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RESEARCH AND TESTING OF TISSUE SIMULATING MATERIALS

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ABSTRACT

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The topic for this thesis was commissioned by Verkotan Oy. Verkotan Oy is providing testing and consulting services at the wireless industry.

The aim of this thesis was to determine mixtures that simulate dielectric properties of the human or animal tissue at larger frequency ranges than the known mixtures and analyze the possibilities of ballistic gel to simulate electrical properties of different parts of the human body. Other part of the thesis was to learn the principles of measuring instruments that can be used to measure the dielectric parameters of the materials.

The work on this subject started by researching tissues dielectric properties and materials that can be used in the mixtures. Recipes found in the research were manufactured and tested.

Many recipes were found in research at different frequency ranges and some of the recipes were tested in practice. Experiments showed that tissue simulating gel is capable of simulating different parts of the tissue dielectric properties at least at known frequency ranges.

Keywords:

Tissue, SAR testing, dielectric properties

CONTENTS

INTRODUCTION

This thesis was commissioned by Finnish company, Verkotan Oy. Verkotan Oy is providing testing and consulting services at the wireless industry.

The aim of this thesis was to research and develop mixtures that simulate dielectric properties of the human or animal tissue at frequency ranges of known mixtures. A tissue simulating mixtures can be used in SAR measurements. SAR (Specific Absorption Rate) is a measure of how much radio frequency energy is absorbed by a human or animal body. Permittivity and conductivity are the dielectric properties of the tissues to be studied in this thesis. Ballistic gelatin is known to simulate human tissue's mechanical properties but it needs to be studied what is the possibilities of using ballistic gelatin phantoms to simulate dielectric properties of the different parts of the body.

Other part of this thesis was to learn what kinds of measuring systems are needed to measure the mixtures and to understand the operating principles of the systems.

In this thesis main sources are RF Exposure standards that define the requirements for the dielectric properties of the tissue simulating liquids.

1 THEORY OF TISSUE SIMULANTS

1.1 Dielectric Properties of Tissue

Human or animal tissue consists mostly of water, salts that are dissolved into the water and other organic compounds, such as amino acids, carbohydrates, nucleic acids and fatty acids. A high water content and cellular structure are the main factors influencing the electrical properties of the tissue. (1, p. 60.)

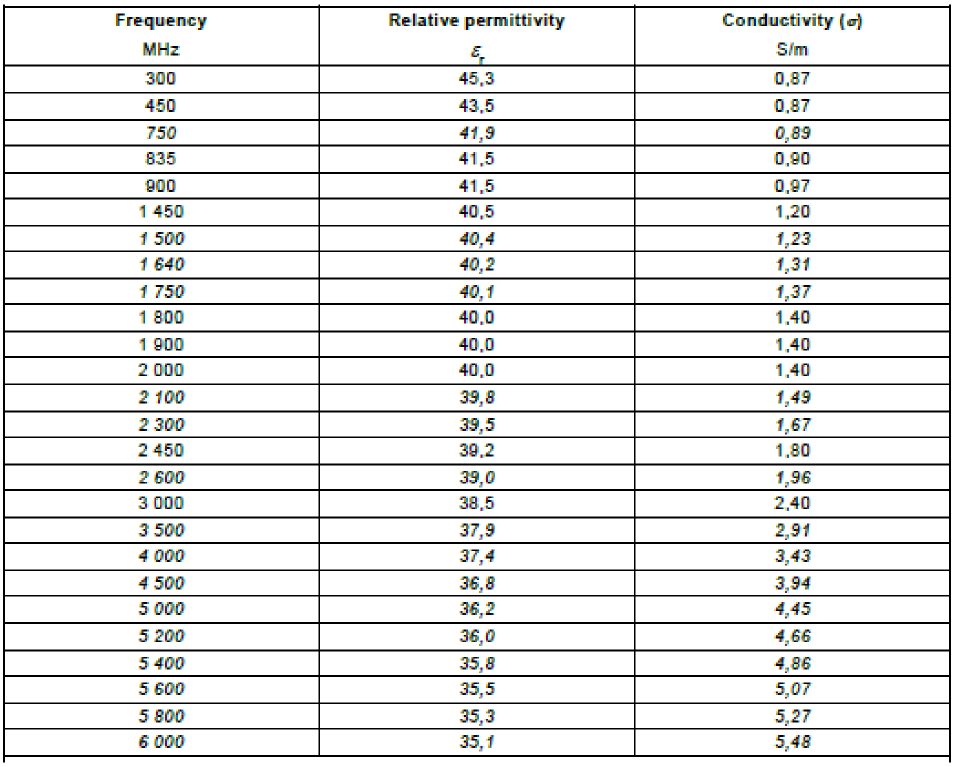
Dielectric properties of the tissues are defined by the complex permittivity. Complex permittivity means how the tissue interacts with an external electric field. Dielectric polarization in the tissue is caused when the electric field is applied. The real and the imaginary terms of the complex permittivity are related by:

$$\varepsilon(\omega) = \varepsilon^{'}(\omega) - j\varepsilon^{''(\omega)} = \varepsilon^{'}(\omega) - j\frac{\sigma(\omega)}{\omega\varepsilon_{\circ}} \tag{1}$$

Where ω is frequency. The real part of the complex permittivity is ε’. The imaginary part of the permittivity is ε’’. It reflects the dissipative nature of the tissue, which absorbs energy. Conductivity is σ, it refers the tissue’s ability to conduct an electric current. Conductivity is linked to the imaginary part of the complex permittivity. (2, p.3.)

Dielectric properties depend on frequency. As the frequency increases, permittivity decreases, and conductivity rises. Temperature affects dielectric properties.

According to the standard EN 62209-1:2016, relative permittivity and conductivity values of the tissue at 300 - 6000 MHz frequency range are shown in figure 1. In SAR testing the measured relative permittivity and conductivity must be within ±5% of the target values. If the SAR correction methodology is applied, a deviation can be within ±10% of the target values. The SAR correction methodology is used to reduce the measurement uncertainty. (3 p. 24, 72.)



Frequency MHz	**Relative permittivity** ε_r	**Conductivity (σ)** S/m
300	45,3	0,87
450	43,5	0,87
750	*41,9*	*0,89*
835	41,5	0,90
900	41,5	0,97
1 450	40,5	1,20
1 500	*40,4*	*1,23*
1 640	*40,2*	*1,31*
1 750	*40,1*	*1,37*
1 800	40,0	1,40
1 900	40,0	1,40
2 000	40,0	1,40
2 100	*39,8*	*1,49*
2 300	*39,5*	*1,67*
2 450	39,2	1,80
2 600	*39,0*	*1,96*
3 000	38,5	2,40
3 500	*37,9*	*2,91*
4 000	*37,4*	*3,43*
4 500	*36,8*	*3,94*
5 000	*36,2*	*4,45*
5 200	*36,0*	*4,66*
5 400	*35,8*	*4,86*
5 600	*35,5*	*5,07*
5 800	*35,3*	*5,27*
6 000	*35,1*	*5,48*

FIGURE 1. Target dielectric properties of the tissue (3, p. 112)

Different tissue types have different dielectric properties. Tissues can be divided into two groups: Tissues having a high water content, such as brains, skin and muscles, and tissues having a low water content, such as fat and bone. High water content tissue's permittivity can be more than ten times higher that of low water content tissues (1, p. 77.)

Different layers of the tissue can increase the RF absorption at certain frequencies. Layers are affected by anatomical variations, such as age, sex or BMI. Therefore, target values of the tissue dielectric properties are a combination of different tissues to provide conservative SAR values. From 150 MHz to 10 GHz relative permittivity values of tissue simulants are approximately 10 % greater than brain gray matter. Conductivity values are similar than brain white matter and muscle tissue. Due to tissue layering in the body, the conductivity has been increased at some frequencies. (4, p.191.)

1.2 Tissue Simulating Liquids

Tissue simulating materials covered in this paper have practical use cases as

- Electrical use
  - SAR measurements
  - OTA (Over-The-Air) measurements
  - MRI performance
  - Simulations of body and implant receivers. (5.)

- Physical use
  - Ballistics
  - Medical training.

1.2.1 Materials for Tissue Simulating Liquids

Human body contains more than 200 types of cells that can be classified into tissues. All types of tissues have its own dielectric properties. Tissue simulating liquids can be manufactured by oneself as long as liquid meets standard requirements. The list of example ingredients that can be used for mixtures are:

- Sucrose
- Salt
- Deionized water
- Hydroxyethyl Cellulose
- Bactericide
- Glycol
- Diacetin
- 1,2-Propanediol
- Polyoxyethylene sorbitan monolaurate
- Emulsifiers
- Mineral oil. (3, p.177.)

1.2.2 Recipes for Tissue Simulating Liquids

The ingredients used in tissue simulating liquids are selected based on the electrical properties of the materials. By mixing the right ingredients with the right ratio, it is possible to get the same electrical properties for the simulating liquid as in the tissue. (3, p. 156.) In studies there are plenty of recipes to make tissue simulating liquids. Many tissue types consist mostly of water, therefore water is often used in the tissue simulating liquids. Water has a high permittivity, and it can be easily mixed with other ingredients.

By mixing the specific ratio of deionized water, salt, polyethylene powder and TX-150, the mixture can be used to simulate the tissue at the frequency range of 13 MHz - 2450 MHz. Studies show that the dielectric properties of the mixture are matched with high-water-content tissues, such as body tissue. TX-150 is a gelling agent. (6 p. 4246.) The mixture of deionized water and polysorbate, such as tween and salt, are known to simulate dielectric properties of the body tissue at the frequency range of 150 MHz - 3000 MHz.

The mixture of tween and deionized water can be used at 8 GHz and 10 GHz. The mixture is sufficiently broadband so that it could cover the frequency range of 6 GHz to 10 GHz within the tolerance of ±10% for permittivity and conductivity. (4 p.178-179.)

The mixture of oxidized oil and deionized water can be used at the frequency range of 450 MHz - 6 GHz. The mixture is corresponding dielectric properties of the body tissue and the mixture remains stable homogeneous through the entire frequency range. (4, p. 178-179)

The gelatin based mixture of ballistic gelatin, deionized water and salt can be used at low frequencies, below 30 MHz. Ballistic gelatin has stable mechanical properties. The gel can be cut easily to a desired shape. The challenge of the gelatin-based mixtures are that when two materials with different gelatin concentrations are mixed, gelatin does not stay stable over a long time. (6, p.4247.)

1.3 Ballistic Gelatin

Ballistic gelatin is known to model mechanical properties, density and viscosity of the human body. A ballistic gel can be used to model surgical needle insertions, burned skin replacements, sports injuries and the penetration resistance of ballistics. (7 p. 1.)

For devices using a radio frequency, a ballistic gel can be used for simulating the tissue in a situation where the device is placed inside the skin, for example implants. A ballistic gel can also be used to simulate electrical properties of the different parts of the body when the ballistic gel is mixed into the tissue simulating liquid. A ballistic gel is made by mixing water and gelatin powder. The gel itself is not suitable to simulate tissues. Parameters of the electrical properties can be modified by mixing salt to the ballistic gel. The ballistic gel is recommended for low frequencies. (8.) Figure 2 shows the effects of salt on impedance in ballistic gelatin.

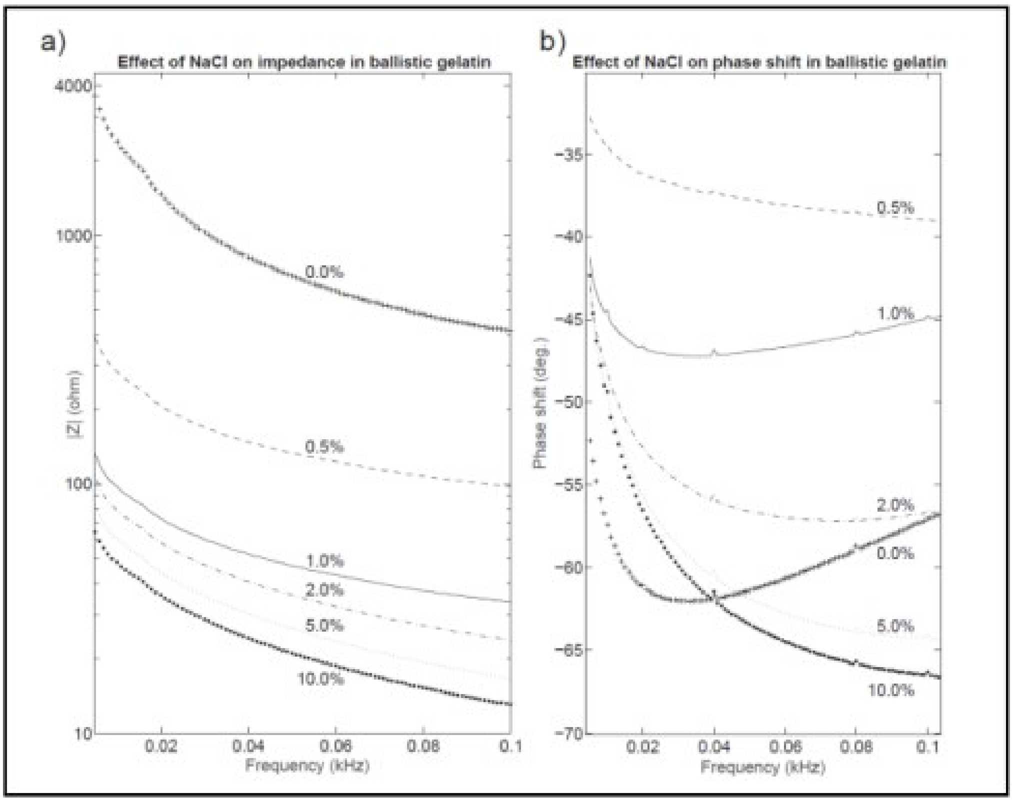


FIGURE 2. Effect of salt loading on ballistic gelatin impedance (8).

2 SPECIFIC ABSORPTION RATE

2.1 What is Specific Absorption Rate?

Specific Absorption Rate (SAR) measures the amount of radio frequency (RF) energy absorbed by a human or animal body. The unit of the SAR is watts per kilogram (W/kg) and the results of the testing are a peak-spatial average of either 1g or 10g tissue volume. For wireless devices such as mobile phones operating in radio frequency SAR values need to be measured. SAR measurements are tested with maximum power to get the worst-case operating conditions in all frequency bands that are operated. Usually in real life, the transmitting power of the device is much lower than tested maximum output power and the devices are transmitting only when power is on. (9.) In actual use the SAR values are much lower than the measured SAR.

In SAR testing standardized phantoms are used to model a human body. Phantoms are filled with a tissue simulating liquid. The liquid simulates dielectric properties of the human or animal tissue. (9.) Each part of the body tissue has different dielectric values, and they depend on frequency.

2.2 Why SAR is measured

In modern times people are using wireless devices such as mobile phones, that use radio frequencies. A mobile phone communicates with a base station by sending radio waves through a network (10). When a mobile phone is transmitting, radio waves create electromagnetic fields that can be absorbed to the human tissue (11). SAR is measured to ensure that RF exposure characteristics of the devices are within the safety limits (9). For wireless devices operating below 6 GHz and which can be used closer than 20 cm from a human body or head, SAR testing is required before the device is brought to market. (11.)

There are many types of wireless devices that use radio frequencies such as devices that are included in the cellular technology, Bluetooth technology or WLAN. For example, laptops, wireless Bluetooth headphones, GPS systems and TV remotes. (12.) An excessive radiation exposure may be a health risk. According to the World Health Organization (WHO), no serious health risks have emerged from the use of mobile phone:

“A large number of studies have been performed over the last two decades to assess whether mobile phones pose a potential health risk. To date, no adverse health effects have been established as being caused by mobile phone use.” (10.)

2.3 SAR Testing for Portable Devices

2.3.1 Organizations and Standards

Standards that define regulations and exposure limits for SAR testing are based on the guidelines of different organizations. Standards used in Europe and in many countries outside the Europe, such as Australia, are based on the ICNIRP (the International Commission of Non-Ionizing Radiation Protection) guidelines. Standards used in the United States of America and Canada are based on the IEEE (the Institute of Electrical and Electronic Engineers) guidelines. (13, p.321.)

2.3.2 Phantoms

According to the standard IEC-62209, phantoms are used in SAR testing to model the human body or head. Phantoms are filled with the tissue simulating liquid. There are two types of phantoms that are used in SAR testing: Specific Anthropomorphic Mannequin (SAM) phantom and flat phantom. (14.)

The SAM phantom is a shape of the human head and it is shown in figure 3. It is used for testing wireless devices that are held against the head at the human’s ear, such as mobile phones. The flat phantom is used for wireless devices that are body mounted or hand held. (14.)

FIGURE 3. SAM phantom filled with tissue simulating liquid

The flat phantom is an open-top container with a flat bottom, and it is used for simulating the human body in SAR testing. The flat phantom is filled with the tissue simulating liquid. The liquid depth should be at least 15 cm to minimize reflections. The device under test is placed under the phantom. The phantom is made of low-loss and low-permittivity material and a thickness of the bottom-wall must be 2 mm with a tolerance of ±0.2 mm. (15, p.14-15.)

2.3.3 SAR Test Positions

There are different positions to measure SAR. For mobile phones, the head position needs to be tested. The head position consists of cheek and tilt positions which are required to be tested. Both positions are measured on the left and right side of the head. In the cheek position a mobile phone is placed under the phantom so that the acoustic output touches the center of SAM-phantom’s ear. The tilt position is the same position as that of cheek’s, but the angle is increased by 15 degrees. (16.) The cheek position and tilt position are shown in figure 4.

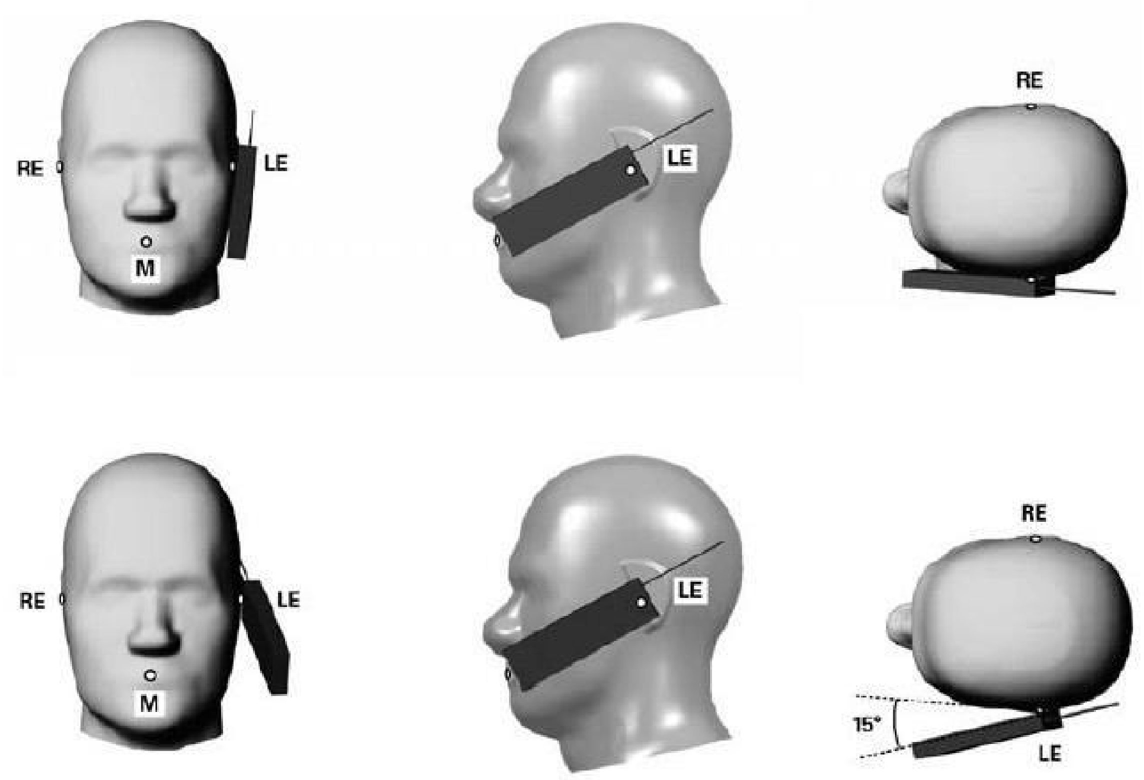


FIGURE 4. Cheek position and tilt position (3, p. 30,32)

When the device is used less than 20 cm of the human or animal body, the body position needs to be tested. In the body position, the device is placed under the phantom and every side of the device is tested. The separation distance between the tested device and phantom is usually 5 mm or less. (15, p. 23-25.) The body position is shown in figure 5.

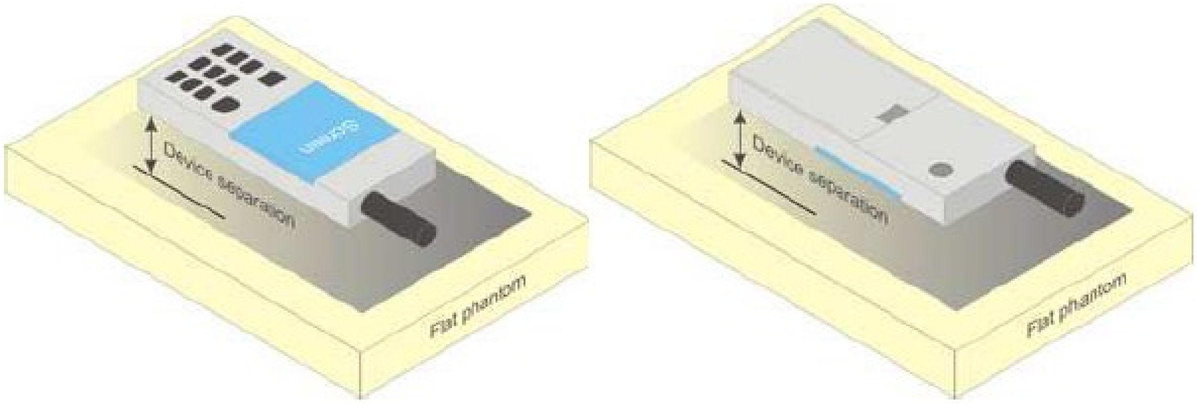


FIGURE 5. Body position, front and back (15, p.24)

The limb position is used when the device is in contact with a human limb, for example a mobile phone, smart watch. In the limb position, the device is placed against the phantom with a 0 mm separation distance. (15, p.29.)

2.4 SAR Testing Regulations and Exposure Limits

There are authorities in different regions who define the exposure limits and regulations of the SAR, such as the European Union (EU), the Federal Communication Commission (FCC) in the United States and Innovation, Science and Economic Development Canada (ISED).

The exposure limits for the head SAR and body SAR are in Europe 2.0 W/kg and they are measured from the tissue volume of 10g. In North America limits are 1.6 W/kg and they are measured from the tissue volume of 1g. For the limb SAR exposure limit is 4 W/kg and it is measured from the tissue volume of 10g. (17.) Exposure limits are shown in figure 6.

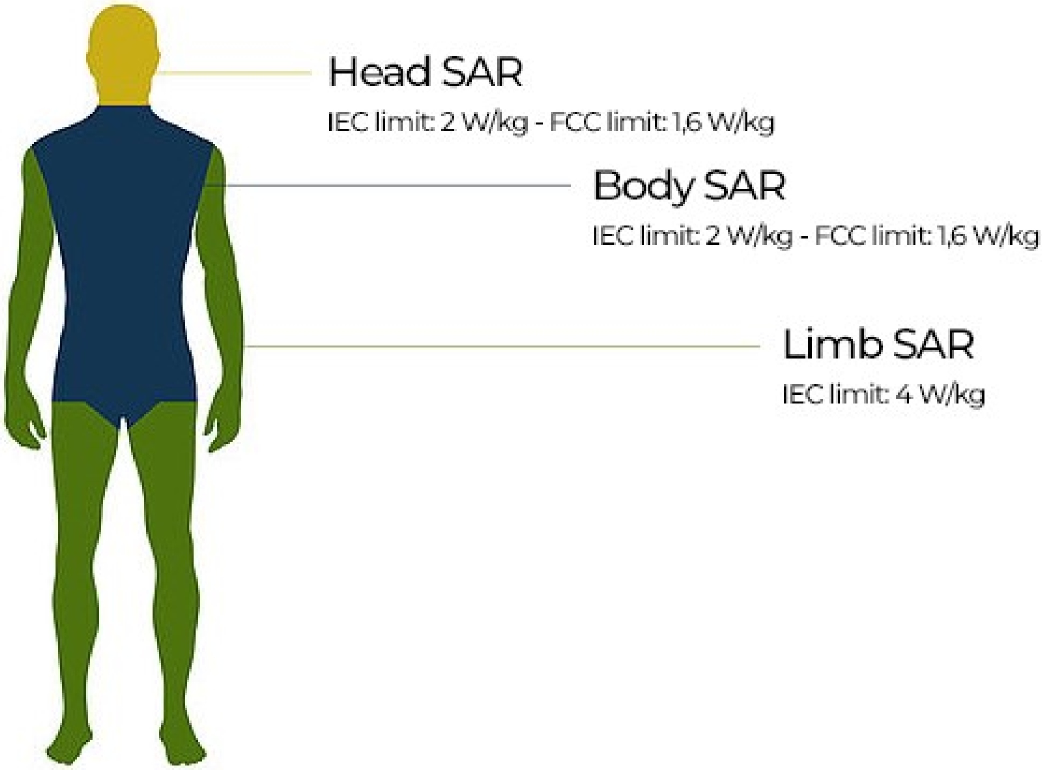


FIGURE 6. Exposure limits (17)

3 MEASURING INSTRUMENTS

3.1 Vector Network Analyzer (VNA)

Vector network analyzer (VNA) operating frequency can range from 1 Hz to 1.5. THz (18). VNA is used to measure the dielectric properties of the tissue simulating liquids above 100 MHz (19 p.16). VNA measures S-parameters of the material and it is converted to the dielectric properties as a function of frequency by the software (20 p. 3).

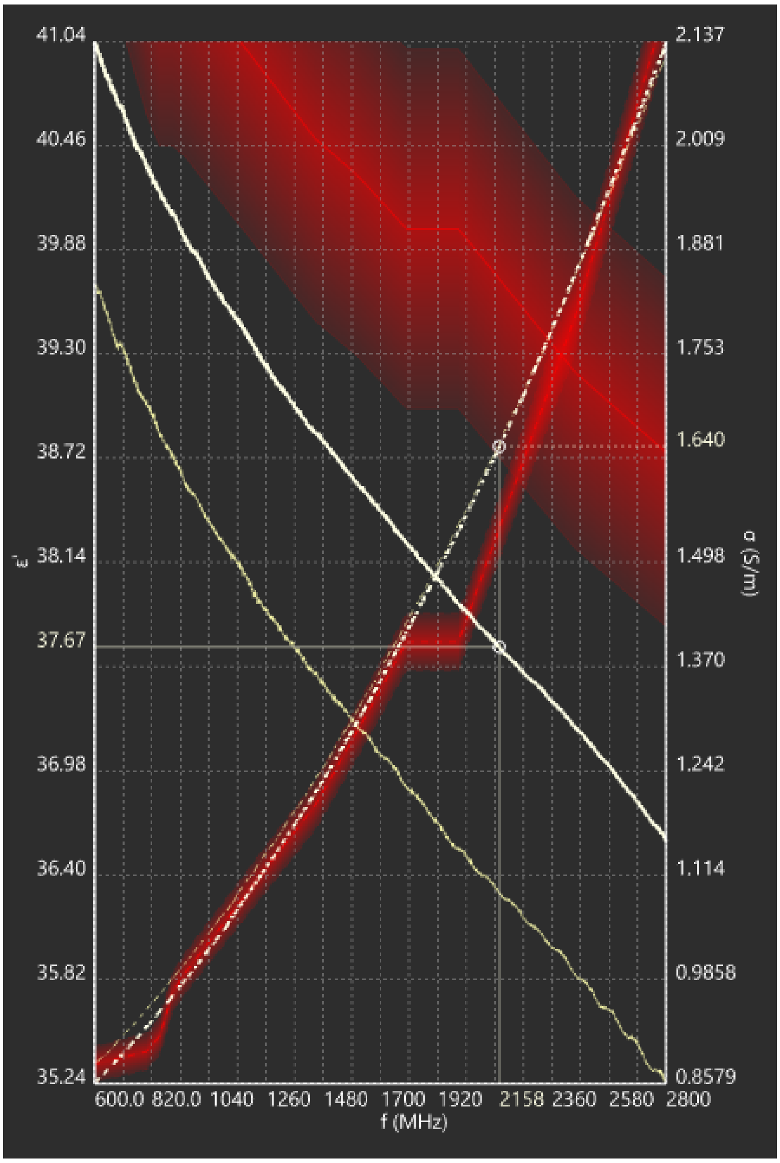


FIGURE 7. Software screen where measured S-parameters are converted to dielectric properties.

Screenshot of the DAK software are shown in figure 7. In figure 7, the left side of the Y-axis is relative permittivity and the right side of the Y-axis is conductivity. Frequency is presented on X-axis. A desired frequency range can be selected while making a test setup. When measuring liquids, the software can be used to check if the measured parameters, shown as white lines, are close to the target values, which are shown in the linear chart as red lines. (21.)

There are several methods to measure dielectric properties by VNA:

- Transmission/reflection line method
- Free space method
- Resonant method
- Open ended coaxial probe method. (20.)

3.1.1 Open-ended Coaxial Probe Method

To measure dielectric properties of the liquid, the open-ended coaxial probe method is the most commonly used over the frequency range of 4 MHz to 10 GHz. The open-ended coaxial probe technique allows to measure homogenous samples that are in good contact with the probe. The probe can be connected to the VNA with a coaxial cable. (22.) There are different sizes of the probes. A smaller probe size is used to measure at higher frequencies and a larger probe size has a better sensitivity at lower frequencies. The probe with an outer diameter of 2 mm to 4 mm is used for measuring tissue simulating liquids at the frequency range of 300 MHz - 10 GHz. (5, p.197.)

Different techniques, which are shown in figure 8, are used to measure dielectric properties with a coaxial probe. Materials can be measured from the surface of the sample or if the measured sample is liquid, a coaxial probe can be immersed into the liquid (22).

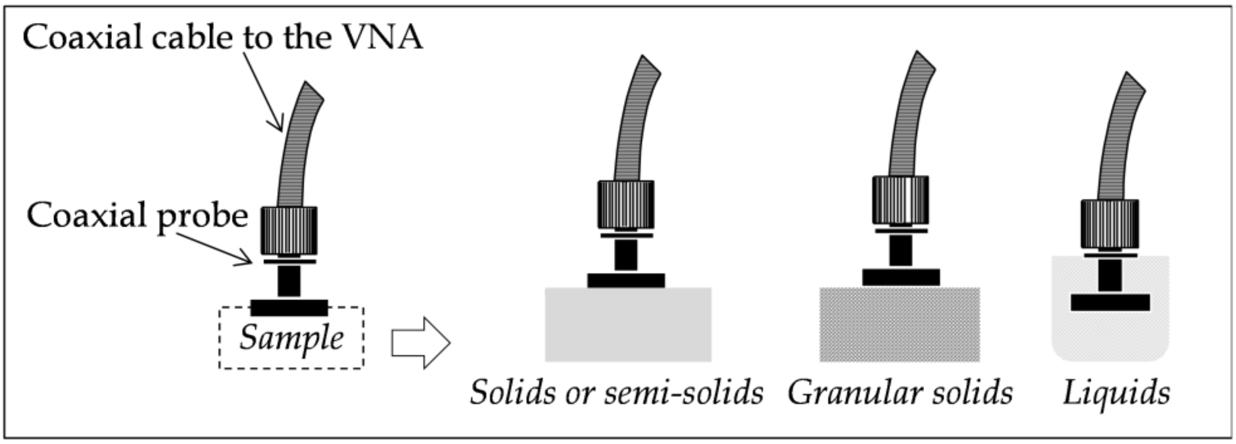


FIGURE 8. Open-ended coaxial probe (22)

3.2 Impedance Analyzer

An Impedance analyzer is a measuring instrument that measures material's complex electrical impedance as a function of frequency (23). The measured material is stimulated with an AC source and the measured values are derived by measuring its capacitance and dissipation factor. As the VNA is used to measure at higher frequencies, over the 100 MHz, the impedance analyzer is used to measure materials at lower frequencies, below 100 MHz. (19, p.16.)

4 EXPERIMENTS

4.1 Measurement Setup

Vector Network Analyzer Agilent 5071B with an open-ended coaxial probe was used to measure the mixtures. VNA was connected to a computer. Software converts the measured S-parameters to dielectric properties and the results are shown as a function of frequency. Before the measurements, the setup must be calibrated. Calibration is done by Open-Short-Load method where the load is a reference liquid with known dielectric properties. Deionized water was used as a load in this work. The measurement procedure is shown in figure 9.

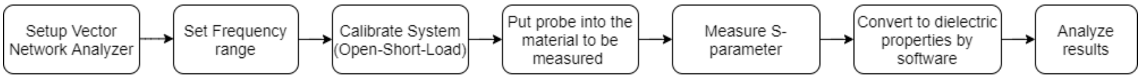


FIGURE 9. Measurement procedure

4.2 Tissue Simulating Gel

4.2.1 Test 1 - Polysorbate Based Tissue Simulating Gel

Deionized water, salt and tween were used as ingredients of this recipe and a 10% amount of gelatin powder was added to the liquid. The mixture was placed inside the fridge for 2 hours and it began the gelatinization. After cooling, the mixture was heated to 39 °C to remove air bubbles. After heating, the mixture was in the fridge for 24 hours in a sealed box.

After cooling, the gel was measured by using VNA at the frequency range of 600 MHz – 3000 MHz. Dielectric properties of the gel remained the same as before when adding the gelatin powder. The consistency of the gel was solid after the cooling, at room temperature the gel started to leak materials out and it did not remain homogeneous.

4.2.2 Test 2 - Oil Based Tissue Simulating Gel

Deionized water, oil, salt and emulsifiers were used as ingredients of this recipe. A 10% amount of gelatin powder was added to the liquid. The gelatin powder was mixed with a bit of water and it was heated before adding to the mixture. The mixture began to solidify immediately and it was put inside the fridge for 2 hours. After cooling, the mixture was solidified and had turned into a stable gel. To remove the air bubbles from the gel, the gel was heated to 39 °C. After heating, the gel was in the fridge for 24 hours in a sealed box.

After cooling for 24 hours, the consistency of the gel was solid. When looking the gel against the light, no air bubbles could be seen inside the surface. Test 1 showed that the polysorbate-based gel began to leak materials out at room temperature, the oil-based gel remained homogeneous. The gel needs to be stored in a sealed container. Contact with air causes the material leakage out of the gel. The gel could be cut easily to the desired shape.

FIGURE 10. Gel after cooling 24 hours in a room temperature.

Dielectric properties of the gel were measured by using VNA. The open-ended coaxial probe measured the gel's dielectric parameters from the gel's surface. Dielectric properties of the gel remained the same as the liquid mixture's parameters before adding the gelatin powder.

Figure 11 shows the measurement procedure. The open-ended coaxial probe which is connected to the VNA via a coaxial cable, is in contact with the gel surface. In the background is a computer with which VNA is connected. The software on the computer converts measured S-parameters to the dielectric properties and the relative permittivity and conductivity are shown on the screen as a function of frequency in the desired frequency range. Measured results are compared with known targets and the targets are shown on the screen as a red line. The white line shows the measured data.

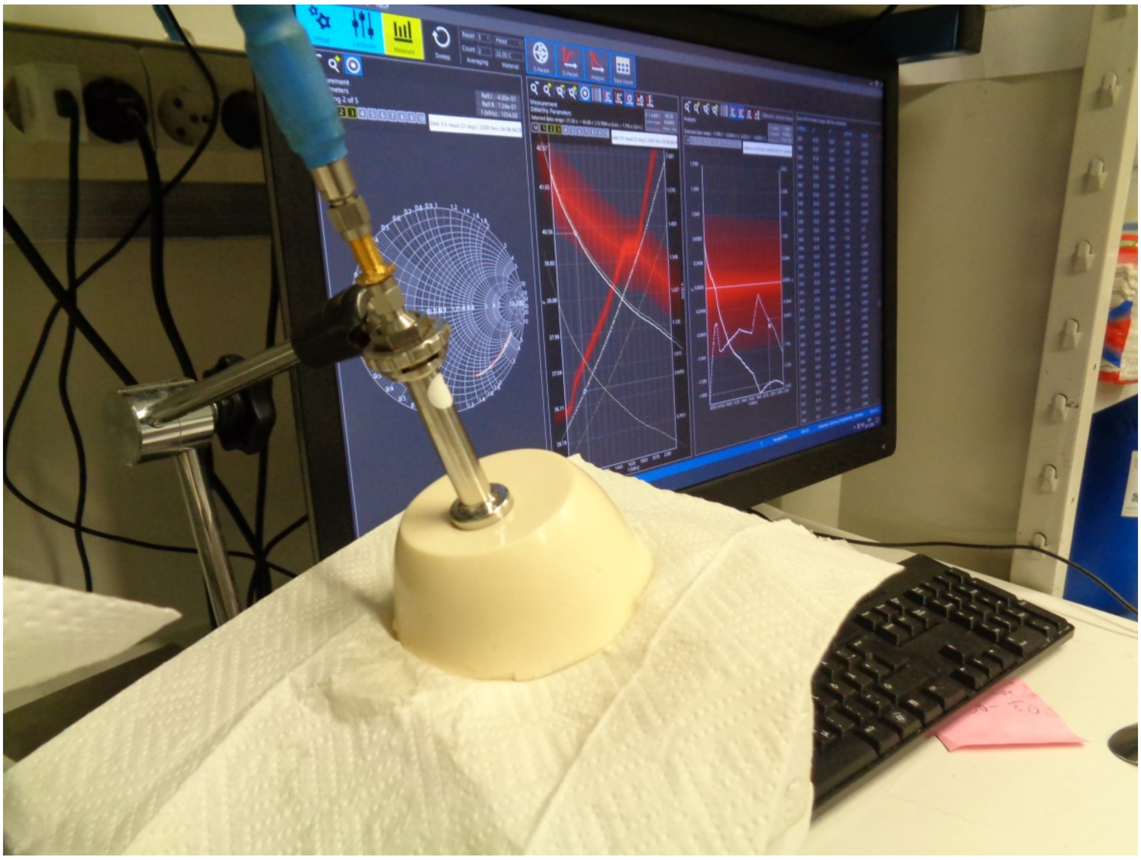
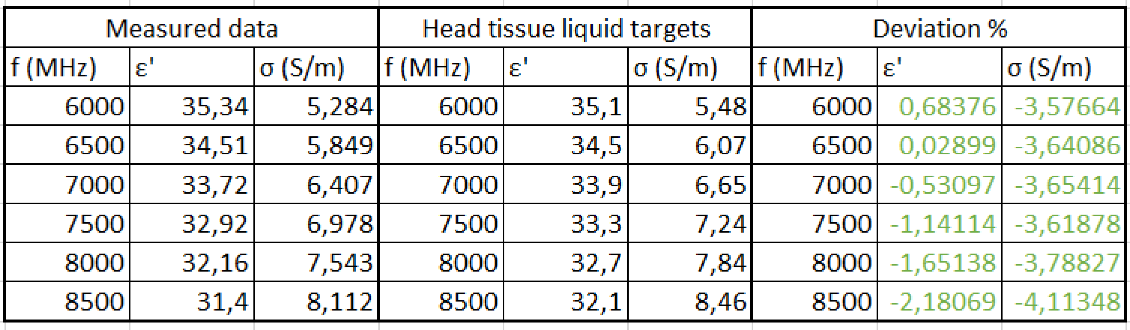


FIGURE 11. Dielectric properties measurement of the gel

4.3 Test 3 – Tissue Simulating Liquid

One mission of this thesis was to determine mixtures that simulate dielectric properties of tissues at high frequency, from 6 GHz to 10 GHz. Deionized water, tween and salt were used ingredients of this recipe. The recipe is known to simulate dielectric properties of tissues at the frequency range of 700 MHz – 3 GHz. The frequency range to be measured was from 6 GHz to 8 GHz. Because available VNA can measure up to 8.5 GHz, the highest frequency to be measured was 8.5 GHz. Dielectric properties of liquids were measured with VNA. The measured data was compared with the known data (table 1).

TABLE 1. Measured data at 6 GHz – 8.5 GHz frequency range, where f = Frequency, ε' = Permittivity, σ = Conductivity



Measured data			Head tissue liquid targets			Deviation %		
f (MHz)	ε'	σ (S/m)	f (MHz)	ε'	σ (S/m)	f (MHz)	ε'	σ (S/m)
6000	35,34	5,284	6000	35,1	5,48	6000	0,68376	-3,57664
6500	34,51	5,849	6500	34,5	6,07	6500	0,02899	-3,64086
7000	33,72	6,407	7000	33,9	6,65	7000	-0,53097	-3,65414
7500	32,92	6,978	7500	33,3	7,24	7500	-1,14114	-3,61878
8000	32,16	7,543	8000	32,7	7,84	8000	-1,65138	-3,78827
8500	31,4	8,112	8500	32,1	8,46	8500	-2,18069	-4,11348

According to standards, the deviation must be within ±5 % of the target when frequency is over 5 GHz. As the Figure 14 shows, the deviation of the permittivity and conductivity are within ±5 % of the target values and it meets the standard requirements. Because the liquid is known to simulate a tissue at 700 – 3000 MHz, the liquid was measured also at 700 MHz – 8.5 GHz to see whether the parameters correspond to the standard requirements throughout the frequency range. At 3 GHz to 6 GHz the dielectic parameters of the liquid did not meet the standard requirements.

5 RESULTS

5.1 Tissue Simulating Gel

Experiments showed that the tissue simulating gel is capable of simulating dielectric properties of different tissues at least at known frequency ranges. Experiments included measurements of different tissue simulants and measured data was compared with known data at the frequency range of 600 - 3000 MHz. By adding more gelatin powder, the gel is even more compact. The gel can be made of different shapes and different sizes. The temperature of the gel affects the results. With the gels used in this work, the experiments showed that the phase change from liquid to solid did not affect to the measured values.

The gel simulant was meant to test also at low frequencies below 30 MHz, but the impedance analyzer was unavailable for measuring the dielectric properties.

The challenge of the gel is its stability over time. The best way to keep the gel usable for as long as possible is to store the gel in a sealed pack in the fridge. Test 1 showed that the gel leaked materials out when it was in contact with air at room temperature for a long time. When the gel is leaking materials out, it is obvious that dielectric parameters may change, and it cannot remain homogeneous. Air bubbles inside the gel could cause measurement errors. Heating the gel and refreezing could be the solution to get rid of the air bubbles. If the gel is stored at a low temperature in a sealed package, it lasts longer. Further studies need to be conducted in this area to see how long time the gel remains homogeneous.

5.2 Tissue Simulating Liquid

Test 3 showed that the mixture of deionized water, tween and salt could be used at a high frequency range. Experiments showed that the mixture meets the standard requirements at the frequency range of 700 – 3000 MHz and 6 GHz –

8.5 GHz. Because the available VNA measures up to 8.5 GHz, higher frequencies could not be measured.

The research showed that oxidized oil could be the best ingredient to the tissue simulant for a large frequency range. The mixture of oxidized oil and water could cover at the frequency range of 450 MHz - 6GHz. The challenge is the availability of oxidized oil and how oil can be mixed with water. Because the oxidized oil was unavailable, the recipe could not be tested in practice.

6 CONCLUSIONS

The aim of this thesis was to research and develop homogeneous materials that can be used to simulate dielectric properties of the human or animal tissues. Materials can be used at larger frequency ranges than known mixtures. Other part of this thesis was to learn what kinds of measuring systems are needed to measure the dielectric properties of the tissues.

A lot of information was found from tissue simulating liquids and the studies showed that there are many recipes for different frequency ranges. In this study, some of the recipes were able to be tested with available ingredients and the mixture that simulates dielectric properties of the tissue at the frequency range of 6 GHz – 8.5 GHz was found. The gelatin powder was used to manufacture a tissue simulating gel. The gel can be used to simulate dielectric properties of different parts of the body.

A Vector Network Analyzer and an impedance analyzer are instruments used to measure the dielectric properties of the tissue simulating liquids. The Vector Network Analyzer with an open-ended coaxial probe was used in this thesis.

The availability of needed ingredients for tissue simulants made work challenging and only some of the recipes could be tested in practice. The studies showed that in theory, mixtures could be used as a tissue simulant. A lot of different materials for the mixtures were found. The materials can be toxic or non-toxic. Since the mixtures need to be handled, in this work non-toxic materials were used.

The subject of the thesis was interesting. During the thesis, I learned a lot about information retrieval since the work included the research part and it will be an important skill for the future. During the thesis, literacy and understanding of standards developed, which is important in my current job.

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