Electrical Properties of Filled PVA-C for Bioelectrical Impedance Spectroscopy Phantoms

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Keywords: PVA Phantom, Hydrogel, Bioelectrical Impedance Spectroscopy, Conductivity, Permittivity, Living Tissue, Electrical Properties.

Abstract: This paper investigates the electrical properties of polyvinyl alcohol cryogel (PVA-C) filled with various materials to develop biological phantoms for bioelectrical impedance spectroscopy (BIS) applications. PVA-C is a hydrogel that undergoes cross-linking through freeze-thaw cycling, known for its long-term stability and mechanical properties, which closely mimic those of living tissue, making it a superior alternative to traditional gelling agents such as agar. To assess the impact of different fillers, samples with varying filler proportions were prepared, and their electrical properties were analysed using BIS across a low-frequency range (1 kHz to 1 MHz). The study was divided into two parts: the first one focused on the effects of PVA concentration, the number of freeze-thaw cycles, molecular weight, and time-dependent behaviour on PVA-C's electrical properties. The second part compared the electrical properties of PVA-C combined with various fillers, including particles, polymers, and ceramics. Finally, the results were compared with existing published data on the electrical properties of living muscle and fat.

1 INTRODUCTION

Bioelectrical impedance spectroscopy (BIS) is a valuable technique for assessing the composition, structure, and functional properties of living tissues. This is achieved by passing an alternating current through a body part and measuring the resulting voltage at low frequencies. To ensure the accuracy and reliability of BIS sensors used in body composition analysis, thorough validation is essential. This involves conducting precise measurements to compare the sensor outputs against known standards or reference methods. However, the inherent variability of human physiology poses challenges to obtaining consistent in vivo data, as short-term fluctuations within individuals (intra-individual) and differences between individuals (inter-individual) can influence results. To address these challenges, researchers utilise phantoms (artificial physical models) designed to replicate the properties of biological tissues. Phantoms provide a stable and repeatable environment for testing and enable precise control over tissue parameters during validation studies.

Phantoms have been extensively developed using biological materials such as vegetable-based substances or gelling agents filled with conductive particles (Anand *et al.*, 2019; Hess *et al.*, 2022; Mobashsher & Abbosh, 2014). While these materials effectively replicate the electrical properties of living tissues, they often suffer from short-term stability and inadequate mechanical strength. To overcome these limitations, researchers have explored alternative materials such as silicones, elastomers, and filled polymers (Dunne *et al.*, 2018; Goyal *et al.*, 2022). Among these polymers, polyvinyl alcohol (PVA) has attracted significant research interest. PVA is soluble in hot water and can be cross-linked through freeze-thaw cycles to form polyvinyl alcohol cryogel (PVA-C), a hydrogel with mechanical properties and texture similar to those of human tissue (Chen *et al.*, 2012; Goyal *et al.*, 2022). While PVA-C exhibits excellent mechanical properties, its electrical properties are not inherently comparable to those of living tissue. To address this, fillers are incorporated into the hydrogel to achieve appropriate conductivity.

This paper investigates the electrical properties of PVA-C samples loaded with various fillers. Conductivity and permittivity measurements were

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performed to evaluate their potential application in the development of electrical phantoms.

2 MATERIALS AND METHODS

2.1 Materials

The materials used in this study are summarised in Table 1.

Table 1: Materials used in this study.

Material	Description	Supplier
PVA **145 kDa**	Fully hydrolysed	Sigma-Aldrich
PVA **60 kDa**	Fully hydrolysed	Sigma-Aldrich
Lignin	Alkali	Sigma-Aldrich
1,2-propanediol	ACS reagent, ≥99.5%	Sigma-Aldrich
Barium titanate	Powder, <3 µm, 99%, M=233.19 g/mol	Sigma-Aldrich
Agar	Industrial agar, CONDALAB	Dutscher
NaCl	M=58.44 g/mol, APPLICHEM	Dutscher
Graphite	Purity 99.9%, particle size 5-10 µm	NanoGrafi
Plaster	Parexlanko	Local market
Glycerine	Cooper	Local market
Corn flour	Maïzena	Local market
“Sommières” earth	‘’La fée du logis vert’’	Local market
Diatomaceous earth	Novatera	Local market
Glass beads	5-20 µm and 150-200 µm	Local market

2.2 PVA-Cryogel: A Brief Overview

Polyvinyl alcohol (PVA) is a versatile synthetic polymer widely used in medical applications such as cartilage replacement and the fabrication of cardiovascular devices (Kobayashi & Hyu, 2010; Wan *et al*., 2014). Its ability to form stable hydrogels through freeze-thaw cross-linking has made it a material of significant interest for tissue engineering and biomedical research. This process results in the formation of polyvinyl alcohol cryogel (PVA-C), which closely mimics the texture and mechanical properties of human tissues, as confirmed in multiple studies (Chen *et al*., 2012; Duboeuf *et al*., 2009; Fromageau *et al*., 2007; Gautam *et al*., 2021; Goyal *et al*., 2022; Khaled *et al*., 2007).

The process of crosslinking PVA to form PVA-C is illustrated in Figure 1. During the freezing process, the formation of ice crystals forces the PVA chains into a more compact configuration, resulting in the creation of a PVA-rich phase. The PVA regions become increasingly concentrated, and the formation of hydrogel bonds is facilitated by an increase in the number of freeze-thaw cycles. Given the slow movement of macromolecules, multiple cycles are required to achieve a robust hydrogel. The strength of the resulting hydrogel also depends on the molecular weight and concentration of PVA in solution (Adelnia *et al*., 2022; Wan *et al*., 2014).

Figure 1: Effect of cycling on the microstructure of PVA-C.

The mechanical and electrical properties of PVA-C are influenced by several factors, including the degree of hydrolysis, molecular weight, concentration, and the freeze-thaw process. These properties change during the course of the cycles (Adelnia *et al*., 2022; Getangama *et al*., 2020; Wan *et al*., 2014). Notably, below a concentration of 5% w/w of PVA, the hydrogel will not form. Furthermore, the mechanical strength of the hydrogel significantly decreases when the concentration is below 10% w/w, whereas concentrations above 30% w/w make the mixture difficult to manipulate (Adelnia *et al*., 2022). The long-term stability of PVA-C is particularly noteworthy, making it a preferred option over traditional gelling agents such as agar or gelatine (Hess *et al*., 2022). Additionally, PVA is considered an environmentally friendly material due to its biocompatibility, biodegradability, and non-toxicity during both the manufacturing and cross-linking processes (Belay, 2023).

2.3 Preparation of the Samples

This paper presents an analysis of two distinct sample types. Both sample types were placed in a standard measuring cell (refer to section 2.4.2) to compare the conductivity and permittivity values of the materials with those of muscle reported in the literature.

The first set of samples enables the investigation of the electrical properties of PVA-C based on various parameters, including the PVA concentration in solution, the number of freeze-thaw cycles, the molecular weight of PVA and the evolution of

PVA-C properties over time. This investigation was conducted on three distinct samples.

The first PVA-C sample was cross-linked from a 10% w/w PVA solution and underwent a single freeze-thaw cycle. The remaining two samples were of considerable size, from which smaller sub-samples were extracted for bioimpedance measurements across varying cycles. One sub-sample was specifically examined to assess its stability over time. During the intervals between measurements, the sample was stored in a plastic film at room temperature. In the case of the 60 kDa sample, the first freeze-thaw cycle resulted in the formation of a hydrogel that lacked the required robustness for handling and measurement. Table 2 summarises the characteristics of the studied PVA-C samples. In this study, weight proportions (% w/w) are expressed in relation to the weight of the material relative to the weight of the solvent (deionised water).

Table 2: Summary of characteristics for the studied PVA-C samples.

	Molecular weight	Cycle	Concentration (% w/w)	Study of stability
1	145 kDa	1	10	
2			15	x
		2	15	
		3	15	
		4	15	
3	60 kDa	2	15	
		3	15	
		4	15	

The second set of samples was prepared to investigate the electrical properties of PVA-C filled with different types of particles, polymers, and other materials. The objective was to examine the effect of varying the proportions of fillers in a solution of PVA, with a molecular weight of 145 kDa and a concentration of 10% w/w, on its electrical properties. All samples were subjected to a single freeze-thaw cycle.

Samples were prepared according to the material proportions detailed in Table 3.

For each sample, the materials were mixed with deionised water in a beaker and mechanically agitated for 30 minutes at 90°C. The resulting mixture was then transferred into the standard measuring cell for a single freeze-thaw cycle, consisting of freezing at -20°C for 20 hours, followed by thawing at room temperature (23°C) for 8 hours (see Figure 2).

Table 3: Summary of sample composition based on PVA (145 kDa, 10% w/w, one freeze-thaw cycle).

Materials	Proportions (% w/w)	Remarks
Lignin	1-5-10-20% w/w	-
1,2-propanediol	5-10-20% w/w	Also known as propylene glycol
Barium titanate	5-15% w/w	Must be handled with protection
Agar	1-2-3% w/w	Gelling agent
NaCl	0.1-0.5-1% w/w	Enhance ionic conductivity
Graphite	0.1-0.5-1-2-5% w/w	
Plaster	0.1-0.5-2-5-10% w/w	
Glycerine	1-2-5% w/w	Also known as glycerol
Corn flour	1-2-5% w/w	
“Sommières” earth	2-5-10-20% w/w	Clay known for its absorbent properties
Diatomaceous earth	2-5-10-20% w/w	Fossilized remains of diatoms (algae)
Glass beads 5-20 µm	2-5-10-20% w/w	
Glass beads 150-200 µm	2-5-10-20% w/w	

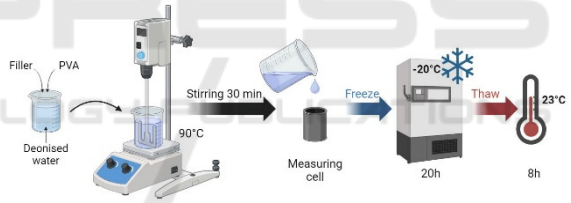

Figure 2: Sample preparation steps. Created in BioRender. Bublex, A. (2025) https://BioRender.com/u47q709.

2.4 Impedance Spectroscopy Measurement

2.4.1 Bioelectrical Impedance Spectroscopy

Bioelectrical impedance spectroscopy (BIS) is a non-invasive technology used to measure the volumes of various body compartments, including total body water and extracellular water. BIS measures impedance at multiple frequencies to analyse cellular membrane integrity and fluid distribution, thereby offering insights into cellular health and hydration status. Impedance, a generalisation of Ohm's law to alternating current, is a complex quantity and is expressed as: (Bera, 2014; Grimnes & Martinsen, 2015)

$$Z = R + jX \quad (1)$$

where Z: impedance
R: resistance
X: reactance

2.4.2 Measurement Tools

In this study, the Multifrequency Impedance Analyzer (MFIA 5 MHz model) from Zurich Instrument served as the reference standard for bioimpedance measurements. The device is capable of performing bioimpedance measurements across a frequency range of 1 mHz to 5 MHz and within a measurement range of 1 mΩ to 1 TΩ. In the present investigation, measurements were conducted over a frequency range of 1 kHz to 1 MHz, with 100 data points acquired at logarithmic intervals. Standard measuring cells were developed based on the model established by Suga (Suga *et al.*, 2013). The cells consist of transparent, extruded polycarbonate cylinders with a length of 50 mm and an inner diameter of 24 mm. Measurements were performed using these standard measuring cells, as illustrated in Figure 3.

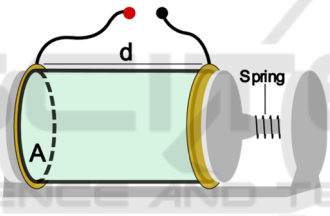

Figure 3: Schematic of a standard measuring cell. Length d = 50 mm, inner surface area A = 4.52 cm².

The electrodes were 30 mm diameter, gold-plated discs, manufactured by JLCPCB, China. The gold coating was specified as ENIG 2U (Electroless Nickel Immersion Gold) with a thickness of 2 µm. The support structure was designed using Autodesk Fusion 360 and 3D printed using polylactic acid (PLA). A spring mechanism was incorporated into the design to ensure a constant force applied to the sample.

2.4.3 Two-Electrode Measurements: Model Extraction of Conductivity and Permittivity

The conductivity and relative permittivity of a sample were evaluated through impedance measurements conducted in a controlled geometry. These data were compared with existing literature values for living tissue (see Figure 4).

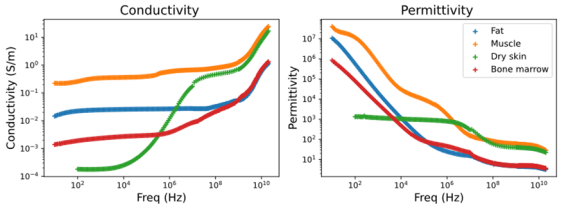

Figure 4: Electrical properties of 4 living tissue - Adapted from Gabriel *et al.* 1996 (Gabriel, 1996).

To extract the values of conductivity (σ) and relative permittivity (ε_r) from bioimpedance measurements (Z), admittance (Y) was calculated according to the methodology proposed by A. Ivorra (A.Ivorra, 2002):

$$Y = \frac{1}{Z} \quad \text{and} \quad Y = G + iB \quad (2)$$

where G is conductance and B is susceptance. The values of conductivity and relative permittivity are expressed as follows:

$$\sigma = \frac{G}{K} \quad \text{and} \quad \varepsilon_r = \frac{B}{K 2\pi f \varepsilon_0} \quad (3)$$

with the cell coefficient $K = A/d$, A is the cross-sectional area and d is the cylinder length (see Figure 3). In this document, the term "relative permittivity" will be used interchangeably with "permittivity".

3 RESULTS

3.1 PVA-C Electrical Properties as a Function of Number of Cycles and Molecular Weight

The evolution of the electrical properties of two PVA-C samples with different molecular weights over multiple cycles is shown in Figure 5. In the case of the 60 kDa sample, the first cycle produced a hydrogel that lacked sufficient robustness for handling and measurement.

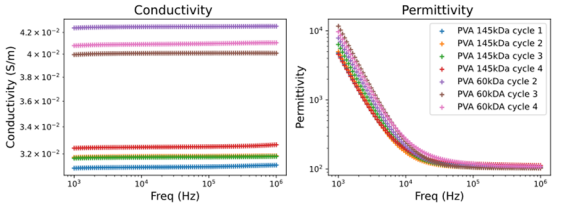

Figure 5: Electrical properties of PVA-C samples over multiple cycles.

The molecular weight significantly influences the conductivity of the samples and the permittivity at low frequencies. Conductivity increases with the number of freeze-thaw cycles, but higher molecular weight correlates with lower conductivity. For both PVA-C samples, permittivity tends to converge at high frequencies.

3.2 PVA-C Electrical Properties as a Function of Concentration

Figure 6 illustrates the electrical properties of two PVA-C samples with varying concentrations of PVA in solution.

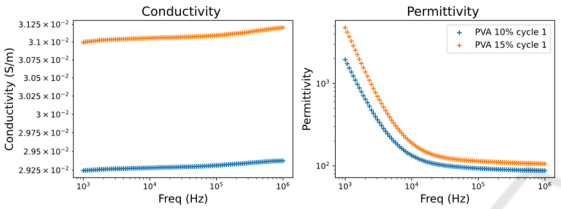

Figure 6: Electrical properties of PVA-C samples with different concentrations of PVA – 10% w/w and 15% w/w.

As the concentration of PVA in solution increases, both conductivity and permittivity show a corresponding rise for samples of a given molecular weight.

3.3 PVA-C Electrical Properties over Time

Figure 7 illustrates the stability of the electrical properties of a PVA-C sample stored in a plastic film at room temperature over a four-day period.

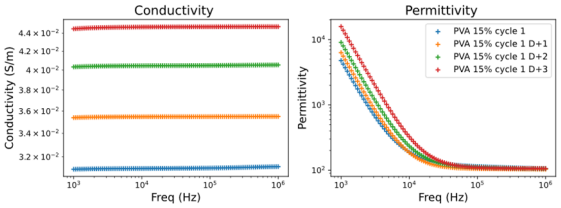

Figure 7: Electrical properties of PVA-C over time.

Both conductivity and permittivity show a notable daily increase. This increase is likely due to water loss from samples that are not completely hermetically sealed.

3.4 Hydrogel Based on Filled PVA-C

This section examines the impact of varying the proportion of fillers in a solution of PVA, with a molecular weight of 145 kDa and a concentration of 10% w/w, on the electrical properties. All samples were subjected to a single freeze-thaw cycle.

3.4.1 Agar

The comparative electrical properties of PVA-C filled with different proportions of agar, along with a pure PVA-C sample, are presented in Figure 8.

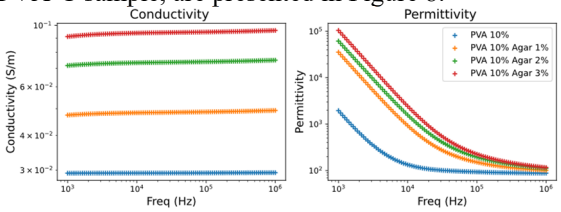

Figure 8: Electrical properties of PVA-C filled with various proportions of agar.

The addition of agar increases both conductivity and permittivity, aligning with its ionic nature, which enhances ion mobility within the hydrogel matrix. This behaviour suggests that agar is a promising candidate for mimicking the electrical properties of biological tissues.

3.4.2 Corn Flour

Figure 9 illustrates the comparative electrical properties of PVA-C filled with varying proportions of corn flour, alongside a pure PVA-C sample.

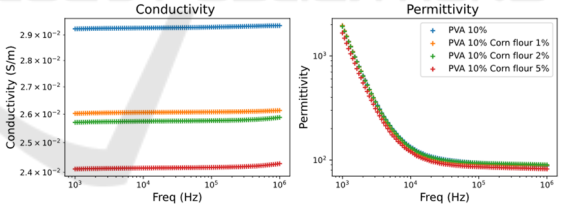

Figure 9: Electrical properties of PVA-C filled with various proportions of corn flour.

The addition of corn flour reduces conductivity without significantly affecting permittivity, suggesting that its primary effect is to obstruct ion flow rather than alter dielectric properties. This characteristic makes it suitable for applications where reduced conductivity is desired.

3.4.3 Glycerine

Figure 10 shows the electrical properties of PVA-C filled with various amounts of glycerine, compared to a pure PVA-C sample.

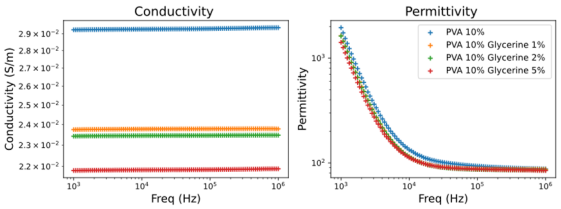

Figure 10: Electrical properties of PVA-C filled with various proportions of glycerine.

Glycerine notably decreases conductivity while leaving permittivity relatively unchanged. This may be due to its insulating properties and ability to reduce free ion concentration. Its inclusion could be beneficial for simulating tissues with low conductivity, but it may require reinforcement to maintain mechanical strength.

3.4.4 NaCl

Figure 11 illustrates the comparative electrical properties of PVA-C filled with varying proportions of NaCl, compared to a pure PVA-C sample.

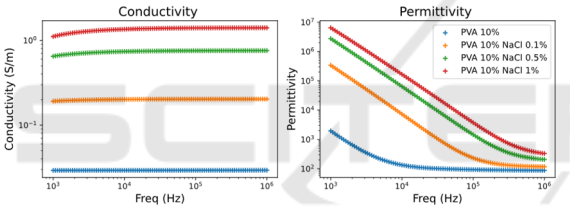

Figure 11: Electrical properties of PVA-C filled with various proportions of NaCl.

NaCl significantly increases both conductivity and permittivity, consistent with its role as an ionic conductor. This makes it highly effective for muscle-mimicking phantoms. The observed linear relationship between NaCl concentration and conductivity supports its controlled application.

3.4.5 Graphite

The comparative electrical properties of PVA-C filled with different proportions of graphite, compared to a pure PVA-C sample, are presented in Figure 12.

The conductivity and permittivity curves exhibit significant changes. When the graphite proportion is less than 1%, conductivity remains lower than that of the pure PVA-C sample. In contrast, for proportions above 2%, the conductivity curve increases beyond that of PVA-C alone at higher frequencies. The permittivity curve is primarily affected at concentrations above 0.5%.

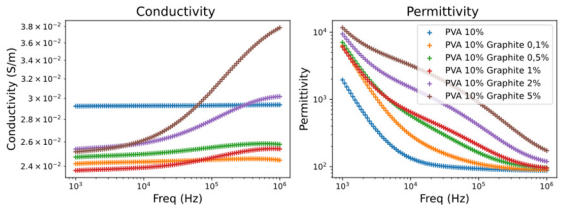

Figure 12: Electrical properties of PVA-C filled with various proportions of graphite.

3.4.6 Lignin

Figure 13 illustrates the comparative electrical properties of PVA-C filled with varying proportions of lignin, compared to a pure PVA-C sample.

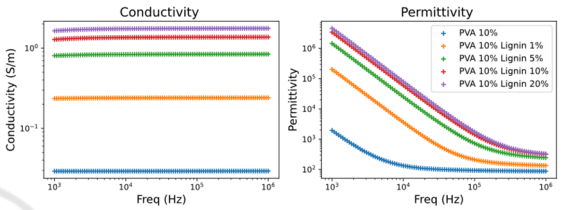

Figure 13: Electrical properties of PVA-C filled with various proportions of lignin.

The incorporation of lignin into the hydrogel leads to a notable enhancement in both conductivity and permittivity, reaching levels comparable to those observed with NaCl. The electrical properties show a rapid increase at low lignin concentrations and appear to plateau at concentrations above 10% lignin.

3.4.7 1,2-Propanediol

Figure 14 shows the electrical properties of PVA-C filled with various amounts of 1,2-propanediol, compared to a pure PVA-C sample.

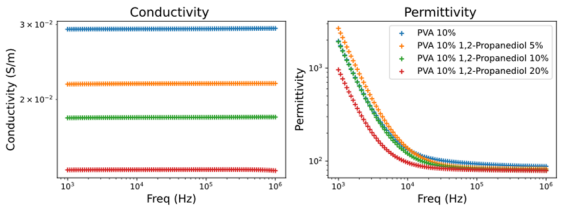

Figure 14: Electrical properties of PVA-C filled with various proportions of 1,2-propanediol.

The reduction in both conductivity and permittivity suggests its use as a dielectric filler for applications requiring a low electrical response. However, its concentration must be carefully controlled to prevent adverse effects on mechanical properties.

3.4.8 "Sommières" Earth

The comparative electrical properties of PVA-C filled with different proportions of "Sommières" earth, compared to a pure PVA-C sample, are presented in Figure 15.

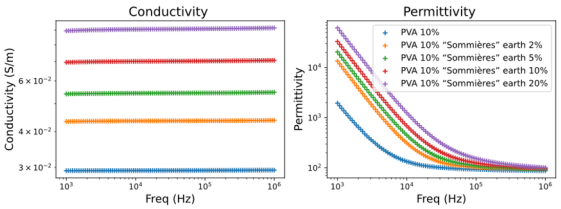

Figure 15: Electrical properties of PVA-C filled with various proportions of "Sommières" earth.

The addition of "Sommières" resulted in a moderate enhancement in conductivity and permittivity relative to NaCl or lignin. This improvement is likely due to its high surface area and ionic exchange capacity. Its effect on mechanical properties should be further explored to determine its practical applicability.

3.4.9 Diatomaceous Earth

Diatomaceous earth is too dense to remain suspended in the PVA mixture during freezing, causing it to settle at the bottom of the sample due to gravity. As a result, the samples exhibit inhomogeneity, and their electrical properties have not been characterised.

3.4.10 Plaster

Figure 16 shows the electrical properties of PVA-C filled with various amounts of plaster, compared to a pure PVA-C sample.

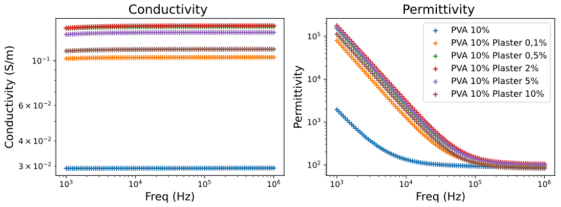

Figure 16: Electrical properties of PVA-C filled with various proportions of plaster.

Plaster exhibited a marked increase in both conductivity and permittivity. Its ease of handling and low cost make it a strong candidate for large-scale phantom development.

3.4.11 5-20 µm Glass Beads

The comparative electrical properties of PVA-C filled with different proportions of 5-20 µM glass beads, compared to a pure PVA-C sample, are presented in Figure 17.

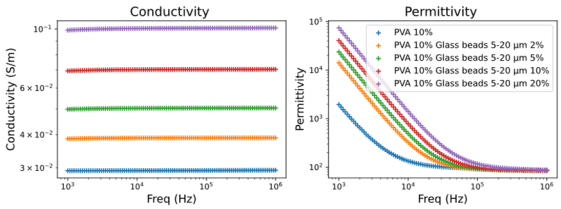

Figure 17: Electrical properties of PVA-C filled with various proportions of 5-20 µm glass beads.

The incorporation of glass beads into the hydrogel matrix results in a significant increase in both electrical conductivity and permittivity.

3.4.12 Glass Beads 150-200 µm

The 150-200 µM glass beads are too dense for the viscosity of the PVA mixture, causing them to settle at the bottom of the sample due to gravity. As a result, the samples lack homogeneity, and their electrical properties have not been measured.

3.4.13 Barium Titanate

Figure 18 illustrates the comparative electrical properties of PVA-C filled with varying proportions of barium titanate, compared to a pure PVA-C sample.

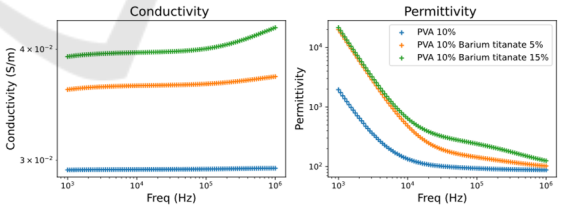

Figure 18: Electrical properties of PVA-C filled with various proportions of barium titanate.

The incorporation of barium titanate into the hydrogel resulted in an increase in both electrical conductivity and permittivity. The addition of 15% barium titanate led to a significant increase in permittivity, with a notable rise observed in the frequency range 10^4 to 10^6 Hz compared to the 5% barium titanate sample. The significant enhancement in permittivity at higher concentrations highlights barium titanate's suitability for applications requiring high dielectric constants.

3.5 Comparison with Literature Data

A comparative graph of the conductivity and permittivity of the samples is presented in Figure 19, alongside literature data from living muscle and fat tissue for reference.

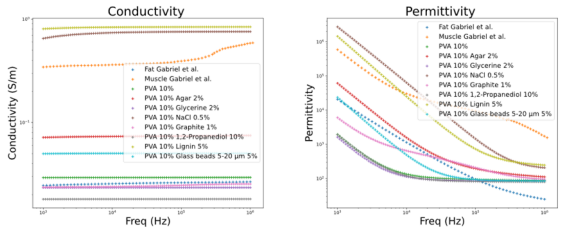

Figure 19: Electrical properties of samples compared with literature data for muscle and fat tissue.

The comparison with literature data confirms the effectiveness of the fillers in replicating the electrical properties of muscle and fat. For instance, NaCl and lignin closely mimic the high conductivity and permittivity of muscle tissue, while agar and glass beads align more closely with the lower values typical of fat tissue. The study highlights the importance of selecting appropriate filler combinations to fine-tune phantoms for specific tissues.

4 DISCUSSION

The influence of fillers on the electrical properties of PVA-C hydrogel are summarised in Table 4.

Table 4: Summary of the principal effects of fillers on the electrical properties of PVA-C hydrogel.

Increase in both conductivity and permittivity	Agar, NaCl, lignin, “Sommières” earth, plaster, glass beads, barium titanate
Decrease in both conductivity and permittivity	1,2-propanediol
Decrease in conductivity	Corn flour, glycerine
Change in conductivity and increase in permittivity	Graphite

It is observed that certain fillers are more effective in modifying the electrical properties of hydrogels. Depending on the objectives of the developed phantom, a combination of different fillers can be used to efficiently mimic the electrical properties of living tissues (see Figure 19). In previous works, the authors developed a muscle phantom by incorporating fillers such as agar, graphite, and NaCl into a PVA-C matrix. This formulation was specifically designed to mimic the electrical properties of living muscle tissue while exhibiting excellent mechanical properties. As a result, it provides a reliable model for bioimpedance studies (Bublex *et al.*, 2024).

The measurements performed on all samples demonstrated a plateau in permittivity at high frequencies (1 MHz). This plateau correlates with the relative permittivity of water ($\varepsilon_r = 80$), which can be attributed to the water-based composition of the samples. This behaviour is consistent with the expected properties of hydrogels and confirms the significant influence of water content on their electrical response.

PVA-C-based phantoms are predominantly investigated for their mechanical properties. However, it is essential to recognise that the incorporation of any filler inevitably impacts the hydrogel’s mechanical properties. For instance, while 1,2-propanediol effectively reduce conductivity, concentrations exceeding 10% result in a notable decline in mechanical strength, rendering the hydrogel difficult to handle.

The study of PVA-C revealed shrinkage and alterations in mechanical properties across freeze-thaw cycles. Further investigations are needed to assess these properties. Additionally, storage remains a significant concern; plastic film is not a viable option for maintaining electrical properties over an extended period. Vacuum packing should be investigated to prevent water loss.

5 CONCLUSIONS

This study comprehensively examined the impact of various fillers on the electrical properties of PVA-C hydrogels to enhance their suitability for bioimpedance spectroscopy (BIS) applications. Through systematic experimentation, the effects of fillers on electrical conductivity and permittivity were quantified and compared with the electrical properties of living tissues such as muscle and fat.

The results underscore the potential of specific fillers, such as NaCl and lignin, to closely mimic the electrical properties of muscle, while other fillers, like agar and glass beads, show promise for developing fat phantoms.

Furthermore, the study revealed that while fillers are essential for achieving the desired electrical characteristics, their incorporation also affects the mechanical properties of the hydrogel. This highlights the importance of optimizing filler

composition to balance both electrical and mechanical performance. The observed correlation between water content and permittivity emphasizes the need for improved storage solutions, such as vacuum packing, to maintain the long-term stability of electrical properties.

In conclusion, the findings of this research provide a robust foundation for developing advanced PVA-C-based electrical phantoms, offering reliable and stable alternatives for BIS studies and other biomedical applications.

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