A Novel Durable Fat Tissue Phantom for Microwave Based Medical Monitoring Applications

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Abstract. Human tissue mimicking phantoms allow development of realistic emulations platforms which are essential for design of several biomedical monitoring and diagnosis systems. This first aim of this paper is to present a novel and durable fat tissue phantom for lower microwave frequency ranges 2.5–10 GHz. The phantom is developed from the liquid propylene glycol (pure) which we found to have similar dielectric properties as the fat tissue and hence, it is suitable to be used as liquid fat phantom. Development steps of solid fat phantoms with different trials are presented to provide insight how each ingredient affect on the dielelctric properties of the mixture. Additionally, phantom's stability over time in terms of dielectric and physical properties are evaluated. The second main aim of this paper is to present a novel approach to verify the feasibility and reliability of phantoms in practical scenarios with tissue layer model simulations. In the simulations, the antenna reflection coefficients are calculated with tissue layer models in which the dielectric properties of the fat tissue layer is varied between the proposed prolyne glycol -based fat phantoms as well as real human fat tissue values. Our goal is to show how small differences in the dielectric properties of the phantoms affect on a practical scenario which is based on antenna impedance measurements. The dielectric properties of the proposed fat phantom have very good correspondence with real fat tissue especially in the range of 5 GHz-10 GHz. Also, at lower ultrawide band (3.1–5 GHz), the difference in dielectric properties is minor. The layer model simulations show that the differences in dielectric properties do not have significant effect when modelling the practical scenarios in the frequency ranges targeted for medical applications. Hence the proposed liquid and solid fat phantoms are suitable to be used in the emulation platforms of biomedical applications.

Keywords: Adipose phantom · Biomedical applications · Dielectric properties · Microwave propagation · Tissue mimicking phantoms

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1 Introduction

Interest on development of microwave -based medical monitoring applications has increased significantly recently due to their non-ionized radiation, low-cost, and possibility for portability [1–6]. Development of new biomedical technology products requires precise modelling of the human body effects. Commonly, this involves large amount of experiments and measurements that need to be carried out with humans and animals, which in general are time consuming, complex, and expensive to perform. Thus, realistic tissue mimicking 3D phantom emulation platforms are suggested to be used when evaluating new concepts of medical applications [6].

The development of human tissue phantoms for microwaves has been an actively studied topic in recent years [7–15]. Different recipes for solution mixtures have been proposed for solid and liquid phantoms for different medical monitoring and imaging applications. Solid phantoms have the advantage of possibility for using realistic shaped 3D molds whereas liquid phantoms have the advantage of easy adjustability in terms of size.

Development of adipose, i.e., fat tissue phantoms for microwave ranges has also been studied actively [10–15]. Numerous of the proposed fat phantoms are targeted for breast cancer detection studies. However, fat phantom development has shown to be challenging due to several reasons: a) some of the proposed recipes contain ingredients which are toxic (e.g. formaldehyde), thereby requiring specific laboratory equipment to be handled, b) incredients are not easily accessible or are very costly, c) the fat phantoms aimed to be solid become oily in the room temperature and hence challenging to be used especially with 3D phantom models, d) or the dieletric properties of the presented fat phantoms have clear differences compared to the dielectric properties of the human fat tissue, e) phantoms are not durable: either the dielectric properties change significantly with the time or mildew appears on phantoms even after short time of storage in the refridgerator.

The first aim of this paper is to present for the first time a novel, easy-to-produce, non-toxic, and durable mixture for fat phantom which is based on pure propylene glycol. The developement procudure with different recipe trials are explained to give insight how different ingredients affect on the dieletric properties. *The second main aim* is to present a novel idea for phantom verifications with tissue layer model electromagnetic simulations. In the simulations, the antenna reflection coefficient is calculated with tissue layer models in which the dielectric properties of the fat tissue layer is varied between the proposed prolyne glycol -based fat phantoms as well as real human fat tissue values. Our goal is to show how small differences in the dielectric properties of the phantoms affect on a practical scenario which is based on antenna impedance measurements.

This paper is organized as follows: Sect. 2 presents the liquid and solid propylene glycol -based fat tissue phantoms. The development prodecure of the solid fat phantom and dielectric properties of different recipe trials are presented. Section 3 verifies the usability of the proposed fat phantoms using layer model simulations. Additionally, stable-of-time properties are evaluated. Summary and Conclusions are given in Sect. 4.

2 Propylene Glycol Based Fat Tissue Phantoms, Liquid and Solid

The development of propylene glycol-based phantoms started from authors' observation that the dielectric properties of the pure proplylene glycol (98%) were close to those of real fat tissue. The relative permittivity and conductivity values for fat tissue and liquid propylene glycol are shown in Fig. 1. Dielectric properties of the fat tissue are retrieved from [16]. As it can be seen, the relative permittivity of the propylene glycol is close to the dielectric properties of fat tissue from 2.5 GHz onwards. The relative permittivity of propylene glycol is slightly higher than the real fat tissue at 2.5–3.6 GHz, whereas from 3.6 GHz onwards, the relative permittivity is slighlty lower. However, the difference at these ranges is maximum 0.2. Also the difference in the conductivity values is minor 0.1–0.2 dB. Hence, the pure propylene glycol can be used as fat tissue phantom in the liquid form especially at lower microwave frequencies.

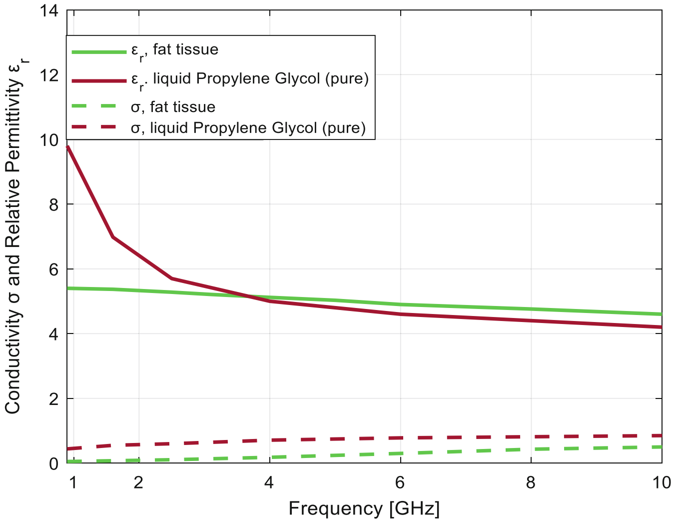

Fig. 1. Relative permittivity and conductivity values for fat tissue and liquid propylene glycol (pure) presented in the same linear scale.

Next, we started investigations for developing propylene glycol -based *solid* phantoms which enable the use of 3D fat phantom models. The aim was to solidify propylene glycol by adding gelatin and xanthan in the mixture. Since gelatin does not get dissolved directly with propylene glycol, small amount of water is needed to be mixed with gelatin first. However, water increases both relative permittivity as well as conductivity and therefore, the amount of water is intended to be minimized. Dishwashing liquid is added to enable smooth mixing of all the ingredients. In this study, we investigate the impact of different amounts of water in the solution mixtures. Additionally, the impact of the amount of gelatin and xanthan is also studied. Altogether 14 different mixture trials are investigated to find a solution with provides best match to a real fat tissue taken into the account of physical characteristics (solidness, possibility to be used in 3D molds). The different mixture solution trials FT1-FT14 with amount of ingredients are summarized in Table 1. Additionally, the corresponding measured dielectric properties of each sample are also presented in Table 1.

The phantom preparation is described briefly in the following: On a hot plate stirrer, presented in Fig. 2a, the distilled water is warmed in a beaker to 65 °C. Then, while keeping the temperature at 65 °C, the gelatin is gently added. The mixture is allowed to be stirred for 5 min. The propylene glycol is heated to around 50 °C and added to the gelatin water-based mixture and stirred continuously till the solution is heated to 65 °C. Then the xanthan is thoroughly combined with the solution. Finally, dishwashing liquid is added and well mixed into the solution. The solution is placed in a small petri dish and refrigerated for 24 h. Before taking any measurements, the phantoms rest at room temperature for about an hour to achieve room temperature 22°.

Firstly, the dielectric properties of the phantoms are measured using and Vector Network Analyzer (VNA) Keysight P9375A connected to a SPEAG's Dielectric Assessment Kit (DAK 3.5) [17]. The DAK software converts the measured complex S_{11} of the phantom sample into the complex permittivity and conductivity. The operation frequency range is 900 MHz to 10 GHz with a sweep of 117 points. The calibration was performed by applying the standard Open Source Load (OSL) calibration. The *open* was measured by holding the probe in the ambient air. The *short* was measured by connecting the probe to the shorting block and the measurement for the *load* was performed by setting the probe to DAK's official calibration liquid "Head" [17]. The success of the calibration was verified by measuring the dielectric properties of the calibration liquid Head and comparing results with the data sheet.

After the calibration, all of the fat phantom mixture solution trials (FT) are measured at room temperature. The dielectric properties of the samples are measured twice at 2–3 different locations and are given as an average of all. The measurement setup of dielectric properties of the phantom is presented in Fig. 2b.

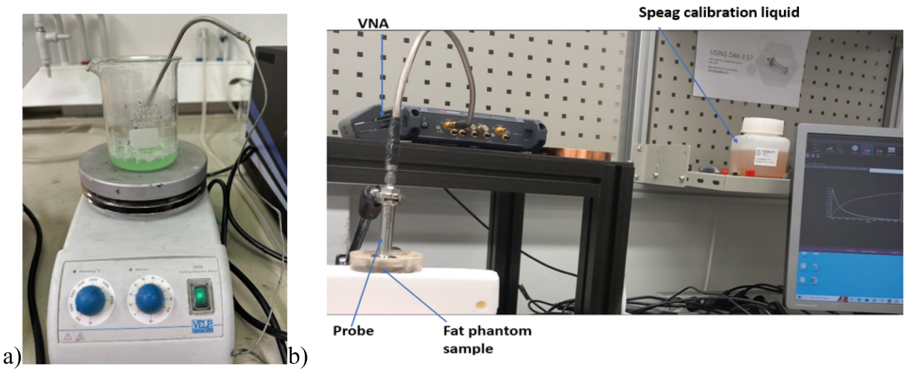

Fig. 2. The setup for measuring dielectric properties of the phantom samples.

The first fat-phantom trial (FT1) is developed only from propylene glycol (20 ml), distilled water (5 ml), and gelatine (3 g). As seen from Table 1, both relative permittivity and the conductivity values are too high compared to the real fat tissue. Therefore, the next trial FT2 includes less water and gelatine, but has incluision of xanthan and dishwashing liquid. FT2 has clearly lower relative permittivity and conductive than FT1, though still excessively high compared to the target values. FT3-FT5 are the trials where amount of water and gelatine are further decreased, both reductions yielding in lower relative permittivity and conductivity. In FT6-FT9, the amount of gelatine is drastically reduced to 0.75 g which however does not lower the relative permittivity to below 5 and also conductivity remains too high. Trials FT10-FT14 evaluates the impact of the increasing the amount of the propylene glycol in the mixture. The addition of propylene glycol requires addition of the water as well and thus, the decrease of the permittivity and conductivity values is more moderate. When using propylene glycol 40 ml and 50 ml (FT13 and FT14), the relative permittivity and conductivity values are already very close to those of the real fat tissue, especially with FT14. However, FT14 is not fully solidified even after several days and therefore is not suitable in its current form for 3D emulation platforms requiring fully solid phantoms. Thus, we chose the fully solid FT13 for the fat tissue phantom mixture solutions since the relative permittivity and conductivity are only 0.2 and 0.3 at higher level than those of the measured fat tissues.

Table 1. Different phantom mixture trials and their dielectric properties.

	Distilled water [ml]	Gelatine [g]	Propylene glycol [ml]	Xanthan [g]	Dish-washing liquid [ml]	Relative permittivity	Conductivity [S/m]
FT1	5	3	20	–	–	10.3/6.9/6.2	1.3/ 1.7/ 2.1
FT2	3	2	20	1	0.5	9.3/6.5 /5.9	1.1/ 1.5 /1.7
FT3	2	1.5	20	1	0.5	8.6/6.1/5.6	1.1/1.5/1.7
FT4	2	1	20	1	0.5	8.15/5.9/5.4	1.0/1.4/1.6
FT5	3	1.5	20	1	0.5	8.9/5.9/5.7	1.1/1.5/1.8
FT6	2	0.75	20	1	0.5	7.7/5.73/5.3	0.9/1.3/1.5
FT7	1.5	0.75	20	1	0.5	7.0/5.4/5.1	0.8/1.1/1.3
FT8	2	0.75	20	2	0.5	7.8/5.8/5.4	0.9/1.3/1.6
FT9	1.5	0.75	20	2	0.5	6.9/5.3/5.0	0.8/1.0/1.2
FT10	3	2	25	1	0.5	7.0/5.2/4.8	0.8/1.1/1.2
FT11	3	2	30	1	0.5	7.1/5.2/4.9	0.8/1.0/1.2
FT12	3	2	35	1	0.5	6.8/5.1/4.8	0.8/1.1/1.1
FT13	3	2	40	1	0.5	6.4/5.0/.4.7	0.75/0.95/1.0
FT14	3	2	50	1	0.5	6.1/4.8/4.5	0.73/0.92/1.0
Final = FT13	**3**	**2**	**40**	**1**	**0.5**	**6.4/5.0/.4.7**	**0.75/0.95/1.0**

The relative permittivity and conductivity values for fat tissue trials and real fat tissue at frequency range 0.9–10 GHz are presented in Fig. 3a-b, respectively.

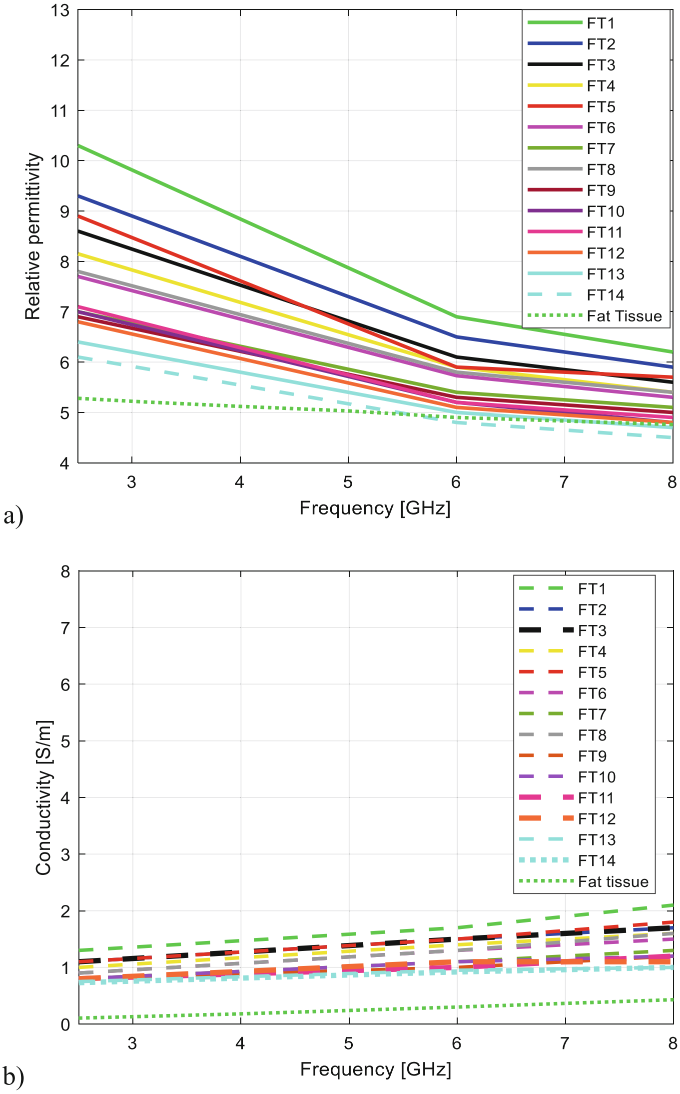

Fig. 3. Dielectric properties of different fat phantom trials (FTs) a) relative permittivity, b) conductivity.

3 Fat Phantom Evaluations

3.1 S11 Parameter Comparison with Layer Models

This paper brings a novel idea for phantom verifications using tissue layer model electromagnetic simulations. In the simulations, the antenna reflection coefficient, i.e. S11 parameter, is calculated with tissue layer models consisting of three layer: skin, fat, and muscle.

For the skin and muscle tissue layers, the dielectric proprties are retrieved from [16]. For the fat tissue layer, the dielectric properties are varied between a) the reference case with real fat tissue values from [16], b) liquid propylene glycol, and c) solid fat phantom with FT13 mixture solutions. The aim is to see how much small differences in the dielectric properties of the phantoms affect on the simulated antenna reflection coefficients. The results will provide insight how close the phantom based antenna performance evaluations are to the realistic case.

The simulations are carried out using the electromagnetic simulation software Simulia Dassault CST Studio Suite [18]. The layer model used in the simulations is presented in Fig. 4a. The thicknesses of the skin, fat and muscle tissues are 1.1 mm, 7 mm, and 8 mm which are summarized in Table 2. For the simulations, human tissue values are automatically found from CST's BioModel material library which correspond to values retrieved in [16]. Those values are used for the reference case simulations. However, in CST, it is possible to edit the tissue properties by changing relative permittivity and loss tangent values manually. Therefore, we first calculate tanδ values for the phantom cases from the measured conductivity values using formula:

$$\tan\delta = \frac{\sigma}{\omega\varepsilon_0\varepsilon_r}$$

in which σ is the conductivity, $\omega = 2\pi f$ with f the evaluated frequency, $\varepsilon_0 = 8.854$ e^{-12} is the free space permittivity and ε_r is the real part of the complex permittivity value [19]. Loss tangent values are listed in Table 2. The antenna used in the simulations is an UWB antenna designed for on-body communications [20]. The antenna simulation model is presented in Fig. 4b.

The simulated S11 values with cases a-c are presented in Fig. 5a for the antenna-skin distance 30 mm and in Fig. 5b for the antenna-skin distance 8 mm. It was found that antenna reflection coefficients simulated with the dielectric properties of the phantom and liquid propylene glycol are almost same as the antenna-skin distance is 30 mm (optimal antenna-body distance with the selected antenna). Also, with the smaller antenna-body distance (8mm), the antenna reflection coefficients have negligible differences at the frequency range 3.5 GHz-8 GHz. At the lowest part of the UWB range (3.1 GHz), the difference is maximum 4.5 dB, whereas at ISM frequency band 2.5 Ghz, the difference is maximum 2 dB. The difference is at largest, 6 dB, at 2.6 GHz but that frequency range is out of the interest for medical applications. These results are in line with the dielectric property differences presented in Fig. 3 since their differences are also larger at lower frequencies.

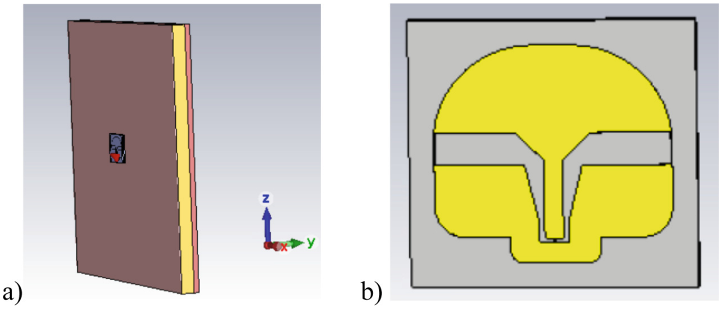

Fig. 4. a) The layer model used in the phantom verifications with S11 parameter simulations, b) UWB loop antenna used in the measurements.

Table 2. Loss tangent values for liquid and solid fat phantoms and real fat tissue

Fat Tissue/Phantom	2.5 GHz	6 GHz	8 GHz
Real fat tissue	0.14	0.19	0.21
Solid phantom	0.25	0.36	0.43
Liquid phantom	0.21	0.34	0.43

3.2 Fat Phantom Stability over Time

Normally, several gelatin-based phantoms last only a limited time especially if no preservatives are used. Mildew appears even in couple of weeks although the phantoms are stored in the refrigerator. Additionally, dielectric properties change remarkably as the water slowly evaporates from the phantoms with the time and hence, the phantom dries slowly.

Next, the proposed fat phantom's stability over time is evaluated measuring dielectric properties of the FT13 after 1, 7, 10, 11, 16, and 67 days. The phantom was stored in the refrigerator and measured at room temperature. After 10- and 67-days of storage, phantom was reheated and resolidified again, and the measurements were taken. Dielectric properties of the phantom after 1, 7, 10, 11, 16, and 67 days are presented in Fig. 6. It is found that dielectric properties change only slightly within the time for the first 16 days. Especially at the frequency range 6–8 GHz, the differences in relative permittivity are negligible: maximum 0.2. In conductivity, the variation is 0.1 S/m. At lower frequency range, the relative permittivity difference is 0.5 and conductivity difference 0.45. The relative permittivity decreases slightly for the first 10 days. Reheating arises the dielectric properties slightly: relative permittivity arises 0.4 units at lower part of the simulated frequency range and 0.1 units at higher frequency range. Differences in the conductivity values are 0.1 S/m over the whole simulated frequency range. After 67 days, the dielectric properties of the phantoms have changes more significantly: relative permittivity is increased 0.5–1 units and conductivity 0.1–0.45 S/m.

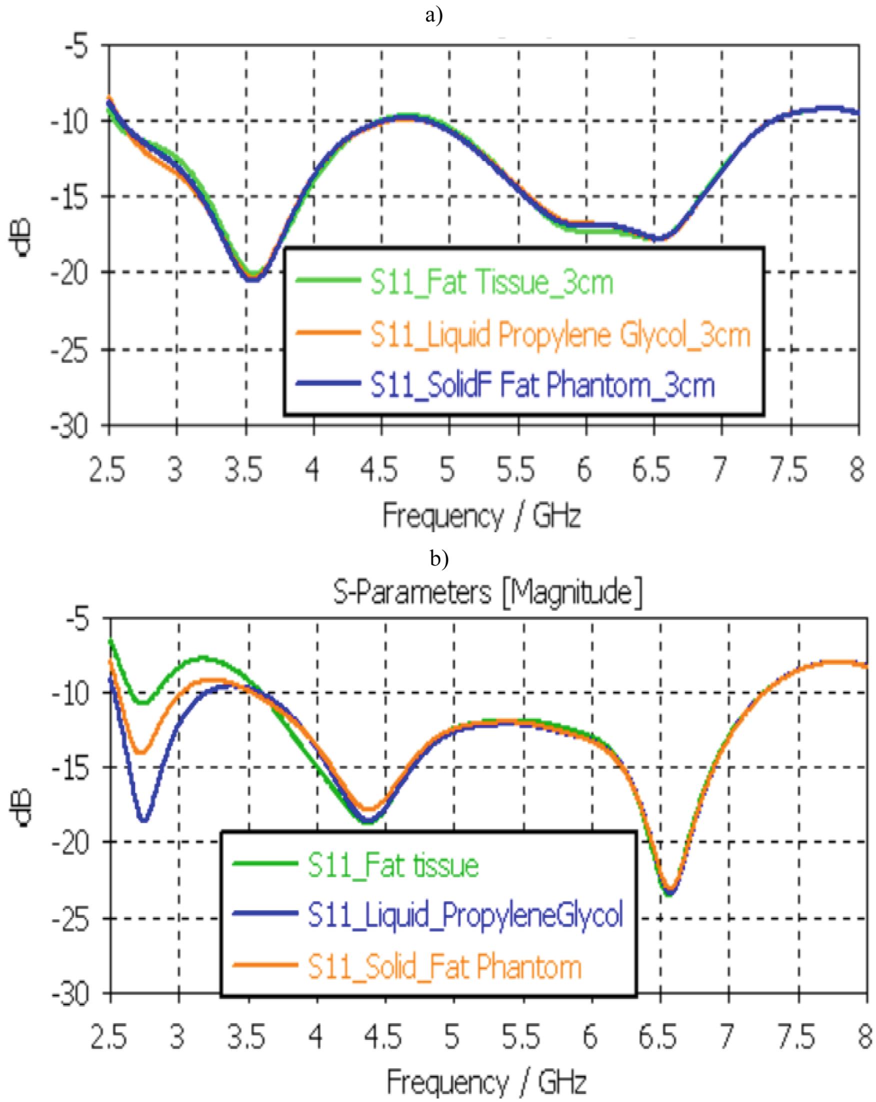

Fig. 5. S11-parameters obtained using dielectric properties of real fat tissue, liquid propylene glycol and solid fat phantom in the fat tissue layer: a) antenna-skin distance 30 mm and b) 8 mm.

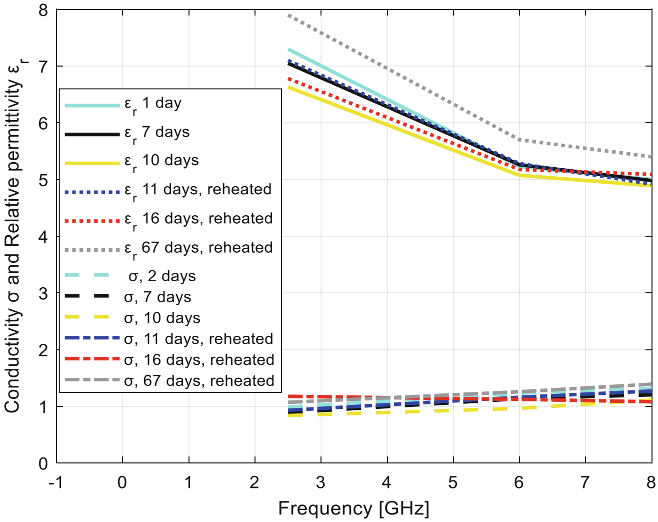

Fig. 6. Relative permittivity and conductivity values for phantom after 1,7,10, 11, 16, and 67 days after preparation.

4 Summary and Conclusions

This paper presented a novel and durable fat tissue phantom for lower microwave frequency ranges. The proposed phantom was developed from the liquid propylene glycol (pure) that we proved to have corresponding dielectric properties as the fat tissue. Development steps of the solid fat phantoms were described to provide insight how each ingredient affects on the dielectric properties of the mixture. The challenge in the development process is that jellying agents gelatin and xanthan do not get mixed directly with liquid propylene glycol and therefore, small amount of distilled water has to be added. However, distilled water and jellying agents affect on the dielectric properties and thus, optimal mixture, which yields to fully solid solution after polymerization, has to be developed taken into the account that the dielectric properties should be enough close to real fat tissue. The dielectric properties of the proposed solid phantom was shown to have very good correspondence with real fat tissue especially from 5 GHz-10GHz: the differences were almost negligible. Also, at lower ultrawide band (3.1–5 GHz), the difference was minor: differences in relative permittivity and conductivity values were 0.4–0.8 and 0.1–0.2, respectively. The differences were at largest around 2.5–2.7 GHz.

This paper also proposed for the first time the idea of evaluating the feasibility and reliability of the new phantoms for practical scenarions with human tissue layer model simulations. The idea is that the dielectric properties of the developed fat phantom is used in the simulation model as dielectric properties of the corresponding fat tissue layer. For other tissue layers, the dielectric properties are set same as in the realistic case. Simulations, e.g. the antenna reflection coefficients simulations, are carried out and compared with the antenna reflection coefficients obtained with the reference case in which also the fat layer has realistic dielectric properties. The proposed method provides the possibility to investigate smoothly the impact of small differences in the dielectric properties of the developed phantoms and compare the results with the ideal case for the selected application.

In this study, the antenna reflection coefficients were calculated with the layer model in which the fat layer‘s dielectric properties were set the same as those of the liquid and solid fat phantoms. The results were compared with the fat layer with dielectric properties of the real fat tissue retrieved from [16]. It was found that antenna reflection coefficients simulated with the dielectric properties of the phantom and liquid propylene glycol were almost same for the whole simulated frequency range as the antenna-body distance is 30 mm (optimal antenna-body distance for the selected antenna). Also, with the smaller antenna-body distance (8mm), the simulated antenna reflection coefficients have negligible differences at the frequency range 3.5 GHz−8 GHz. At the lowest part of the simulated frequency range, the differences were larger, which is in line with the comparison results on the differences of the dielectric properties. However, the maximum difference was 6 dB at 2.6–2-7 GHz, which are the frequencies out of the interest of medical applications. Instead, at ISM band 2.5 GHz, which is commonly used in medical applications, the differences in simulated antenna reflection coefficients were smaller: maximum 2.5 dB.

Based on the presented results, the pure propylene glycol can be considered as an excellent fat phantom in liquid form for the frequency range 2.5–10 GHz with only minor differences in the dielectric properties compared to those of the real fat tissue. The developed solid fat phantom is also very good for the frequency range 3–10 GHz and also good at the ISM band 2.5 GHz. Hence, it can be concluded that the proposed propylene glycol -based liquid and solid fat phantoms are suitable to be used in the emulation platforms of biomedical applications.

As a future work, we plan to test usability of novel fat phantoms with different antennas, both on-body and implant antennas. Additionally, we will use novel fat phantoms (both solid and liquid) to different medical monitoring application studies for which we already have realistic simulation -based results available: e.g. for realistic capsule endoscopy radio channel modelling [21] and breast cancer detection studies [22].

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References

1. Vrba, D., Vrba, J., Fiser, O., Cumana, J., Babak, M., Vrba Senior, J.: Applications of microwaves in medicine and biology. Recent Microwave Technol. (2022). https://doi.org/10.5772/intechopen.105492
2. Khan, S., Saied, I.M., Ratnarajah, T., Arslan, T.: Evaluation of unobtrusive microwave sensors in healthcare 4.0-toward the creation of digital-twin model. Sensors (Basel). **22**(21), 8519 (2022). https://doi.org/10.3390/s22218519. PMID: 36366218; PMCID: PMC9657877
3. Li, C., Tofighi, M., Schreurs, D., Horng, T.: Principles and Applications of RF/Microwave in Healthcare and Biosensing, Elsevier,1st Edition (2016)
4. Kiourti, A., et al.: Next-generation healthcare: enabling technologies for emerging bioelectromagnetics applications. IEEE Open J. Antennas Propag. **3**, 363–390 (2022). https://doi.org/10.1109/OJAP.2022.3162110

5. Rafique, U., Pisa, S., Cicchetti, R., Testa, O., Cavagnaro, M.: Ultra-wideband antennas for biomedical imaging applications: a survey. Sensors. **22**(9), 3230 (2022). https://doi.org/10.3390/s22093230
6. Särestöniemi, M., Reponen, J., Myllymäki, S., Myllylä, T.: Remote diagnostics and monitoring using microwave technique – improving healthcare in rural areas and in exceptional situations, under review for FinJeHew journal (2023)
7. Costanzo, S., Cioffi, V., Qureshi, A.M., Borgia, A.: Gel-Like human mimicking phantoms: realization procedure, dielectric characterization and experimental validations on microwave wearable body sensors. Biosensors (Basel). **11**(4), 111 (2021). https://doi.org/10.3390/bios11040111.PMID:33917777;PMCID:PMC8068187
8. Garrett, J., Fear, E.: Stable and flexible materials to mimic the dielectric properties of human soft tissues. IEEE Antennas Wirel. Propag. Lett. **13**, 599–602 (2014). https://doi.org/10.1109/LAWP.2014.2312925
9. Castelló-Palacios, S., Garcia-Pardo, C., Fornes-Leal, A., Cardona, N., Vallés-Lluch, A.: Tailor-made tissue phantoms based on acetonitrile solutions for microwave applications up to 18 GHz. IEEE Trans. Microw. Theory Tech. **64**(11), 3987–3994 (2016). https://doi.org/10.1109/TMTT.2016.2608890
10. Pollacco, D.A., Conti, M.C., Farrugia, L., Wismayer, P.S., Farina, L., Sammut, C.V.: Dielectric properties of muscle and adipose tissue-mimicking solutions for microwave medical imaging applications. Phys. Med. Biol. **64**(9), 095009 (2019). https://doi.org/10.1088/1361-6560/ab0dda. PMID: 30844769
11. Di Meo, S., et al.: Tissue-mimicking materials for breast phantoms up to 50 GHz. Phys Med Biol. **64**(5), 055006 (2019). https://doi.org/10.1088/1361-6560/aafeec. PMID: 30650384
12. Lazebnik, M., Madsen, E.L., Frank, G.R., Hagness, S.C.: Tissuemimicking phantom materials for narrowband and ultrawideband microwave applications. Phys. Med. Biol. **50**(18), 4245–4258 (2005)
13. Porter, E., Fakhoury, J., Oprisor, R., Coates, M., Popovic, M.: Improved tissue phantoms for experimental validation of microwave breast cancer detection. In: Proceedings of the Fourth European Conference on antennas and Propagation (EuCAP 2010), pp. 1-5. Barcelona, Spain (2010)
14. Martellosio, A., et al.: Dielectric properties characterization from 0.5 to 50 GHz of breast cancer tissues. IEEE Trans. Microw. Theory Tech. **65**(3), 998–1011 (2017). https://doi.org/10.1109/TMTT.2016.2631162
15. Di Meo, S., et al.: Realization of tissue mimicking materials for breast phantoms using waste oil hardeners. In: 13th European Conference on Antennas and Propagation (EuCAP 2019), 31 March-5 April (2019)
16. IT IS dielectric properties (2022). https://www.itis.ethz.ch/virtual-population/tissue-properties/databaseM
17. Speag DAK SPEAG, Schmid & Partner Engineering AG
18. Dassault Simulia CST Suite. https://www.3ds.com/
19. Orfanidis, S.J.: Electromagnetic Waves and Antennas (2002) 2016. http://www.ece.rutgers.edu/~orfanidi/ewa/
20. Tuovinen, T., Yekeh Yazdandoost, K., Iinatti, J.: Comparison of the performance of two different UWB antennas for the use in WBAN on-body coimmunications. In: European Conference on Antennas and Propagation (EUCAP2012), pp. 2271-3374 (2012)
21. Särestöniemi, M., Wisanmongkol, J., Taparugsanagorn, A., Hämäläinen, M., Iinatti, J.: Radio channel model for WBAN capsule endoscopy with anatomical voxel models. IEEE Access (2023)
22. Särestöniemi, M., Reponen, J., Sonkki, M., Myllymäki, S., Pomalaza-Ráez, C., Tervonen O., Myllylä T.: Breast cancer detection feasibility with UWB flexible antennas on wearable monitoring vest. In: TELMED2022, pp. 751–756. Italy (2022)