ALTERING THE PERMITTIVITY OF DIELECTRICS FOR PRACTICAL APPLICATION

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STATEMENT OF CANDIDATE

I, John Goggin, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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ABSTRACT

Dielectric materials have a vast potential for application in technology. This project is focused on the use of dielectric phantoms to develop technology. More specifically, the development of more accurate phantom solutions by the development of a skin tissue analogue is explored.

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Chapter 1

Introduction

1.1 Dielectric Materials

1.1.1 Overview of Dielectrics

Dielectrics are materials which, when exposed to an electric field, become polarised, instead of merely passing electric current. They can be categorised by their permittivity, or dielectric constant, and loss factor.

Dielectric Constant

The dielectric constant of a material affects how an electrical signal passes through it. Sardar and Mishra write that, depending on the relative dielectric constant and conductivity of a dielectric material, the reection or transmission signal changes in terms of its amplitude and spread. [3]. These signal changes can be measured and analysed, to calculate the dielectric constant of a sample

1.1.2 Agar Based Dielectrics

This project mostly dealt with agar-based dielectrics. Due to their high water content, they a very accurate simulation of human tissue over a 300MHz to 2.5GHz frequency range. /citeito00 A useful recipe for such a material is based on powdered agar and deionised water, combined with polyethylene powder, sodium chloride, TX-151 (a binding agent), preservatives.

1.2 Applications of Dielectrics

1.2.1 Antenna Shielding

Due to the nature of dielectrics being polarised by electric fields, rather than acting as a conductor, they are the ideal substance for coating antennas. Their ability to be polarised means that wireless signals can quite effectively be passed through them. Additionally, their resistance to electrical signals allows them to still insulate the antenna, helping to prevent any short circuiting or electrocution.

For example, polydimethylsiloxane (PDMS) has proven to be an effective and reliable material for this. A silicone based substance, PDMS is flexible yet incredibly durable. This allows it to successfully protect bendable antennas, while doing little to compromise their motion or flexibility. On top of this, PDMS is low cost and simple to manufacture, allowing it to be produced rapidly and in large quantities.

However, it is still not the most ideal material to be utilised for antenna insulation. PDMS has a relatively low permittivity compared to other dielectric substances which are otherwise unsuitable, and fails to bond with many conductors. In order to produce more ideal iterations of PDMS for antenna coating, manufacturing processes need to be updated to raise its dielectric constant, and to allow it be combined with conductive wires and plates more effectively.

1.2.2 Dielectric Phantoms

Dielectric materials have the ability to pass electrical signals, but often absorb some of the signal's energy. As a result, certain dielectric materials can be calibrated to mimic the electrical properties of biological tissue across a range of frequencies. It is possible to create materials which act as analogues for the permittivity, loss factor, and scattering parameters of tissue for a desired signal. These analogues are known as phantoms.

This can be harnessed for a variety of practical applications. The fact that they can be used in place of human flesh provides opportunity for utilisation in the development and testing of various devices and technologies that would otherwise require human testing, completely removing any ethical or health isues that may arise. Such technologies include mobile phones and medical equipment. It is also possible to design specific phantom samples for use in the development of biomedical processes and technologies, such as the detection of cancerous growths and other irregularities.

However, most analogues are modelled from a single phantom. In reality, though, different types of tissue have distinct electrical properties, meaning that a homogeneous phantom is not the most accurate substitute. In order to fabricate a more realistic analogue, a layered sample should be created, with each material calibrated to represent different types of tissue, such as muscle and skin.

Chapter 2

Measurement with a Network Analyser

2.1 Overview

The network analyser is a dielectric probe kit. It allows for the measurement of dielectric constant, conductivity, loss factor, and scattering parameters of a sample.

It proved to be a vital tool for the completion of this project, providing information about materials that were being fabricated. This allowed for calibration of the materials as they were being created in order to reach the desired results.

2.2 Calibration

In order to accurately measure the dielectric properties of a sample, the equipment must be properly calibrated first.

This involves measuring the permittivity and conductivity of open air, a short circuit, and 25°C deionised water. Doing so allows the equipment to recalculate the relative permittivities of any samples that are measured thereafter.

2.3 Measurement

Measurement with the network analyser involves placing a probe on the surface of a sample. It is recommended that several measurements are taken, and then averaged, to reduce any errors that arise due to issues with the contact between the surface of the sample and the probe, irregularities in the makeup of the sample itself, and the positioning of the external wires that connect the probe to the equipment.

Chapter 3

The Development of Accurate Tissue Phantoms

3.1 Agar-Based Dielectrics

The dielectric material in focus is a solid agar-based phantom. The recipe consists of a mix of ceramic powders, which are congealed into a solid by the use of agar [2].

3.1.1 Advantages and Disadvantages of Agar-Based Phantoms

Advantages

There are several advantages to using such a recipe, including:

- Simple to manufacture.
- Relatively cheap, and ingredients are easy to obtain.
- Fairly accurate for a range of biological tissues.
- Electrical properties are easily calibrated to simulate various biological tissues.

In their 2006 paper, Onishi and Uebayashi mention some additional advantages [2]:

- Shape is maintained by the substance, so containers are not necessary once the sample is set.
- Arbitrarily shaped and multi-layered samples are achievable.
- Can simulate biological tissues with a high water content, including muscle and brain tissues.

Disadvantages

However, they are subject to some disadvantages, which need to be considered on the decision to utilise an agar-based dielectric as a phantom:

- Subject to rot after extended periods of time.
- Care must be taken not to inhale dusts and powders while manufacturing the material, as they can cause health issues.
- The recipe often sets with pockets of air inside, which can affect measurements pertaining to permittivity and conductivity.
- When solidified, samples tend to 'sweat', causing water to rise to the surface, again affecting measurements.
- Limitations exist on what can be created with this recipe. For example, polyethylene powder (used to decrease the permittivity of the phantom) increases the conductivity [2], which can sometimes render the creation of a low-permittivity low-conductivity tissue such as fat impossible to simulate.

It is feasible to avoid, or to at least minimise, the impacts of these issues though. Ensuring that the materials are not left uncovered for extended periods of time, and that a suitable amount of preservatives are added to the recipe, can delay any degredation of the sample.

Adequate safety equipment should be utilised while manufacturing to ensure powders are not inhaled. Such equipment includes masks, and mixing recipes inside fume hoods in order to contain the ingredients.

When testing, it is more accurate to take numerous measurements around various points across the surface of the sample. This will minimise the impact of water and air affecting the measurements. A significant impact of air on a measurement is very apparent, as it causes the permittivity to decrease by approximately 50-75%. Additionally, ensuring both the sample and the measuring instruments are dry in between uses will negate any issues arising from water covering the surface of the phantom.

3.2 The Necessity of Accurate Phantoms

3.2.1 The Current State of Agar-Based Phantoms

Many samples currently used as analogues for the human body are effectively homogeneous, comprised solely of one type of phantom. While this has its advantages, including:

- Easy to manufacture, especially in bulk.
- Simple to accurately replicate structures with complex shapes.

- No need to consider percentages and depths of different types of tissues.

However, this gives rise to problems involving the accuracy of testing, especially with small signals or high frequencies, which have a low level of penetration depth [1].

3.2.2 Layered Phantoms

It is proposed that a layered phantom sample would be a more accurate analogue than one which is homogeneous. Since the effectiveness of each layer would depend on the individual phantom solutions, it follows logically that this would be the case. The question raised, however, relates to whether the extra degree of realism would outweigh any issues caused in the manufacturing stages of a more complex structure.

A layered phantom would provide greater accuracy for testing of equipment intended to operate in close proximity to the human body, especially for devices operating externally such as mobile phones. Additionally, it would aid the development of non-invasive methods and technologies for the detection of medical irregularities, such as cysts and tumours.

Conversely, in manufacturing such a sample, it may be necessary to address a few challenges depending on the required body part. Care must be taken to achieve the correct proportions for each layer to ensure the effectiveness of the phantom. Also, for example, with complex structures such as faces or hands, issues can arise in achieving a suitable level of accuracy in the shape and proportions of each material, and the structure as a whole. Unlike a homogeneous material, a layered phantom may not be manufacturable with a simple mould, as each layer must be in a liquid state as it is added to the structure.

Chapter 4

Muscle Tissue Phantom

A recipe for the muscle phantom had been developed prior to initiating this project, from [2].

4.1 Properties of Muscle Tissue

Figures 4.1 and 4.2 show the relative permittivity and loss factors of biological muscle tissue respectively. These set the desired characteristics for the muscle phantom.

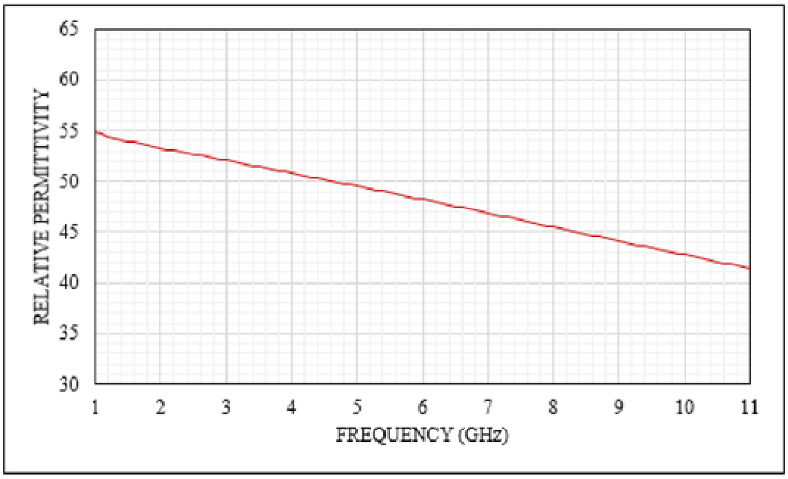

Figure 4.1: Relative permittivity of biological muscle tissue across a 1GHz-11GHz frequency sweep, sourced from the IT'IS Foundation Virtual Population database

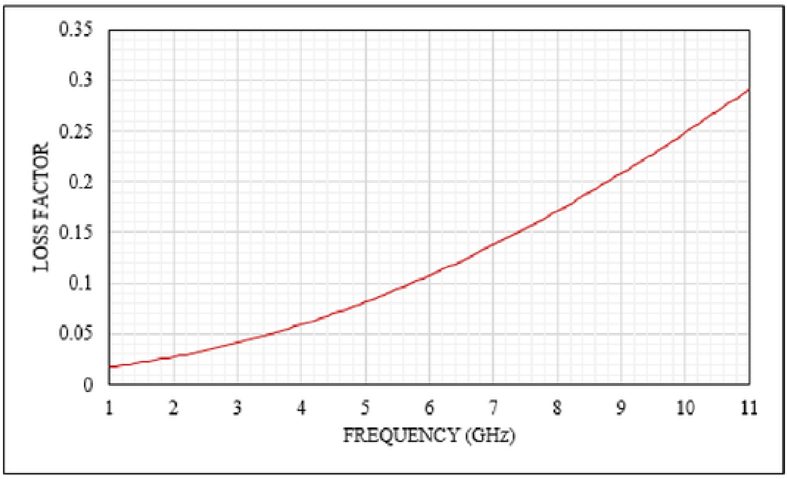

Figure 4.2: Loss factor of biological muscle tissue across a 1GHz-11GHz frequency sweep, sourced from the IT'IS Foundation Virtual Population database

4.2 Phantom Recipe

The method of creating the muscle phantom involves adding various substances to an amount of water to gradually alter its properties. Due to its relatively high permittivity at room temperature, and the fact that it is readily available, water is a highly effective base material. The mixture also relies heavily on agar and polyethylene powder (PEP) to allow it to be calibrated to faithfully mimic the desired substance.

In this case, 500g of the muscle tissue phantom was created. The amounts listed in table 4.1 relate to this quantity.

The phantom recipe for muscle consisted of the following:

Ingredient	Percentage	Amount Used (g)
Deionised Water	85.15%	425.75
Powdered Agar	2.64%	13.2
Dehydroacetic Acid Salt	0.05%	0.25
TX151	1.46%	7.3
PEP	10.52%	52.6
Sodium Chloride	0.18%	0.9

Table 4.1: Muscle phantom recipe, percentages are relative to mass.

The desired amount of each material was first measured and set aside, as per table 4.1 allowing for a more efficient mixing process. The deionised water was bioled first, and the powdered agar was added. This created a liquid agar base for the mixture, which solidified as it cooled. While this caused the resulting phantom solution to do the same, care had to be taken to work quickly and prevent it from congealing prematurely. The mixture had to be stirred thoroughly and vigorously to ensure it was correctly combined. The dehydroacetic acid salt was added simultaneously to the powdered agar. This acted as a preservative, helping to prevent degredation of the sample over time. Following that, the TX151 binding agent was added, which allowed the oil-based PEP to be combined with the water-based agar mixture. Subsequently, the PEP was mixed in. This lowered the permittivity of the phantom, allowing it to mimic that of muscle tissue. Finally, sodium chloride was added to raise the conductivity, and hence the loss factor, of the phantom material to the desired level.

Each substance was stirred intensively, with care taken to ensure they had been combined correctly before the next material was added. If the mixture is not combined correctly, it will not have uniform electrical characteristics. As such, an incompletely mixed solution will not provide an accurate simulation of biological tissue.

Immediately after all of the ingredients had been combined, it was poured into a square moulding dish. It was covered with plastic wrap to ensure the phantom did not dry out as it solidified.

In this instance, approximately 500 g of muscle phantom was created in order to verify the dielectric properties of the recipe.

Figure 4.3 shows the completed solution before it has completely set. The result is a very thick liquid, though the sample displayed in figure 4.3 had already begin the process of solidification. Meanwhile figure 4.4 shows the sample after solidification and moulding.

4.3 Phantom Properties

The relative permittivity and loss factor of the muscle phantom were measured using a network analyser. Due to the nature of the agar-based dielectric, five measurements were taken across various places on the surface. These results were then averaged, to reduce the impact that any air pockets, stray water, or inconsistencies in the sample had on the results.

The sample was subject to a frequency sweep from 1 GHz to 11 GHz. This provided a wide enough range to determine whether the measured properties of the phantom correspond satisfactorily to those of the biological tissue which they are simulating.

Figures 4.5 and 4.6 display the relative permittivity and loss factor of the muscle tissue phantom. Note their approximate correspondence with figures 4.1 and 4.2.

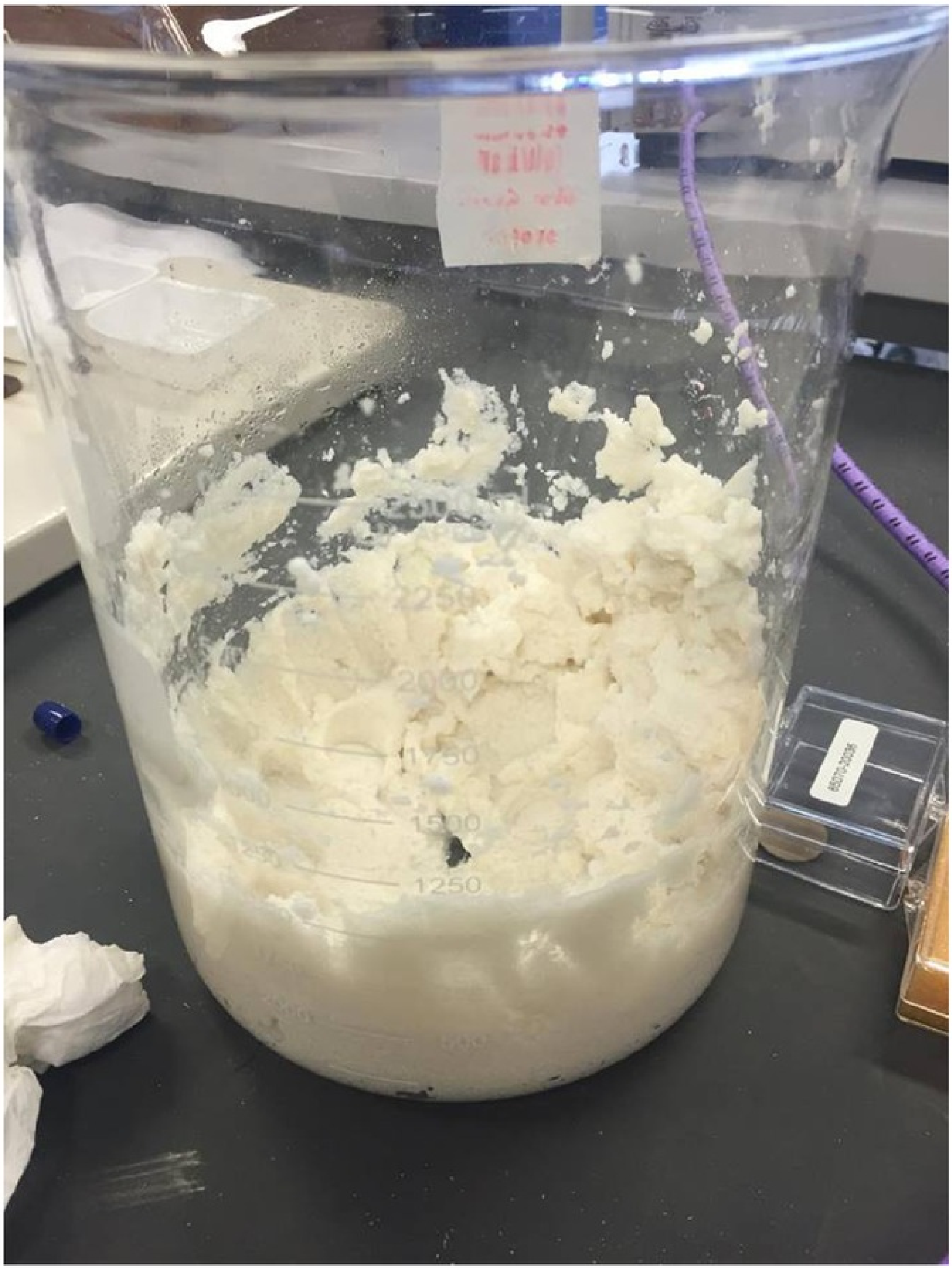

Figure 4.3: Muscle phantom before solidification

Figure 4.4: Muscle phantom after solidification

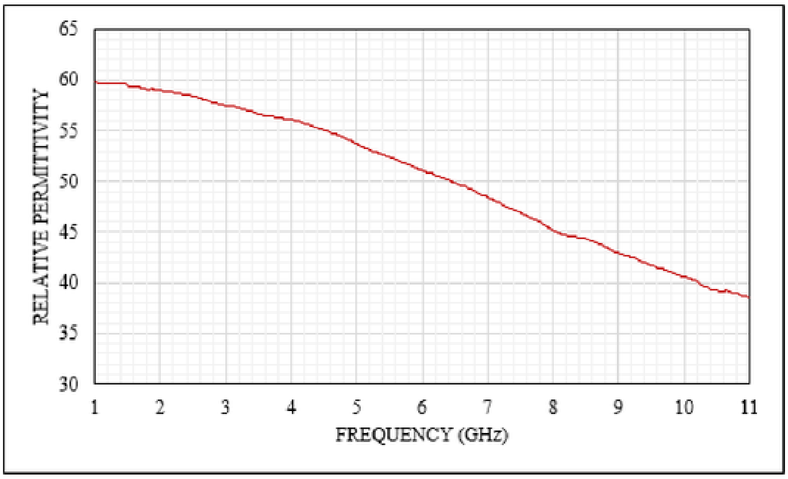

Figure 4.5: Average relative permittivity of the muscle tissue phantom across a 1GHz-11GHz frequency sweep

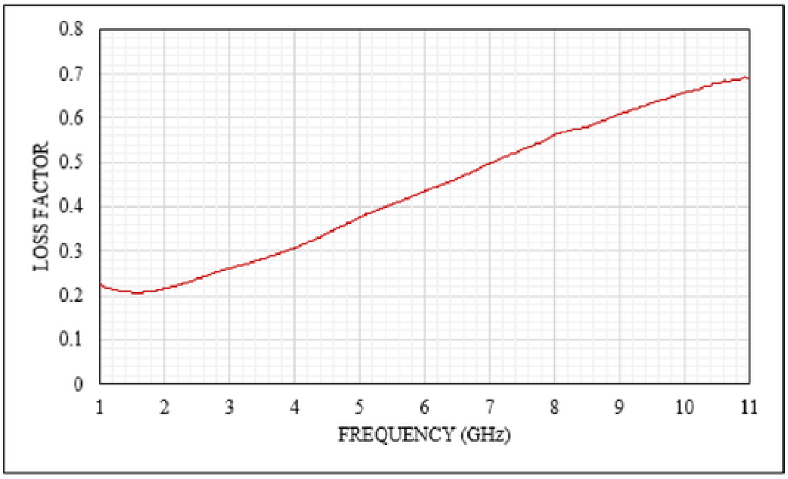

Figure 4.6: Average loss factor of the muscle tissue phantom across a 1GHz-11GHz frequency sweep

Chapter 5

Skin Tissue Phantom

The recipe for an effective skin tissue phantom had to be developed. It was created by adapting the muscle tissue phantom recipe from table 4.1.

5.1 Properties of Skin Tissue

Figures 5.1 and 5.2 show the relative permittivity and loss factors of biological skin tissue respectively. These set the desired properties for the phantom.

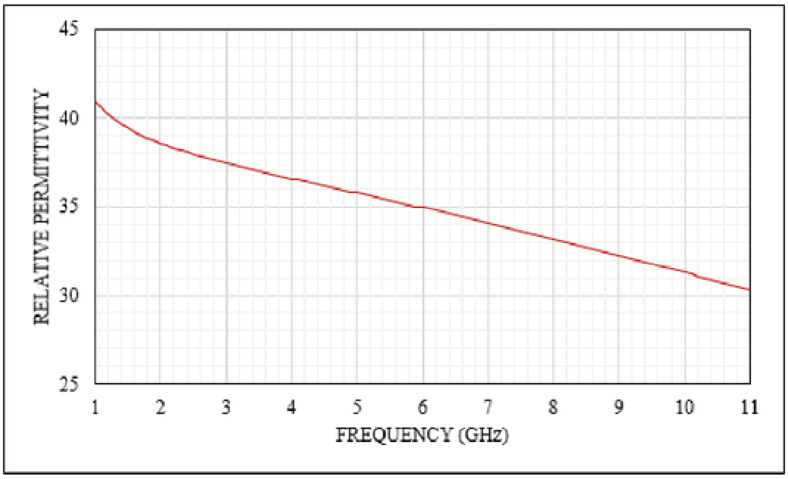

Figure 5.1: Relative permittivity of biological skin tissue across a 1GHz-11GHz frequency sweep, sourced from the IT'IS Foundation Virtual Population database

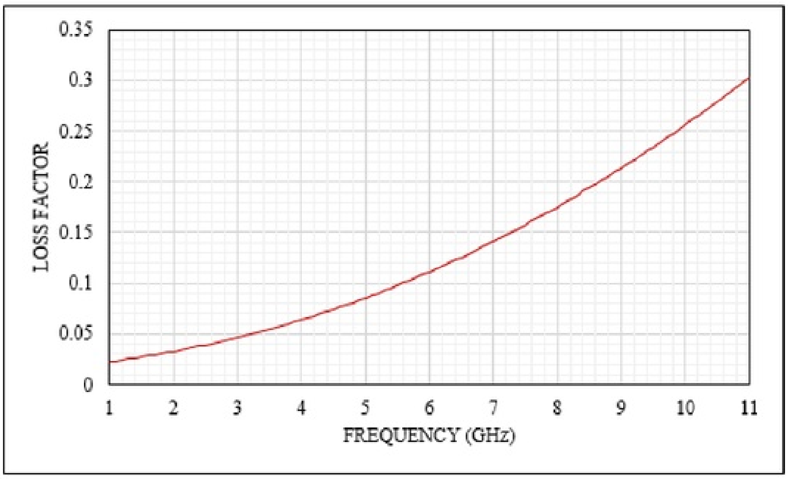

Figure 5.2: Loss factor of biological skin tissue across a 1GHz-11GHz frequency sweep, sourced from the IT'IS Foundation Virtual Population database

5.2 Recipe Development Method

The skin tissue phantom recipe was developed by carefully altering the recipe for the muscle tissue phantom solution until the desired characteristics were met.

The first step in developing the recipe for the phantom was to approximate the amount of PEP that would be required. Since the percentage of PEP in a solution and the resulting relative permittivity have an approximately linear relationship [2], it was possible to extrapolate an approximate value from known data. The two samples considered were pure deionosed water and the muscle tissue phantom. While the PEP is technically added to a mixture of water, agar, dehydroacetic acid salt, and TX151, their effect on the relative permittivity is negligible enough to be overlooked for an approximation.

The values for ϵ_r were taken at 1 GHz, and at a temperature of approximately 25^{o}C. Under these conditions, deionised water has a relative permittivity value of $\epsilon_r \approx 80$, with no PEP added. Meanwhile, with a PEP concentration of 10.52%, the muscle tissue phantom recipe has $\epsilon_r \approx 60$ as its permittivity. Due to slight differences in permittivity and loss factor across the surface of the phantom samples, which arise as a result of the quality of the mixture and interior air pockets, the properties of the finished sample should be within a range to be considered successful. The desired range of permittivity for the skin tissue phantom was as per equation 5.1. By the use of figure 5.3, an extrapolation of these values, this gave an approximate percentage range of PEP as per equation 5.2.

$$40 \leq \epsilon_{r,skin} \leq 45 \tag{5.1}$$

$$15.78 \leq \%PEP \leq 18.41 \tag{5.2}$$

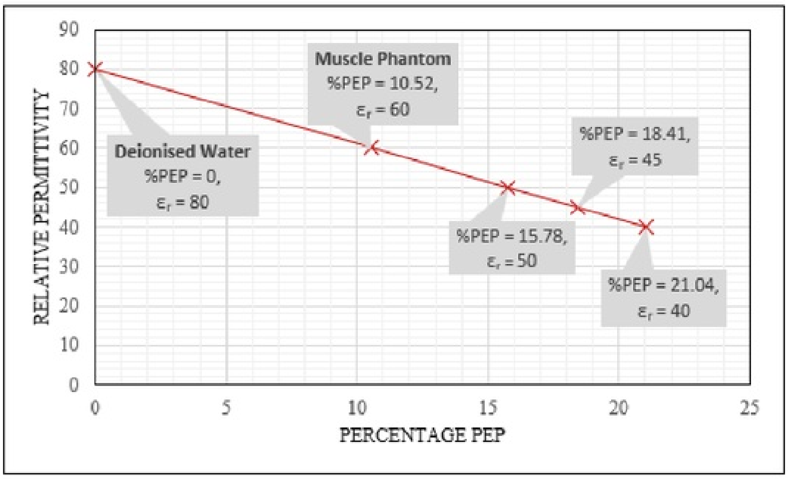

Figure 5.3: Extrapolated relative permittivity graph used to approximate the required amount of PEP for the skin tissue phantom

The recipe for the muscle phantom was then followed until the TX151 was combined. 78.9 g of PEP was then added (approximately 15.78% of a total 500g phantom mixture) was added to the solution. Measurements of the relativity taken revealed the average relative permittivity value to be above the required range. As such, more PEP was added carefully until the desired result was achieved. In order to be certain how much was added, a measured amount was taken to be added, and any remaining PEP was subtracted from this total.

The required value of sodium chloride was reached by use of the same method. However, since the amount was very small (<1g), an approximate mass was not predicted beforehand. This was done in the interest of conserving time. Additionally, variations in consistancy and electrical properties throughout the mixture may have rendered any predictions redundant.

This method revealed the required amounts of PEP and sodium chloride to be 87.65 g and 0.4 g respectively for a total mass of 500 g. The percentage concentrations of these are as per table 5.1.

5.3 Phantom Recipe

The resulting skin phantom recipe was fairly similar to the muscle phantom, with the amounts of PEP and sodium chloride having merely been adjusted. Table 5.1 shows the final amounts and concentrations used for the skin tissue phantom.

The phantom produced by this recipe was visually identical to the muscle phantom displayed in figure 4.4.

Ingredient	Percentage	Amount Used (g)
Deionised Water	78.55%	392.42
Powdered Agar	2.43%	12.15
Dehydroacetic Acid Salt	0.04%	0.23
TX151	1.35%	6.75
PEP	17.55%	87.65
Sodium Chloride	0.08%	0.4

Table 5.1: Skin phantom recipe, percentages are relative to mass.

5.4 Phantom Properties

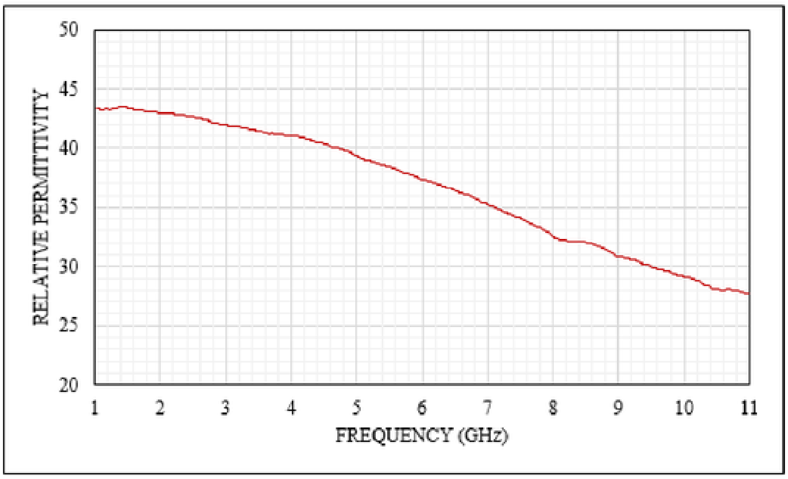

Figure 5.4: Average relative permittivity of the skin tissue phantom across a 1GHz-11GHz frequency sweep

Measurements were taken as per the process for measuring the muscle tissue phantom as described in section 4.3.

Figure 5.4 shows the relative permittivity of the skin tissue phantom, while figure 5.5 displays the loss factor. Note their approximate correspondence with their respective biological counterparts, as per figures 5.1 and 5.2.

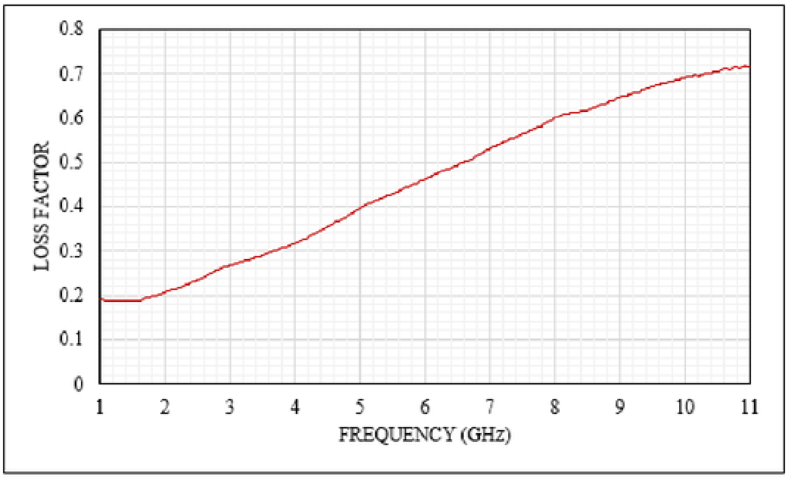

Figure 5.5: Average loss factor of the skin tissue phantom across a 1GHz-11GHz frequency sweep

Chapter 6

Layered Phantom

6.1 Hypothesis

It is logical that a layered phantom sample would more realistically represent the human body than a uniform phantom. However, whether the benefits of enhanced accuracy and precision outway the extra use of required resources to produce such a sample, as opposed to fabricating a sample of muscle or skin tissue phantom with the same dimensions, is a topic for exploration.

The hypothesis for here is that the more intricate sample will give significantly different results to the uniform muscle phantom.

The proposed structure for the layered phantom sample is as per figure 6.1.

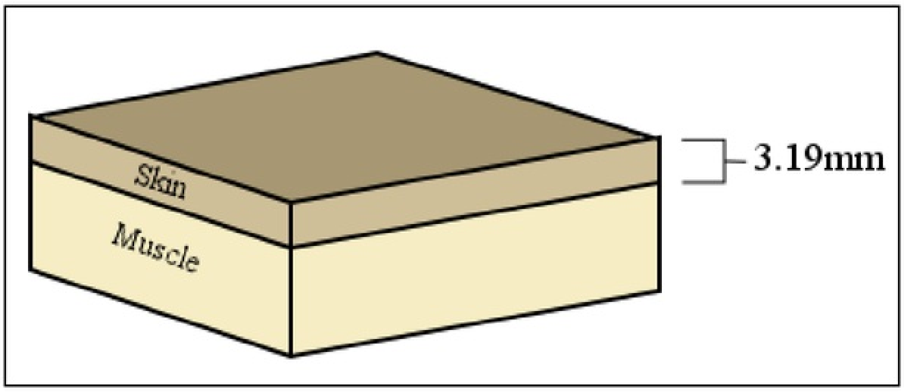

Figure 6.1: Structure of layered phantom sample

6.2 Method of Creating the Layered Phantom

6.2.1 Fabricating the Layers

Each layer, muscle and skin phantoms, of the sample were mixed according to their aforementioned recipes in sections 4.2 and 5.3 respectively.

6.2.2 Layering the Phantoms

The sample was built from the bottom upwards. First the muscle phantom was placed and the top was neatened up by cutting through it with fine string. The same was done to the bottom of the skin tissue phantom. This was to ensure satisfactory contact was made between the two, preventing air pockets from forming and affecting the measurements.

The skin sample was then cut to the desired thickness using the string. The thickness was selected to be approximately 3.19 mm, which is the thickness of the skin on the average human shoulder [4]. This was chosen due to its significant size, giving the best indication of any differences between the inclusion of the skin layer, and the pure muscle and samples. Finally, the edges of the layered phantom were cut to reduce any interference that the shape of the sample would have with the results.

Figure 6.2 shows the completed layered phantom sample.

6.2.3 Layered Phantom Properties

The relative permittivity and loss factor of the layered phantom sample were measured using the network analyser, in the same manner as described in section 4.3.

Figure 6.3 displays the relative permittivity of the phantom, displayed with those of the individual muscle and skin phantoms. Let it be noted how it more closely follows the permittivity of the skin tissue phantom than that of the muscle, though still with an amount of deviation. Meanwhile the loss factor, as displayed in figure 6.4, follows both that of the skin and muscle phantoms quite closely at lower frequencies, but oscillates as the frequency increases.

Figure 6.2: Layered phantom sample

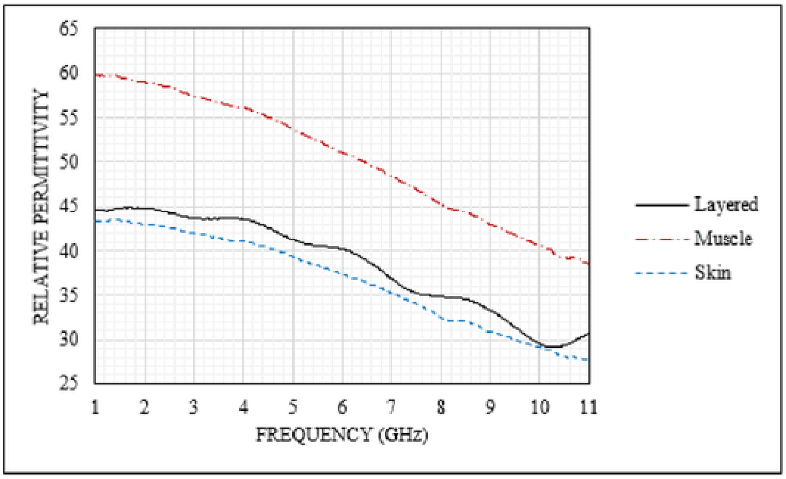

Figure 6.3: Comparison of the average relative permitivities of the muscle, skin, and combined phantoms across a 1GHz-11GHz frequency sweep.

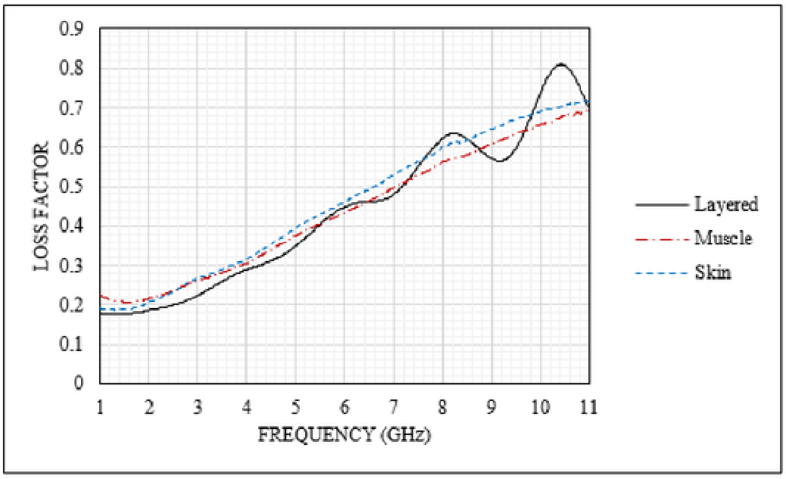

Figure 6.4: Comparison of the average loss factors of the muscle, skin, and combined phantoms across a 1GHz-11GHz frequency sweep.

Chapter 7

Discussion

It is apparent that both of the uniform material phantoms adhere to the required characteristics, as established by their biolgical counterparts. However, there is still further room for improvement, both in the results, and the methods used to obtain them.

More accurate phantoms can be created with careful experimentation with the recipe. Additionally, they can be more precisely calibrated for a specific frequency.

This would further increase the accuracy of the layered phantom. Interestingly, the layered sample more closely resembled the skin tissue phantom than the muscle phantom, even though the latter seems to be more popularly used to approximate the human body [2]. It is apparent that, for frequencies higher than those used for medical application, a layered sample is necessary, as the oscillation in the loss factor is rather significant.

While the use of the agar-based phantom recipe was effective and successful to a degree, there are still some issues to be overcome. Most importantly, it can be difficult to ensure that the solution is mixed uniformly, causing significant variation depending on where on its surface measurements are taken. Additionally, the creation of pockets of air during its creation, and the fact that the mixture 'sweats' water as it sets can affect the relative permittivity and loss factor of the phantom.

Another issue with the agar-based recipe is the fact that a phantom analogue for human fat in unobtainable with the current ingredients. The permittivity needs to be lowered to a point such that the required amount of PEP raises the conductivity and loss factor above that of biological fat. As such, a different recipe would be required in order to achieve this. The inclusion of a fat layer would further enhance the accuracy of the layered phantom sample.

The methods for creating and calibrating the phantoms could also be improved. The current method is to measure while slowly pouring the PEP and sodium chloride, mixing each time. However, this poses two problems. The first relates to the difficulty of mixing the solution uniformly, especially with a narrow time frame to ensure the mixture does not solidify before the desired amount is reached. On top of this, if too much of an ingredient is added, the process must be completely restarted. In the development of the skin phantom, several attempts had to be made in order to achieve the correct level of sodium chloride, wasting time and physical resources.

However, overall, the phantoms produced satisfactory and insightful results.

Chapter 8

Conclusion

The endeavour to develop a recipe for skin tissue proved to be somewhat successful. The development of a skin tissue phantom recipe can be implemented in several applications, such as antenna testing and medical equipment development. Additionally, the results produced by the layered phantom proved especially interesting, showing that the uniform skin tissue phantom more accurately reflects the electrical properties of a composite sample.

Chapter 9

Future Work

Further research and experimentation can improve upon the results presented here.

While technically functional, there is room for improvement in the methods and recipes used to create the phantoms. More specifically, more accurate methods to calibrate and mix the phantoms would prove vital to future research.

Similarly, research into the development of a fat tissue phantom would heighten the accuracy of the layered sample. Additionally, recipes for bone, organ, and other phantoms could further enhance this.

This would allow for improved applications, such as the development of non-invasive medical equipment to externally detect the presence of biological irregularities, such as tumours, cysts, and cancerous growths.

Improved methods in accurately structuring and shaping layered phantom samples into complex shapes would allow for more effective technology to be developed. Both in the medical industry, but also for mobile phones and other devices that operate wirelessly in close proximity to the human body.

Finally, efforts in improving antenna technology that operates in and around the human body would be highly useful and relevant to further research into phantom technology. For example, raising the dielectric constant of PDMS, and allowing it to be more easily combined with conductive materials would allow for more effective devices to be developed.

Chapter 10

Abbreviations

PDMS	polydimethylsiloxane
PEP	polyethylene powder

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