. Frequency dependent permittivity and permeability of S2850 and W19 epoxies.

of W19 is mixed with 15 g of C9 hardener and 35 g of Ca-alg spheres are added. The mixture is poured into silicone molds and left 24h at room temperature to cure. The samples were of circular plane-parallel shape (Figure 2). Procedure is repeated for the S2850 epoxy (100 g of S2850 is mixed with 4 g of C9 hardener and into that mixture 7 g of Ca-alg spheres are added). At higher filling ratios, a vacuum chamber can be useful to remove air bubbles.

Figure 2. Fabricated sample of W19 epoxy and Ca-alg spheres as inclusions.

The two samples contain different volume fractions of Ca-alg microspheres, 23 vol% in case of W19 epoxy and 13 vol% in case of S2850.

2.2. Dielectric Parameters Extraction

2.2.1. Effective Dielectric Parameters

The effective dielectric parameters of the two composites are extracted by following a procedure described in [20]. Samples that we examined are of plane parallel circular shape (Figure 2) and composite material is non-magnetic. It means material has only dielectric characteristics. Complex and frequency dependent dielectric permittivity is modeled with Debye model (Eq. (1)). Transmission parameter is measured with two aligned corrugated horn antennas (connected to the VNA) and sample is placed on the aperture of one antenna. Measured transmission parameter is fitted with simulated S_{21}, both amplitude and phase. From the fitting procedure, unknown Debye model parameters of composite materials are extracted. Real part of Debye model represents effective dielectric permittivity, while imaginary part, when transformed with Eq. (2), represent effective conductivity of the composite.

$$\varepsilon(f) = \varepsilon_\infty + \frac{\varepsilon_s + \varepsilon_\infty}{1 + j\frac{f}{f_r}} \tag{1}$$

where f is the frequency, ε_s the static dielectric permittivity, ε_∞ the permittivity at infinite frequency (optical permittivity), and f_r the relaxation frequency.

$$\sigma = \frac{\varepsilon''}{60 \cdot \lambda} \tag{2}$$

where σ is the conductivity, and λ stays for the wavelength.

Figure 3 represents extracted effective dielectric parameters of two synthesized composites. For comparison, breast fat dielectric parameters (taken from [30]) are on the same graph.

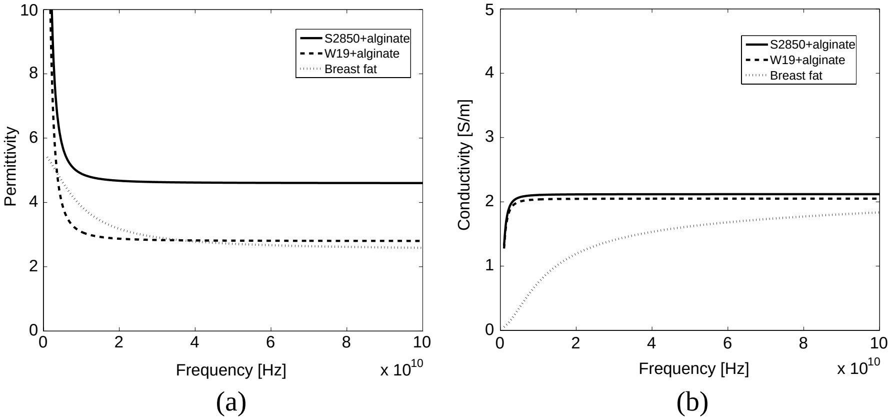

Figure 3. Extracted effective permittivity and conductivity of S2850 and W19 epoxy composites. For comparison, breast fat dielectric parameters are also presented.

2.2.2. Mixing Formulas

There are some examples in literature [21–25] related to numerical predictions and estimations of dielectric parameters of the tissue mimicking composites. Composite material that we propose consists of two components and is homogeneous with respect to the observed frequencies (Ca-alg spheres are much smaller than the wavelength). For these reasons, its effective parameters follow known mixing rules. Thus, mixing formulas are developed to quantitatively predict the effective complex permittivity of the composite materials by knowing the dielectric properties of its constituents. Different mixing formulas are discussed and examined in [26–29]. Looyenga (Eq. (3)), Maxwell-Garnett (Eq. (4)) and Lichtenecer (Eq. (5)) formulas are some examples of popular mixing rules. The relationship between the imaginary permittivity and the conductivity is given in Eq. (2).

$$\varepsilon_{eff}^{\frac{1}{3}} = v_1 \cdot \varepsilon_1^{\frac{1}{3}} + (1 - v_1)\varepsilon_2^{\frac{1}{3}} \tag{3}$$

$$\varepsilon_{eff} = \frac{\varepsilon_2 \cdot (\varepsilon_1 \cdot (1 + 2 \cdot v_1) - \varepsilon_2 \cdot (2 \cdot v_1 - 2))}{\varepsilon_2 \cdot (2 + v_1) + \varepsilon_1 \cdot (1 - v_1)} \tag{4}$$

$$\varepsilon_{eff} = \varepsilon_1^{v_1} \cdot \varepsilon_2^{(1-v_1)} \tag{5}$$

where ε_{eff} is the complex effective permittivity of the composite material, ε_1 is the complex permittivity of inclusions, ε_2 is the complex permittivity of the host matrix and v_1 is a volume fraction of the inclusions in the host matrix.

In order to allow for predicting the effective properties of samples containing different volume fractions of inclusions, it is necessary to extract the dielectric properties of the Ca-alg spheres themselves. That is done for both epoxy composites by using the Looyenga formula (Eq. (3)). The extracted permittivity and conductivity are represented in Figure 4. There is a very good agreement between the parameters extracted from the samples made of the two different epoxies and containing different volume fractions of inclusions.

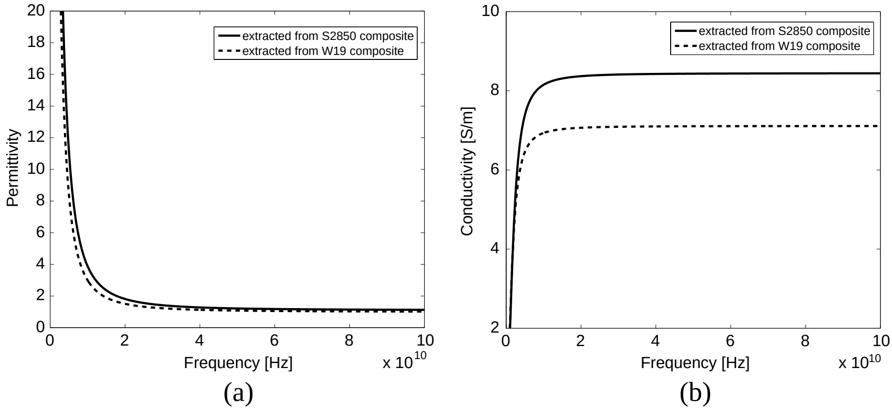

Figure 4. Extracted permittivity and conductivity of Ca-alg spheres from S2850 and W19 epoxy composites.

According to [26], the Lichtenecker formula (Eq. (5)) is more accurate in predicting the real part of the effective complex permittivity, while the imaginary part (conductivity) can be predicted with a lower error by using the Maxwell Garnett model (Eq. (4)). Following these statements, we calculated the effective permittivity and conductivity of samples containing different amounts of Ca-alg sphere inclusions. The results are presented in Figures 5 and 6. As expected, resulting dielectric properties of composite material depend on volume fraction of inclusions.

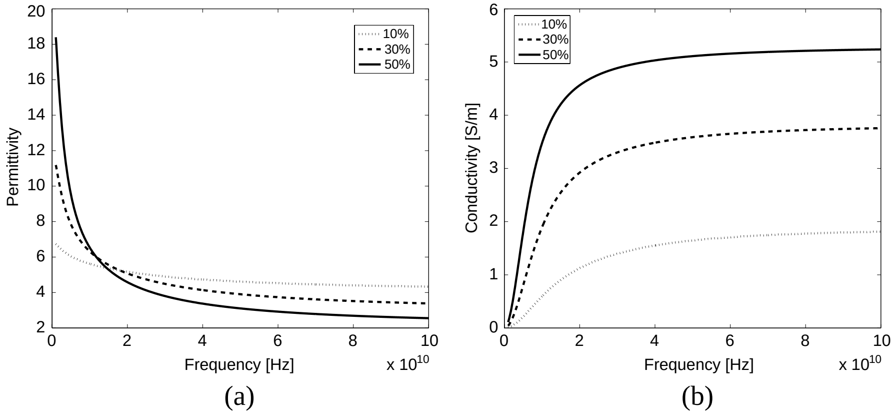

Figure 5. Calculated permittivity and conductivity of composites of S2850 with varying volume fraction of Ca-alg inclusions.

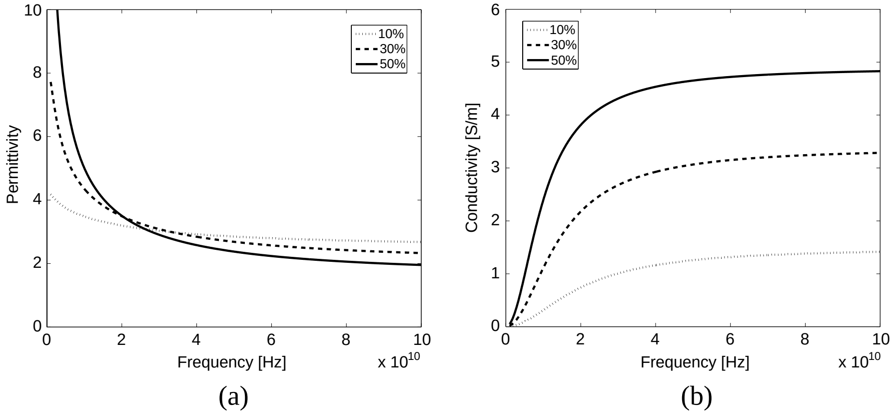

Figure 6. Calculated permittivity and conductivity of composites of W19 with varying volume fraction of Ca-alg inclusions.

3. RESULTS AND DISCUSSION

Figure 3 shows extracted effective dielectric parameters of fabricated samples. It is seen that parameters of the fabricated composite containing alginate microspheres incorporated into W19 epoxy matrix are in very good agreement with a breast fat dielectric parameters.

Comparing Figures 5 and 6, a difference becomes obvious between the effective parameters calculated for the samples prepared with S2850 or W19 epoxies. This results from the initial differences in the epoxy

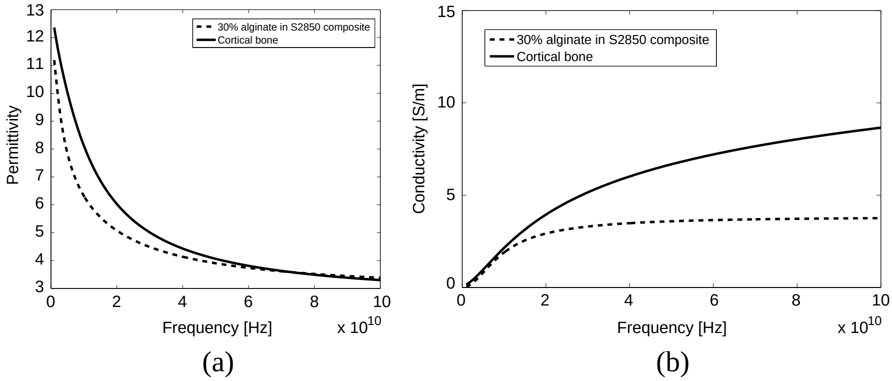

Figure 7. Comparison of permittivity and conductivity of S2850 composite with 30 vol% of Ca-alg inclusions with cortical bone parameters.

parameters (presented in Figure 1). This difference can be used for fine tuning of the composite properties in order to achieve desired parameter values.

Figure 7 represents predicted effective parameters of composites containing 30 vol% of Ca-alg spheres incorporated into S2850 epoxy. The values of the dielectric parameters of cortical bone, which were taken from [30], are plotted in the same figure for comparison. In general, very good agreement over the entire frequency range exists between the dielectric properties of low water content tissues (breast fat, cortical bone, filtrated and infiltrated fat, etc.) and the proposed new material.

This demonstrates that the proposed composite material has the potential to be used as a phantom material. The dielectric properties of the composite can be tuned for a specific range of interest by varying the volume fraction of the Ca-alg spherical inclusions and by using different epoxy materials as a matrix.

Epoxy samples with inclusions of Ca-alg spheres containing iron particles were also prepared and examined. Figure 8 presents a microphotograph of Ca-alg sphere homogeneously loaded with iron microparticles (size of iron particles was a few microns). In this way, the dielectric properties of the resulting composite are further increased but also magnetic permeability of the composite is introduced since iron is a magnetic material. In order to increase the dielectric properties of the resulting composites, Ca-alg microspheres can be loaded with carbon nano particles, for example. The samples described herein have a circular plane-parallel shape due to the shape of the

Figure 8. Photograph of Ca-alg microsphere homogeneously loaded with iron particles.

silicone mold in which they are cured. However, any other shape can be produced using a mold of the desired geometry.

4. CONCLUSIONS

We presented a composite material that contains Ca-alg microspheres incorporated into epoxy resin. So far, polysaccharides are used as tissue mimicking materials, but their use is restricted by several factors. They are difficult to handle (they must be in airtight containers or need special holders), non-durable (parameters change over time), mechanically sensitive, etc.. The proposed composite material overcomes the restricting factors and can be cast in any arbitrary shape. In order to increase the values of the dielectric parameters and to produce a material that will cover even a broader range of tissue properties, microencapsulation of carbon particles within alginate microspheres and as such incorporated into an epoxy matrix is intended.

REFERENCES

1. Madsen, E. L., E. Kelly-Fry, and G. R. Frank, "Anthropomorphic phantoms for assessing systems used in ultrasound imaging of the compressed breast," *Ultrasound in Medicine and Biology*, Vol. 14, 183–201, 1988.
2. Surry, K. J. M., H. J. B. Austin, A. Fenster, and T. M. Peters, "Poly (vinyl alcohol) cryogel phantoms for use in ultrasound and MR imaging," *Physics in Medicine and Biology*, Vol. 49, 5529–5546, 2004.
3. Fong, M. P., D. C. Keil, M. D. Does, and J. C. Gore, "Polymer gels for magnetic resonance imaging of radiation dose distributions

at normal room atmosphere," *Physics in Medicine and Biology*, Vol. 46, 3105–3113, 2001.

4. Davis, S. K., H. Tandradinata, S. C. Hagness, and B. D. Van Veen, "Ultrawideband microwave breast cancer detection: A detection-theoretic approach using the generalized likelihood ratio test," *IEEE Transactions on Biomedical Engineering*, Vol. 52, 1237–1250, 2005.
5. Fukunaga, K., K. S. Watanabe, and Y. Yamanaka, "Dielectric properties of tissue-equivalent liquids and their effects on specific absorption rate," *IEEE Transactions on Biomedical Engineering*, Vol. 46, 126–129, 2004.
6. Fukunaga, K., S. Watanabe, H. Asou, and K. Sato, "Dielectric properties of non-toxic tissue-equivalent liquids for radiowave safety tests," *2005 IEEE International Conference Dielectric Liquids*, Vol. 26, 425–428, 2005.
7. Chang, J. T., M. W. Fanning, P. M. Meaney, and K. D. Paulsen, "A conductive plastic for simulating biological tissue at microwave frequencies," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 42, 76–81, 2000.
8. Youngs, I. J., A. S. Treen, G. Fixter, and S. Holden, "Design of solid broadband human tissue simulant materials," *IEE Proceedings Science, Measurements and Technology*, Vol. 149, 323–328, 2002.
9. Gabriel, C., "Tissue equivalent material for hand phantoms," *Physics in Medicine and Biology*, Vol. 52, 4205–4210, 2007.
10. Nikawa, Y., M. Chino, and K. Kikuchi, "Soft and dry phantom modeling material using silicone rubber with carbon fiber," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, 1949–1953, 1996.
11. Lazebnik, M., E. L. Madsen, G. R. Frank, and S. C. Hagness, "Tissue-mimicking phantom materials for narrowband and ultrawideband microwave applications," *Physics in Medicine and Biology*, Vol. 50, 4245–4258, 2005.
12. Mazzara, G. P., R. W. Briggs, Z. Wu, and B. G. Steinbach, "Use of a modified polysaccharide gel in developing a realistic breast phantom for MRI," *Magnetic Resonance Imaging*, Vol. 14, 639–648, 1996.
13. Kato, H., M. Hiraoka, and T. Ishida, "An agar phantom for hyperthermia," *Medical Physics*, Vol. 13, 396–398, 1986.
14. Robinson, M. P., M. J. Richardson, J. L. Greent, and A. W. Preece, "New materials for dielectric simulation of tissues,"

Physics in Medicine and Biology, Vol. 36, 1565–1571, 1991.
15. Mitchell, M. D., H. L. Kundel, L. Axel, and P. M. Joseph, "Agarose as a tissue equivalent phantom material for NMR imaging," *Magnetic Resonance Imaging*, Vol. 4, 263–266, 1986.
16. In, E., H. E. Naguib, and M. Haider, "Fabrication and characterization of polymer gel for MRI phantom with embedded lesion particles," *Proceeding of SPIE*, Vol. 8348, 2012.
17. Freed, M., J. A. de Zwart, J. T. Loud, R. H. E. Khouli, K. J. Myers, M. H. Greene, J. H. Duyn, and A. Badano, "An anthropomorphic phantom for quantitative evaluation of breast MRI," *Medical Physics*, Vol. 38, 743–753, 2011.
18. Sunaga, T., H. Ikehira, S. Furukawa, M. Tamura, E. Yoshitome, T. Obata, H. Shinkai, S. Tanada, H. Murata, and Y. Sasaki, "Development of a dielectric equivalent gel for better impedance matching for human skin," *Bioelectromagnetics*, Vol. 24, 214–217, 2003.
19. Zivkovic, I., C. Wandrey, and B. Bogicevic, "Alginate beads and epoxy resin composites as candidates for microwave absorbers," *Progress In Electromagnetics Research C*, Vol. 28, 127–142, 2012.
20. Zivkovic, I. and A. Murk, "Free-space transmission method for the characterization of dielectric and magnetic materials at microwave frequencies," *Microwave Materials Characterization*, 73–90, InTech, Rijeka, Croatia, 2012.
21. Leonard, J. B., K. R. Foster, and T. W. Athey, "Thermal properties of tissue equivalent phantom materials," *IEEE Transactions on Biomedical Engineering*, Vol. 31, 533–536, 1984.
22. Bini, M., A. Ignesti, L. Millanta, R. Olmi, N. Rubino, and R. Vanni, "The polyacrylamide as a phantom material for electromagnetic hyperthermia studies," *IEEE Transactions on Biomedical Engineering*, Vol. 31, 317–322, 1984.
23. Hartsgrove, G., A. Kraszewski, and A. Surowiec, "Simulated biological materials for electromagnetic radiation absorption studies," *Bioelectromagnetics*, Vol. 8, 29–36, 1987.
24. Kanda, M. Y., M. Ballen, S. Salins, C. K. Chou, and Q. Balzano, "Formulation and characterisation of tissue equivalent liquids used for RF densitometry and dosimetry measurements," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, 2046–2056, 2004.
25. Lopresto, V., R. Pinto, R. Lodato, G. A. Lovisolo, and M. Cavagnaro, "Design and realization of tissue-equivalent dielectric simulators for dosimetric studies on microwave antennas

for interstitial ablation," *Physica Medica*, Vol. 28, 245–253, 2012.

26. Kiley, E. M., V. V. Yakovlev, K. Ishizaki, and S. Vaucher, "Applicability study of classical and contemporary models for effective complex permittivity of metal powders," *Journal of Microwave Power and Electromagnetic Energy*, Vol. 46, 2012.
27. Sihvola, A., *Electromagnetic Mixing Formulas and Applications*, IEE Electromagnetic Waves Series, Vol. 47, TJ International, UK, 1999.
28. Merrill, W. M., R. E. Diaz, M. M. Lore, M. C. Squires, and N. G. Alexopoulos, "Effective medium theories for artificial materials composed of multiple sizes of spherical inclusions in a host continuum," *IEEE Transactions on Antennas and Propagation*, Vol. 47, 142–148, 1999.
29. Yang, R. B., S. D. Hsu, and C. K. Lin, "Frequency-dependent complex permittivity and permeability of iron-based powders in 2–18 GHz," *Journal of Applied Physics*, Vol. 105, 2009.
30. Gabriel, S., R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues," *Physics in Medicine and Biology*, Vol. 41, 2271–2293, 1996.