

PEG-100 Stearate Based Emulsification for Tissue Phantom Development, Covering Relative Permittivity Values from 7 to 77

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Abstract—Phantoms are an essential part of the testing procedure for wearable and implantable devices. There are various ways of developing phantoms in different forms. Here PEG-100 Stearate is proposed to be used as an emulsifying agent to create a wide-band liquid phantom. The protocol to develop the phantom is detailed along with the analysis of the effect of each component on dielectric properties. The protocol is demonstrated through a muscle phantom, a bone phantom and a phantom representing human average with a wide-band performance where the dielectric properties are mimicked between 1 GHz and 6.7 GHz with less than 10% error.

Index Terms—phantoms, human tissues, body area networks, wearable antennas, implantable antennas.

I. INTRODUCTION

In the growing field of wearable and implantable technologies, phantoms that mimic the dielectric properties of human tissues have a critical role in testing. The conductivity and relative permittivity of the phantom can be tuned separately. It can be argued that tuning the conductivity is relatively easier than the permittivity. While salt is the most commonly used conductivity-tuning agent, glycerol is used to tune the derivative of the conductivity curve which can be used for wide-band tuning [1].

The permittivity of human tissues ranges from 3 to 77 at 1 GHz since they contain varying amounts of water [2]. To match the relative permittivity of the phantom to a target tissue, one can start from pure water and use a permittivity-decreasing agent. Some of the known agents commonly used in the literature that lower the permittivity of the water and mimic the human tissues in a wide frequency range include oil [3], Triton X-100 (TX-100) [4], acetonitrile [5], polyethylene powder [6], dithylen glycol butyl ether (DGBE) [7], ECOSURF SA-9 [8], Tween [9], ethanol [10], isopropanol [11], sugar [12] and acrylamide [13].

If oil, the most cost-effective option, is chosen as the permittivity-decreasing agent, a surfactant is required to emulsify the oil and water homogeneously. Previous studies have utilized various emulsifiers such as TX-100, ECOSURF SA-9, Tween. Although TX-100 has been used widely, it is not cost-effective and the safety data sheet (SDS) claims that it causes skin irritation, serious eye damage and it is toxic to aquatic life. Similarly, ECOSURF SA-9 is a costly option as opposed to other options. For example, detergents have been used broadly as a cost-effective emulsifier [14], but they can cause bubbles

and affect the homogeneity and stability of the phantom. In this study, Polyethylene Glycol (PEG) 100 Stearate is selected due to its cost-effectiveness and non-toxicity.

PEG-100 stearate is a type of non-ionic surfactant made by combining PEG-100 with stearic acid. PEG-100 stearate has never been used as an emulsifier in a phantom before to the best of the authors' knowledge. In addition to its emulsification performance, its effect on permittivity and conductivity is analyzed here.

In Fig. 1, you can find a comparison of our phantom proposal with other phantoms in the literature. It can be seen that the proposed phantom distinguishes itself by its wide-band, cost-effective and ability to cover low permittivity tissues. Additionally, it stands out from [3] and [5] for being non-toxic. The composition and the protocol are detailed in Section II. The effect of each ingredient on the dielectric properties is presented in Section III. Section IV gives three examples: muscle tissue, bone tissue and human average. Finally, the paper concludes in Section V.

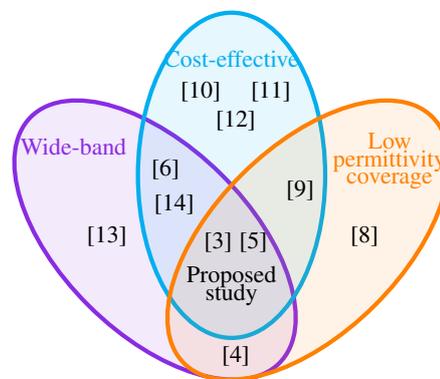


Fig. 1: A comparison of the proposed study with human tissue mimicking phantoms in the literature.

II. PHANTOM COMPOSITION AND PROTOCOL

The ingredients of the proposed phantom are water, PEG-100 stearate, oil, glycerol and salt. High and low permittivity values can be covered by mixing varying amounts of water, oil and PEG-100 stearate, and the conductivity can be adjusted by adding salt and glycerol. The electrical property analysis of the proposed tissue mimicking phantoms is conducted using SPEAG DAK 3.5 [15] probe as seen in Fig. 2.



Fig. 2: Measurement of the proposed phantoms using SPEAG DAK 3.5 dielectric assessment kit.

The development of the proposed phantoms follows the steps outlined in Fig. 3. First, a mixture of salt, glycerol, and water is stirred and heated until it becomes homogeneous and reaches 60°C . In a separate beaker, the PEG-100 stearate and sunflower seed oil are also stirred and heated until they form a homogeneous mixture at 60°C . Next, the water mixture is gradually poured into the PEG-100 stearate mixture while stirring continuously until the combined mixture reaches 80°C . Heating is then turned off, and the mixture is stirred until it cools to room temperature. The phantom should be stored in a closed container to prevent water loss from evaporation, which could change the phantom's dielectric properties over time. Note that the shelf life of the phantom can be extended using antimicrobial agents, which is left out of the scope of this paper.

III. TUNING THE DIELECTRIC PROPERTIES

A. Relative Permittivity Tuning: Effect of PEG-100 and Sunflower Seed Oil

The relative permittivity tuning of the phantom can be divided into two regions. For relative permittivity values higher than 50 at 1 GHz, the phantom can be developed without the addition of the sunflower seed oil. For lower values, the addition of oil becomes essential since the PEG-100 stearate and water mixture becomes too viscous for these values.

Fig. 4 shows the mixtures with increasing PEG-100 stearate concentrations. These mixtures demonstrate how the relative permittivity of water decreases as the PEG-100 stearate concentration is increased, as presented in Fig. 5. It can be observed that this effect is across the whole band. In a similar fashion, the conductivity decreases with increasing the PEG-100 stearate as seen in Fig. 6. However, the decrease is more prominent at the higher end of the band.

For relative permittivity values lower than 50, the effect of varying concentrations of sunflower seed oil on relative

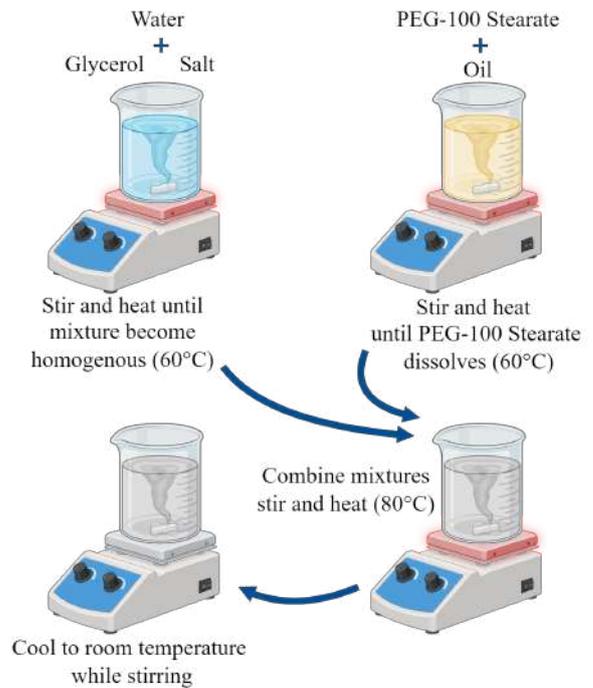


Fig. 3: Phantom composition steps. Created with BioRender.com.



Fig. 4: Phantoms with PEG-100 stearate concentration increasing from left to right.

permittivity and conductivity of the PEG-100 stearate and water mixture are shown in Fig. 7 and Fig. 8. The permittivity decreasing effect across the whole band, as well as the decrease in conductivity, is similar to that observed with the PEG-100 stearate.

B. Conductivity Tuning: Effect of Salt and Glycerol

The conductivity of the phantom can be adjusted by salt and glycerol. The well-known effect of salt on increasing the conductivity of water is illustrated in Fig. 10, and it has a minimal impact on the relative permittivity of water, as shown in Fig. 9. In addition to salt, glycerol can be used in the phantom recipe to change the rate of change in conductivity with respect to frequency. Therefore, it provides one more point of freedom for wide-band tuning. The effect of the glycerol on the conductivity of salted water can be seen in

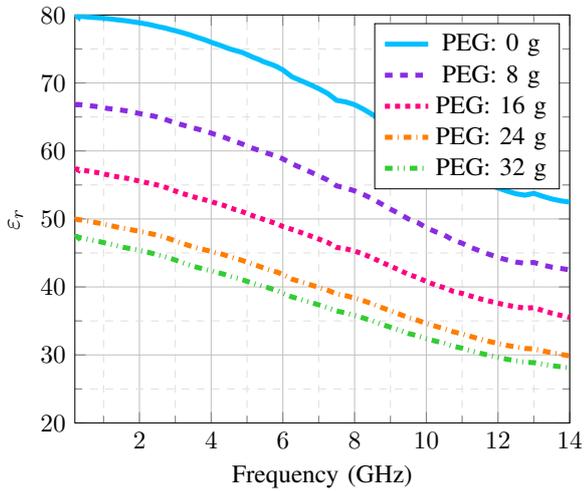


Fig. 5: The relative permittivity of varying concentrations of PEG-100 stearate in 100 ml of water.

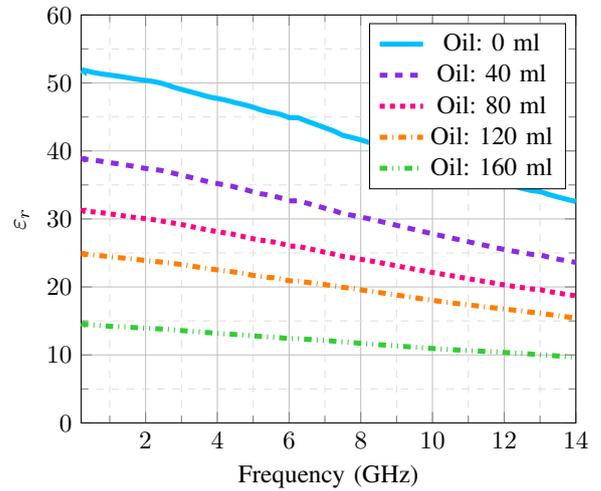


Fig. 7: The relative permittivity of varying concentrations of sunflower seed oil in 100 ml of water containing 18 g of PEG-100 stearate.

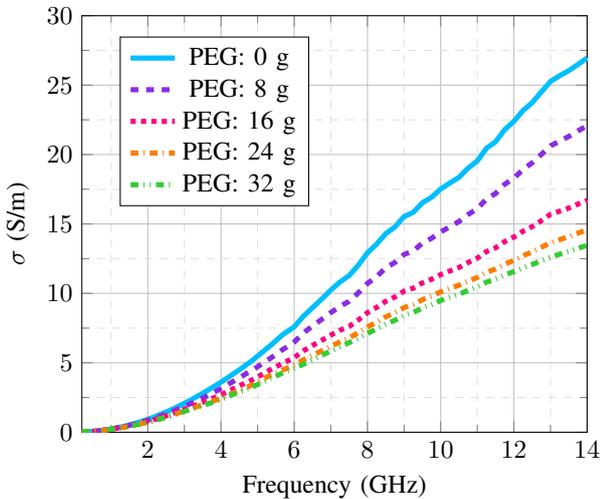


Fig. 6: The conductivity of varying concentrations of PEG-100 stearate in 100 ml of water.

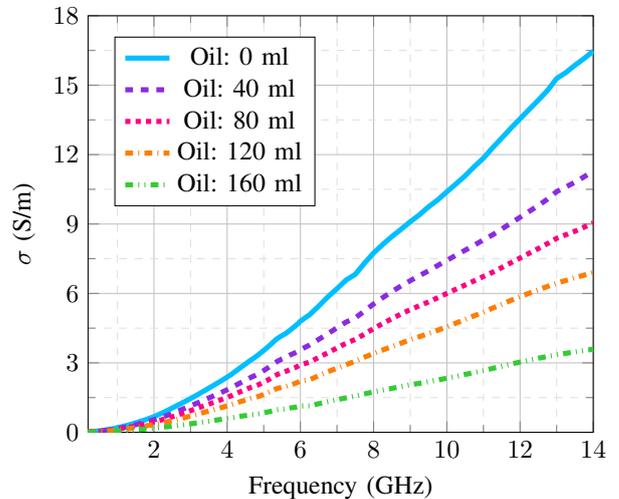


Fig. 8: The conductivity of varying concentrations of sunflower seed oil in 100 ml of water containing 18 g of PEG-100 stearate.

Fig. 12. It should be noted that glycerol has a decreasing effect on the relative permittivity of salted water as shown in Fig. 11. Therefore, the concentrations of glycerol and other permittivity-reducing agents should be considered together when formulating the phantom recipe.

IV. RECIPES FOR SELECTED TISSUES

To demonstrate the proposed protocol, three example of phantoms are developed: a muscle tissue phantom, a bone tissue phantom and a phantom representing human average. These tissues were selected based on their relative permittivity values, representing the start, middle, and end of the permittivity scale.

A. Human Muscle

The proposed human muscle phantom consists of 100 ml water, 16.2 g PEG-100 stearate and 0.25 g salt. All the

ingredients for muscle phantom can be stirred into one beaker until the mixture becomes homogeneous. Note that there is no oil in this mixture. The permittivity and conductivity of the phantom covers a frequency range from 1 GHz to 7 GHz under 10% error as seen in Fig. 13.

B. Bone Cortical

The proposed human bone cortical phantom consists of 100 ml water, 22.6 g glycerol, 177.4 ml sunflower seed oil, 9.7 g PEG-100 stearate and 0.97 g salt. The permittivity and conductivity of the phantom cover a wide frequency range from 1 GHz to 6.7 GHz within a 10% error margin as seen in Fig. 14. It should be noted that to achieve lower permittivity values, the oil-to-water ratio must exceed 1. Therefore, a high-

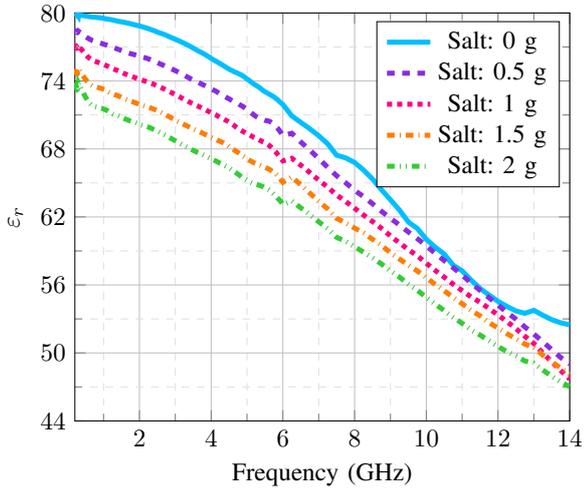


Fig. 9: The relative permittivity of varying concentrations of salt in 100 ml of water.

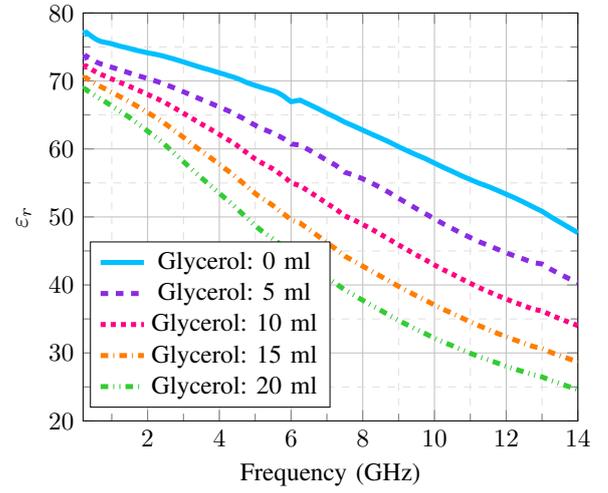


Fig. 11: The relative permittivity of varying concentrations of glycerol in 100 ml of water containing 1 g of salt.

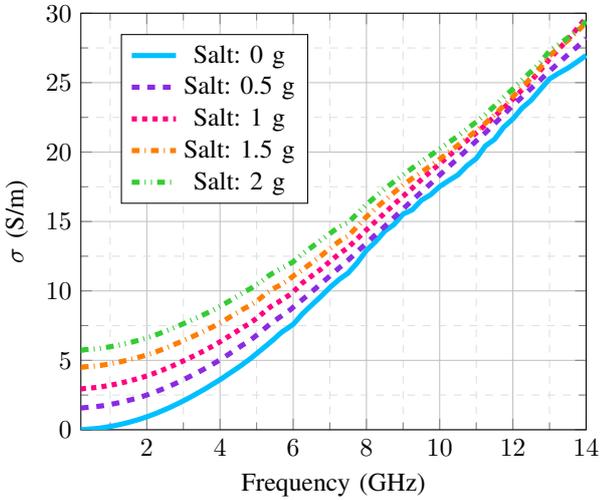


Fig. 10: The conductivity of varying concentrations of salt in 100 ml of water.

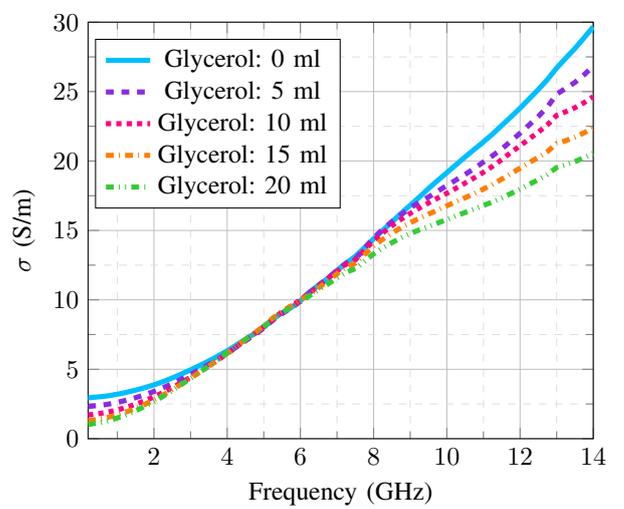


Fig. 12: The conductivity of varying concentrations of glycerol in 100 ml of water containing 1 g of salt.

speed mixer has been used to ensure the mixtures with high oil ratios become homogeneous.

C. Human Average

The phantom that represents human average consists of 100 ml water, 16.7 g glycerol, 77.3 ml sunflower seed oil, 16.7 g PEG-100 stearate and 1.92 g salt. The permittivity and conductivity of the phantom cover a frequency range from 1 GHz to 7 GHz within a 10% error margin as seen in Fig. 15.

V. CONCLUSION

This study presents the development of a wide-band liquid phantom, utilizing PEG-100 stearate as an emulsifying agent. The influence of each component on the relative permittivity and conductivity is analyzed, providing a guideline for developing recipes for phantoms for tissues with permittivity values

ranging from 7 to 77. PEG-100 stearate was used not only as an emulsifier but also to reduce permittivity and conductivity. The effect of the oil on the slope of the conductivity curve was mitigated by the slope-increasing effect of the glycerol. The protocol is demonstrated through muscle, bone, and average human phantoms, all exhibiting wide-band performance, from 1 GHz to 7 GHz. It has been shown that the proposed phantom offers a cost-effective, reliable, and efficient method for testing implantable and wearable antennas.

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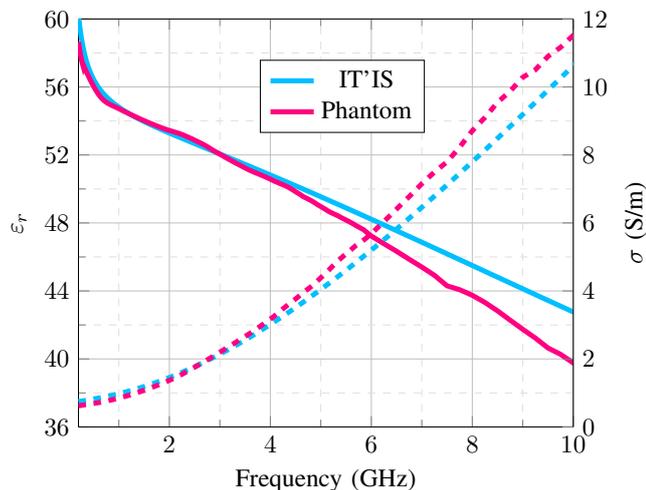


Fig. 13: Comparison of the relative permittivity of the human muscle phantom with the reference data from the IT'IS database.

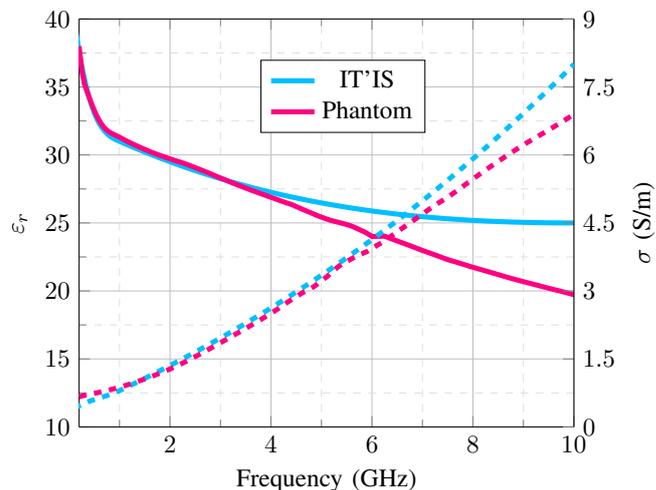


Fig. 15: Comparison of the relative permittivity of the human average phantom with the reference data from the literature.

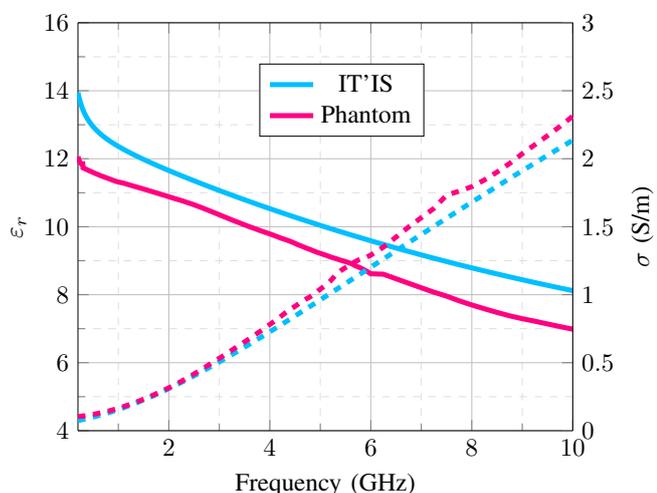


Fig. 14: Comparison of the relative permittivity of the bone (cortical) phantom with the reference data from the IT'IS database.

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