Bovine Calf Serum: Broadband Dielectric Properties and an Emulating Phantom

Vigyanshu Mishra, Zeke Z. Dalisky, and Asimina Kiourti
ElectroScience Laboratory, Department of Electrical and Computer Engineering
The Ohio State University
Columbus, OH, USA
mishra.186@osu.edu, dalisky.1@osu.edu, kiourti.1@osu.edu

Abstract*—Bovine calf serum (BCS) is often used as a substitute to emulate synovial fluid, a fluid found in the human joints such as the elbow, knee, shoulder, and hip. To date, the dielectric properties of BCS are unknown, in turn limiting the development of RF/microwave solutions to monitor the joint(s). In this work, we report the first measurements of BCS dielectric properties (permittivity and loss tangent) in the 200 MHz to 20 GHz range. In addition, we present a phantom that accurately emulates the frequency-dependent dielectric properties of BCS. An example demonstration matches the BCS dielectric properties from 0.9 GHz to 1.9 GHz with a deviation of less than ±0.6 in relative permittivity and ±0.031 in loss tangent. Our recipe relies on readily available water, sugar (0.35 M), and salt (0.35 M), making the phantom an easy alternative to BCS for conducting RF/microwave experimental studies. By tweaking the sugar and salt content, our phantom can ultimately match the BCS dielectric properties in any desired frequency band.

I. Introduction

Synovial fluid is found in human joints known as synovial joints, viz. elbow, knee, hip, and shoulder. As would be expected, samples of synovial fluid are not easily available to perform experimental studies. Hence, Bovine Calf Serum (BCS) is often used as a substitute given its increased accessibility [1]-[3] and its similar physical properties to synovial fluid, including viscosity [1] and material composition [2]. In [3], BCS with 30g/L in protein concentration was shown to best mimic the genuine synovial fluid mechanically.

Due to such similarities, BCS could be considered as an electrical substitute for synovial fluid as well. However, the dielectric properties of BCS are unknown, in turn limiting the development of RF/microwave solutions to monitor the joint(s). To overcome such limitations in the state-of-the-art, we herewith report the broadband dielectric properties (permittivity and loss tangent) of BCS from 200 MHz to 20 GHz. Noting that BCS is by itself a biological specimen, a BCS-emulating phantom is further proposed to ease RF/microwave experimental testing. Our proposed phantom is made of easily available ingredients i.e., salt, sugar, and water, the content of which can be fine-tuned to match the properties in any desired frequency band. As an example demonstration, we show that a mixture of 0.35-M salt and 0.35-M sugar can emulate the BCS dielectric properties from 0.9 GHz to 1.9 GHz quite accurately. We note that this formulation is by no way limiting and the solution can be tweaked to match the dielectric properties in other bands as well.

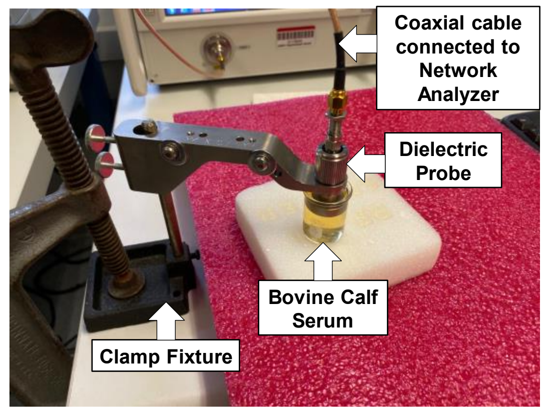

Fig. 1. Set-up for measurement of dielectric properties (permittivity and loss tangent) of bovine calf serum (BCS) sample using Keysight's high temperature probe N1501A-101 and a network analyzer.

II. Experiments and Results

A. Dielectric Properties of Bovine Calf Serum (BCS)

Our experimental set-up consists of: (a) a 30g/L protein concentration BCS sample [3], (b) Keysight's high-temperature dielectric probe N1501A-101, and (c) a PNA-L N5235A network analyzer, Fig. 1. A clamp fixture is used to hold the dielectric probe and provide stability for reliable and consistent measurements. The coaxial cable that connects the dielectric probe to the network analyzer is placed so as to avoid any movement that would cause discrepancy in our measurements. The probe is calibrated at a temperature of 22° C and the calibration is verified using known standards multiple times to ensure reliability. The probe is then carefully inserted inside the BCS sample ensuring that no bubbles are formed to further enhance accuracy. For repeatability purposes, we collect seven (7) sets of measurements, including relative permittivity (ϵ_r) and loss tangent (ϵ''/ϵ'). All measurements are conducted in the 200 MHz to 20 GHz frequency range.

Measurement results are summarized in Fig. 2(a). Here, solid lines represent the 7 different set of measurements, while the dashed line shows the average of all 7 measurements. As seen, all 7 measurements overlap quite well along with the average, hence confirming the reliability and reproducibility of our experimental approach.

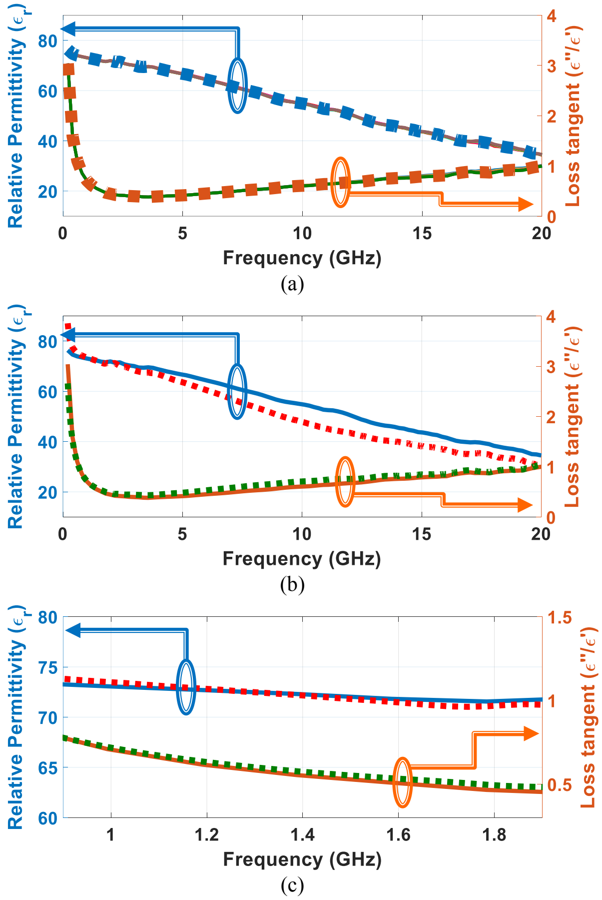

Fig. 2. (a) Measured dielectric properties of Bovine Calf Serum (BCS) at 22°C with 7 iterations represented by solid lines and average of all 7 data represented by dashed curve from 0.2 GHz to 20 GHz. Reproducibility across all 7 data confirms the reliability of our measurements. Measured dielectric properties of BCS data (solid lines) with 0.35-M salt + 0.35-M sugar phantom data (dashed curves) across (b) 0.2 GHz to 20 GHz and (c) 0.9 GHz to 1.9 GHz. Although similar trend can be obtained using phantom for both permittivity and loss tangent as shown in (b), deviation of less than ±0.6 in permittivity and less than 0.031 in loss tangent can be obtained in the spectrum ranging from 0.9 GHz to 1.9 GHz as demonstrated in (c).

B. BCS-Emulating Phantom

Our proposed phantom used to emulate the BCS dielectric properties is a solution of sugar (solute), salt (solute), and water (solvent). It has been shown in [4], that increasing sugar concentration primarily decreases the permittivity, while increasing salt concentration primarily increases conductivity. With these in mind, several trials are conducted with various concentrations of salt and sugar. For each concentration, we measure the corresponding permittivity and loss tangent and - based on the requirement - we increase the salt and/or sugar concentration in small steps. The employed experimental set-up is identical to that described in Section II.A, with the exception that only one measurement is conducted for each phantom formulation. This approach is valid as the small step variations enable us to confirm reproducibility and reliability.

After several iterations, an optimal solution of 0.35-M salt and 0.35-M sugar is found to accurately emulate the BCS dielectric properties. The properties of this phantom (dashed) along with BCS data (solid) are plotted in Fig. 2(b) from 200 MHz to 20 GHz. As seen, the phantom shows similar trend for both relative permittivity and loss tangent across the band. However, the deviation in actual numbers becomes large across certain frequencies, restricting the reliable conduction of experiments throughout the band. Instead, Fig. 2(c) plots the dielectric properties of BCS and phantom solution from 0.9 GHz to 1.9 GHz, showing good agreement: the deviation for relative permittivity and loss tangent is less than ±0.6 and 0.031, respectively. Nevertheless, this should not be treated as a limiting case of this phantom, but rather as an example demonstration. If an application demands the properties to be matched in a different band, the concentration of salt or sugar can be modified accordingly [4]. This is possible due to the similar trend depicted by the phantom and BCS in Fig. 2(a) across the band (200 MHz to 20 GHz).

III. CONCLUSION

This work reported the first measurements of BCS dielectric properties (relative permittivity and loss tangent) across the 200 MHz to 20 GHz range. The goal is to use BCS as a means of emulating synovial fluid in RF/microwave experiments of the joints that is not easily available otherwise. The above is possible because BCS has similar physical properties and material composition as those of synovial fluid, and has long been used to emulate synovial fluid in the literature. An alternative and easy-to-make phantom was also proposed which can emulate the dielectric properties of BCS, thus circumventing the necessity to obtain BCS which is also a biological specimen. An example demonstration of a water solution with 0.35-M salt and 0.35-M sugar was found to follow the trend of BCS dielectric properties from 200 MHz to 20 GHz, with a deviation of less than ±0.6 in relative permittivity and 0.031 in loss tangent from 0.9 GHz to 1.9 GHz. By tweaking the sugar and salt content, our phantom can ultimately match the BCS dielectric properties in any desired frequency band. We note that the electrical properties of synovial fluid itself are still unknown and hence future dielectric measurements of synovial fluid need to be conducted and compared against BCS.

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