A brain-computer interface inside your earphones

Phantom design

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DELFT UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING, MATHEMATICS
AND COMPUTER SCIENCE

ELECTRICAL ENGINEERING PROGRAMME

Abstract

Contents

Chapter 1

Introduction

Living cells and tissues of human beings and animals generate electric signals, also often referred to as bioelectrical signals. These signals reflect the physiological state of organs and/or tissues. Thus, detecting bioelectrical signals can be useful in the diagnosis of neurological diseases (epilepsy, tumours, brain death among others). More so, stimulating bioelectrical signals in some way might be beneficial in treating said diseases. Methods have already been developed to detect bioelectrical signals. An example of this is an electroencephalography (EEG). I.e., the recording of the brain's bioelectrical signals. Typical scalp-EEG systems have their limitations however, as they are bulky, tethered (see Figure 1.1) and require electrodes to be attached on the scalp via use of a conductive gel.

Figure 1.1: Example of standard issued equipment used to record EEGs with

This creates difficulty when trying to monitor brain activity over a long period of time. An example scenario of this is trying to monitor the on-set detection of epileptic events in a person when in a non-clinical environment (in their day-to-day life). Additionally, the conductive gel dries out over time and the electrode-skin contact can cause scarring. Recent developments therefore show an interest in brain-computer interfaces (BCIs): small wearable external devices that provide a direct communication link to the nervous system. In other words, wearable devices that can be used, for example, to monitor brain activity 24/7 in a non-clinical environment, prosthetic control, and/or even be used for consumer-related applications such as three factor authentication. However, to create a desirable BCI for both patients and consumers, the BCI has to maintain a good appearance and has to avoid publicising illnesses. Thus, the scalp electrodes used in conventional EEG systems are not suited for this application. For this matter, the ability to record EEGs using dry electrodes placed in and around the ear has been investigated in recent years. Specifically in and around the ear, because hair causes too much interference in EEGs when a conductive gel is not applied. Currently, the development of dry electrodes is still being min-maxed and newly developed electrodes require extensive testing to determine their bio- and skin-compatibility (and therefore their functionality in recording EEGs). It is unwise to perform these tests on in vivo subjects as the electrode-skin contact might cause irreversible damage to the skin. Furthermore, in vitro human tissue is not readily available. For this reason, phantoms are often used. Phantoms are objects that mimic or imitate the electrical, mechanical and/or physical properties of the human body, like skin tissue.

This BSc thesis will look into the design of a skin phantom such that CNT/PDMS dry electrodes (to be placed inside an ear BCI) can be tested. Particularly, such that the electrodes can be tested for their functionality in recording EEGs and stimulating brain activity. Chapter 2 will hereby give an analysis on what has currently been achieved by others when it comes to mimicking human tissue and concludes with a problem definition that is realistically achievable in this BSc Thesis. Sub-sequentially, chapter 3 provides the requirements needed to solve the problem. Chapter 4 describes the first process steps in solving the problem: fabrication of the phantom(s). Chapter 5 discusses the measurement procedures used to extract the phantom's electrical and mechanical properties to verify the correctness of the fabricated phantom(s). Chapter 6 provides the results obtained from the measurements and finally, chapter 7 and chapter 8 provide a discussion and conclusion.

Chapter 2

State of the art analysis

The fabrication of skin phantoms has been widely researched and are typically categorised into 3 types when considering the head. These are the homogeneous phantoms (single skin layer), multi-layer phantoms representing the scalp, skull and brain, and real-tissue phantoms (donor tissue from humans and/or animals) [1, 2, 3, 4, 5, 6, 7, 8, 9]. The latter is not considered applicable for this BSc Thesis, because it requires donor tissue, but is still a noteworthy mention. A 3D skin model can be cell cultured via the use of bioreactors [10]. Bioreactors provide biochemical and physical regulatory signals to cells and encourage them to undergo differentiation [10]. Simply said, stimulating cells for growth and regeneration such that in vitro tissue can be formed. The main use when engineering tissue via bioreactors is to perform grafts, but the engineered tissue can also be used as external organ support devices or provide reliable model systems [11]. Thus, in the application of phantoms, skin can be modelled via use of bioreactors as long as donor tissue/cells are available.
When considering the other two phantom types, the single layer- and the multi-layer phantoms, gel-based solutions are mainly used. Gel-based phantoms are favourable as they are high in water-content (just like the human body) and provide selective "tuning" of the electrical properties by changing said water content [1, 2]. In other words, the conductive and dielectric properties of gel phantoms can be adjusted by adding fillers. The same can be done to mimic the mechanical properties of human skin. Hereby, a wide variety of materials has been documented to fabricate skin phantoms. Some materials used are wax, silicon, plastic clay, plastic moulds and gelatin; with gelatin being the most common one by far [2]. Fabricating skin phantoms via the use of gelatin seems logical, as gelatin is obtained from various animal by-products. However, this can be considered animal testing and the use of gelatin is therefore sometimes avoided. A popular alternative to gelatin is Agaragar (agar in short). Agar is a jelly-like substance made from algae, and just like gelatin, agar has similar electrical properties to that of human skin [3].

2.1 Phantom design

Sodium chloride (NaCl), also known as salt, is essential to the human body and is used to regulate the electrolyte balance of fluids in a person's body. Thus, to construct gel-based skin phantoms that mimic human skin, NaCl is often added to the gel. There has been shown that varying concentrations of NaCl relative to gelatin or agar powder shift the solution's phase/frequency response profile [3]. Gelatin/NaCl solutions show similar non-linear frequency dependency to that of human skin. Agar/NaCl solutions also show similar properties. However, a lesser similarity when compared with the gelatin-based solutions. In [4] is mentioned that the same concentration of NaCl in gelatin-based phantoms showed higher dielectric properties than that in agar-based phantoms at all frequencies.

According to Thomas J. Yorkey [12], the relationship between the salt concentration and the agar's conductivity σ is given by:

$$\left(\sigma, {}^{S}/\mathrm{m}\right) = 200\,(S \cdot mL/m \cdot g) \times \frac{\text{grams of NaCl})}{(\text{ solution volume },mL)} \tag{2.1}$$

According to D. Bennett [3] that relationship can be expressed as the frequency-independent linear model given below.

$$\left(\sigma, {}^{S}/\mathrm{m}\right) = 215 \times \frac{(\text{ grams of NaCl})}{(\text{ solution volume, mL})} + 0.0529 \tag{2.2}$$

With these expressions, the Agar/NaCl solutions can be modelled such that solutions with desired conductivities are obtained.

Some examples of previously fabricated gelatin- and agar-NaCl tissue phantoms are:

- Muscle tissue has been mimicked by mixing gelatin powder and agar powder with deionized water [4]. Aqueous NaCl was then added to improve conductivity such that the solution had similar conductive properties as muscle tissue. Glycine and aluminium powders were fillers added to increase the permittivity such that the solution had similar permittivity when compared to muscle tissue.

- Three phantom heads were fabricated using agar [5]. A one-layered spherical phantom, a three-layered spherical phantom and a human MRI-based three-layered phantom. The one-layered phantom represented the brain, whereas the three-layered phantoms represented the scalp, skull and the brain of a human. Plastic moulds were fabricated to recreate a three-layer shell structure. These moulds were built using a 3D printer. The moulds were then filled with three different Agar/NaCl mixtures containing isotropic permittivities close to the scalp, skull and brain.

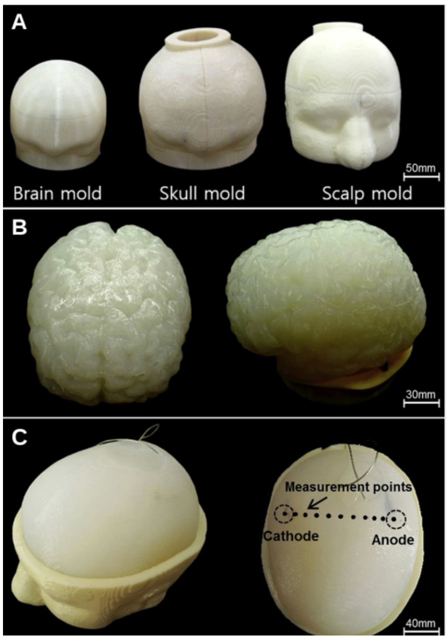

Figure 2.1: Image of the three agar phantom heads fabricated by [5].

2.2 Electrical properties of skin and electrode-skin interface

Skin tissue can be subdivided into different layers. In short, these different layers are the epidermis (pigment cells), the dermis (nerve endings, sweat glands and hair follicles) and subcutaneous tissue (fat, blood vessels and nerves). Each of these layers can be modelled to have a capacitive and resistive property. An example of is this is the Tregear model of the skin, which models every component of the skin down to micro-anatomical structures. However, such a model is mostly over complicated and only the main contributors to impedance are usually considered. A Neuman model is then often used. Additionally, the Neuman model also takes into account the capacitive and resistive properties of the electrode-skin interface.

2.3 Measuring electrical properties of phantoms

There are numerous methods to measuring/extracting the conductive and dielectric properties of phantoms. The most common approach in measuring the electrical properties of phantoms for EEG applications is the parallel plate capacitor method [1, 4, 6, 9]. This method involves placing a thin phantom sample between two electrodes to form a capacitor.
For determining the electrode-skin contact impedance, some example methods are given below:

- **One approach of calculating the electrode-skin contact impedance** is through the three- and four-electrode measurement method [13]. This involves attaching three electrodes (along with an additional ground electrode) to a phantom sample and measuring the impedance. Sub-sequentially, the same is done when four electrodes are attached. The two measured impedances are then subtracted and the remainder is the electrode-skin contact impedance.

- **Another approach of calculating the electrode-skin contact impedance** is with an LCR meter. The impedance is measured between an internal reference electrode and an external electrode. The internal electrode is inserted while the mould is being made. The impedance is measured across a frequency range beginning at low frequencies. The measurements need to be done soon after taking the sample out of the fridge at 2.3°C.

It is worth to mention that for each of these measurements, contact pressure is to be remained constant as this may effect the measurements [14]. This will be further discussed in the next section.

2.4 Mechanical properties of skin and electrode-skin interface

As mentioned in the previous section (section 2.4), an important electrical property in recording EEGs is the electrode-skin interface. Specifically, this was dependent on humidity. However, the electrode-skin interface is also dependent on two mechanical properties. Namely, the force applied when pressing the electrodes against the skin and the elasticity of the skin. Both influence electrode-skin contact. Pressure applied to the electrode-skin interface is hereby of importance, because it changes the electrode-skin contact area. Elasticity of skin is considered because motions like chewing, sprinting, jumping and walking among others stretch out the skin. Thereby, the position of the BCI relative to the ear is shifted and the electrode-skin contact changes.
Elasticity of material is often modelled via the Young Modulus: the relationship between stress and strain in a material. For human skin, Young's modulus ranges anywhere from 0.42 MPa to 0.85 MPa [15]. Additionally, the durability and rigidity of electrodes can also be described by Young's Modulus.

2.5 Measuring mechanical properties of phantoms

As mentioned in the previous section (section 2.4), the two mechanical properties of importance in the electrode-skin interface are the force applied when pressing the electrode against the skin, and the Young Modulus.

To measure the effects of force applied on the electrode-skin (or electrode-phantom) contact impedance, simply requires to perform the electrode-skin impedance tests, but now pressing the electrodes with different known forces against the phantom and observe how this changes the measured electrode-skin contact impedances.
The Young Modulus of phantoms can be determined by mounting a phantom sheet sample onto a testing machine and stretching it out with a set amount of force until it breaks. Additionally, the same test can be performed to determine the durability and rigidity of the electrodes by using a sheet containing the electrode material. [6] performed this test for CNT/PDMS dry electrodes and provided the stress-strain curve given in Figure 2.2. CNTs were dispersed 4.5% in PDMS relative to the entire mass of the solution. This often also denoted as the wt percentage.

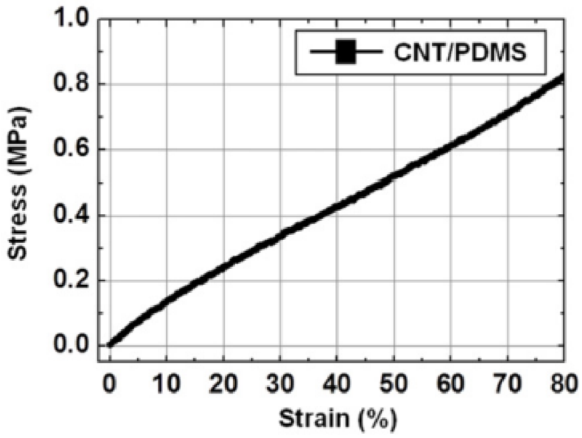

Figure 2.2: Stress-strain curve of 5% wt CNT/PDMS dry electrodes

2.6 Bio- and skin-compatibility tests for electrodes

To assess the response of the skin to long-term electrode contact, bio-compatibility tests are performed. An example is the cytotoxicity assessment of electrode materials (how toxic is the material to living cells). Joong Hoon Lee et al. [6] cultured skin fibroblast (CCD986sk) cells on a 4.5% wt CNT/PDMS sheet for seven days. They determined the cell viability using a live/dead assay kit. After seven days, the cell viability was >93%. Furthermore, they attached a CNT/PDMS sheet via airpermeable tape on the upper arm of a volunteer and monitored the condition of the skin for a week. They observed no adverse effects (no itching, swelling and redness).

2.7 The problem definition

Having to model the characteristics of the human ear where, transepidermal water loss (TEWL), mostly affected by cerumen, sweating or epidermal activity, causes the most significant change in impedance (therefore conductivity of the skin). Changes in impedance are also caused by skin conditions like eczema and dermatitis (dryer skin, so higher impedance) or conditions like allergies, diabetes or kidney-disease. Furthermore, the applied pressure of the electrode onto the skin can also cause changes in the impedance. Applying light to moderate pressure results in large decreases in the skin-electrode impedance of dry electrodes. These changes are also irreversible, lasting at least minutes even after the applied pressure is released. Applying too much force will result in an impedance increase [14].

Chapter 3

Programme of requirements

An inexpensive ear-shaped phantom will be created that mimics or imitates the electrical and mechanical properties of human skin-tissue in an repeatable manner. The final product, the in-vitro ear-shaped skin phantom, will be used to test the functionality of dry electrodes to be placed inside an ear, with the aim of being implemented in the design of an ear-EEG piece.

3.1 Functional requirements

Functional requirements, given in Table 3.1, are requirements that are fundamental for an acceptable end-result.

Table 3.1: Functional requirements: mandatory requirements are classified as A and trade-off as B.

Number	**Name**	**Description**
A.1	function	The ear-shaped phantom must support testing the functionality of a dry electrodes to be implemented in an ear-EEG piece.
A.2	function	The phantom slab must support testing the effect of pressure by measuring the change in skin-contact impedance of a dry electrode whilst applying and removing a known magnitude of force.
A.3	performance	The phantom must have the same permittivity as dry human skin at a constant temperature and pressure with an accuracy of 90% in the spectrum extending from 5 Hz to 1 kHz.
A.4	performance	The phantom must have the same conductivity as dry human skin at a constant temperature and pressure with an accuracy of 90% in the spectrum extending from 5 Hz to 1 kHz.
A.5	performance	The phantom must have the same impedance as dry human skin at a constant temperature and pressure with with an accuracy of 90% in the spectrum extending from 5 Hz to 1 kHz.
A.6	performance	The Young modulus of the stress-strain curve must be in the range of 0.42 till 0.85 MPa.
A.7	dimension	The phantom must have the form and dimensions of an average human ear.
A.8	dimension	The phantom must have an ear-canal of at least 1.5cm deep to perform in-ear experiments.
A.9	equipment	The reference electrode must be inserted inside the phantom.
B.1	performance	The phantom should preferably imitate cerumen and epidermal activity like an in-vivo ear.
B.2	performance	The phantom should preferably imitate sweat by using the sweat ducts as the source.

3.2 Non-functional requirements

The non-functional requirements, given in Table 3.3, describe the attributes and qualities which the end-product must have or that increase the satisfaction of the end-user if the end-product complies with these requirements.

Table 3.2: Non-functional requirements: mandatory requirements are classified as C and trade-off as D.

Number	Name	Description
C.1	ethics	The phantom must be composed of animal friendly materials.
C.2	safety/law	The procedure should be performed in a safe environment following the lab rules/instructions.
D.1	lifetime	The phantom should keep its electrical and mechanical properties for at least 7 days with a maximal decay of 5%.
D.2	price	The price of the phantom should preferably be kept to a minimum.
D.3	performance	All equipment used (3D-printer, impedance meter, weighing scale, calipers, Young's Modulus measurement setup) should be as precise as possible.
B.4	ecological	The reference electrode should preferably be reusable.

Table 3.3: Non-functional requirements: mandatory requirements are classified as C and trade-off as D.

Chapter 4

Fabrication of phantom

4.1 Selection of Sample Materials

For the fabrication of a tissue-mimicking material, agar powder was selected as a matrix material, a constituent of a composite material, to achieve the desired gel-like substance. The plant-based material agar is a jelly-like substance made from algae and was chosen over gelatine due to ethical reasons. Its dielectric properties are similar to the human skin, and, because of its high water content, can be "tuned" by adding filler materials to the agar mixture [4]. Promising filler materials are sodium chloride (NaCl), aluminium (Al) powder and glycine (Aminoacid), as they will add to the electrical conductivity as well as the relative permittivity of the phantom. In particular, adjusting the NaCl concentration is suitable for tuning the impedance [1], as well as ensuring non-linear frequency response of the phantom [16].

4.2 Phantom samples fabrication

The fabrication method as shown in Figure 4.1 is in line with methods used in other studies [4] [17]. First, gel-only samples were created by mixing various concentrations agar powder (E 406) with deionized water (DI) for the characterisation of the mechanical and dielectric properties of agar. DI by itself is not conductive because, as the name implies, the ions are removed from water. The agar powder and DI were weighed by mass fraction (wt%) with a Fisherbrand Analytical Series. The quantities of these gel-only samples are shown in rows 1 to 7 of Table 4.1. The range of concentrations of agar used matches [4], [8] and [18]. Thin film samples and cylinder samples were manufactured in petri-dishes [DIMENSIONS] for electrical and mechanical tests respectively. The solution was stirred with a magnetic stir bar (Spinbar magnetic stir bar, PTFE-coated, polygon, size 6 mm x 15 mm, white) on a stirring hotplate (Thermo Scientific Cimarec^{+}) for 1 minute at 400 RPM in a 80 ml beaker, then heated to 90 °Cwhile stirring at 600 RPM and thereafter transferred to the mould or petri-dishes covered with Teflon spray (Griffon PTFE spray) to prevent the samples from sticking to the dish/mould. To research the effects of adding filler materials to the phantom sample, various quantities of NaCl (table salt) are added to the solutions of rows 8 to [ROW] of Table 4.1 before transfer to the mould, while stirring at the lowest speed for three more minutes. The range of concentrations of NaCl used matches [1], [2], [8] and [9]. Thereafter, the samples were placed for [AMOUNT OF TIME] in vacuum to remove air bubbles. [2] suggested heating the solutions in a standard microwave for 1 minute for this purpose. A reference electrode (Skintact ECG electrode foam, solid gel, round, 30mm ref F-301) was placed in the sample before it solidified for later impedance measurements [2]. After 24 hours congealing at room temperature, the samples were removed. Their thickness was measured with an analogue caliper with 0.1 mm precision. Finally, they were stored in the fridge at [TEMPERATURE] to minimise water evaporation.

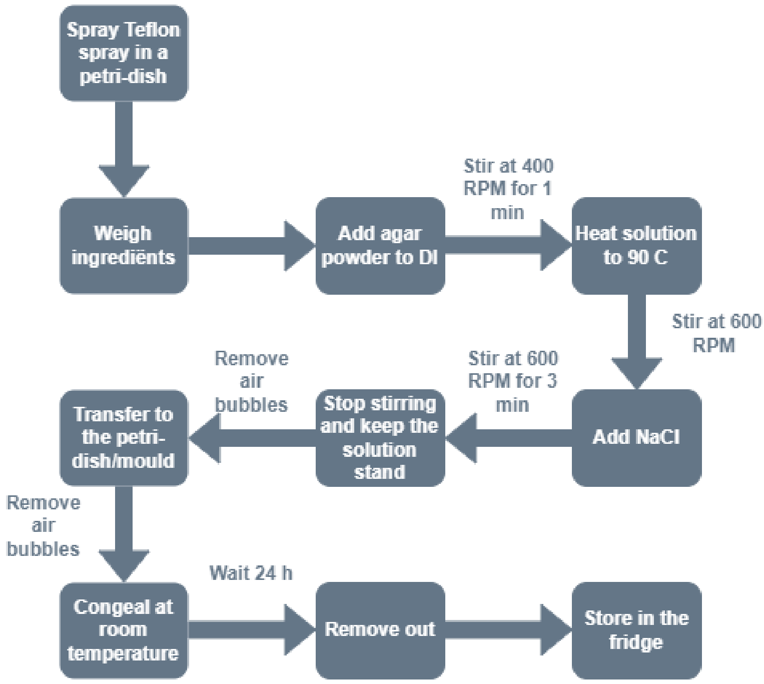

Figure 4.1: Flowchart sample fabrication

Table 4.1: Table showing quantities used to produce samples, given in mass fraction weight (wt.%).

Solution #	DI wt.%	Agar wt.%	NaCl wt.%
1	99.5	0.5	0
2	99.0	1.0	0
3	98.5	1.5	0
4	98.0	2.0	0
5	97.5	2.5	0
6	97.0	3.0	0
7	96.5	3.5	0
8			0.1
9			0.2
10			0.4
11			0.6
12			0.8
13			1.0

Chapter 5

Measurement procedures

5.1 Measuring electrical properties of phantoms

Since the goal of this project is to mimic dry-human skin, the phantom needs to have the same fundamental parameters that define human skin. The tissue can be divided into several layers that have different parameters. For simplicity reasons, only the outer layer of skin (also called the *stratum corneum*, the outer layer of the *epidermis*) is modelled because this is the layer that is in contact with the electrodes and consequentially will conduct the most current between the electrodes. The AC equivalent electrical circuit of the contact impedance can be seen in Figure 5.1.

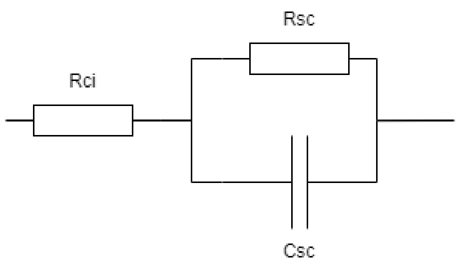

Figure 5.1: Electrical model of stratum corneum interface

A simplified dry human skin model consists of two resistors and one capacitor representing the contact impedance of the stratum corneum. C_{sc} is the stratum corneum capacitance and depends on the permittivity of the dielectric so the permittivity ϵ is the fundamental parameter. R_{sc} is the leakage resistance across this layer and depends on the conductivity of the tissue so conductivity σ is the fundamental parameter. R_{ci} is the series resistance related to interface effects and due to resistance in the tissue or electrolyte [19]. For large values of the magnitude of the contact impedance (|Z| > XΩ), the parallel connection becomes a series connection because [TODO] []. The permittivity and conductivity of human skin will need to be pursued into the phantom.

For dry electrodes, the interface impedance is orders of magnitude higher than for wet electrodes since air gaps and noise are present between the contact [20]. New electrodes have the benefit of lowering the interface impedance [2]. Conductive gels are used in wet electrodes to lower this impedance and reduce noise in this bridge. Dry electrodes have the benefit of lowering discomfort in the ear and allow multi day use.

The phantom has to have the same permittivity[A.3] and conductivity[A.4] as dry human skin with an accuracy of 90% in the spectrum extending from 5 Hz to 1 kHz.

Graphs of the dry skin conductivity and permittivity can be seen in Figure 5.2 and Figure 5.3. These are the desired values that will be pursued into the phantom over the frequency band ranging from 5 Hz to 1 kHz.

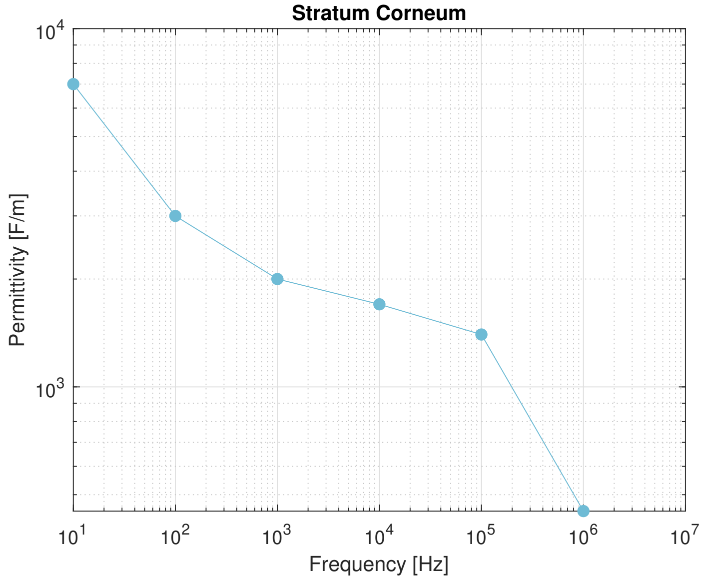

Figure 5.2: Permittivity of stratum corneum [21]

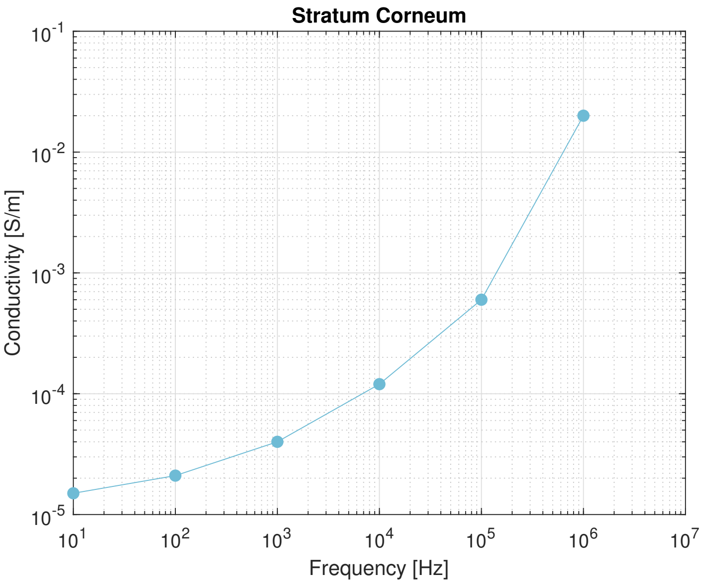

Figure 5.3: Conductivity of stratum corneum [21]

5.1.1 Measure impedance

The impedance of the phantom determines the amount of voltage that the stimulator needs to deliver into the electrodes to have a constant current between the electrodes.
It is thus necessary to have a well-known model of the impedance in dry-human skin that will need to be replicated in the phantom.
A precision LCR meter can determine the real and complex part of the impedance by using the probes at fixed frequencies. Since the impedance vary a lot based on frequency, an impedance analyser is used that can plot the impedance in a certain frequency range.
In our case, the impedance will be measured by two electrodes present in the sample. Both electrodes were chosen to be external since it is more accurate for the parallel plate capacitor measurements but ads to the interface impedance. The distance between the two electrodes is the length of the sample. The reason electrodes are used instead of the normal probes is increased accuracy and the omission of noise. They are also excellent to use for reference electrodes that have a stable and well known potential.

Measurement Process

An Autolab PGSTAT302N impedance analyser is used to perform the experiments. The PGSTAT302N is the successor of the popular PGSTAT30. The maximum current is 2 A, the current resolution is 30 fA at a current range of 10 nA.This high end, high current potentiostat/galvanostat, with a compliance voltage of 30 V and a bandwidth of 1 MHz, combined with our FRA32M module, is specially designed for electro-chemical impedance spectroscopy.

the process of measuring a sample is explained below [TODO after training]:

1. Turn the Impedance analyser on.
2.

5.1.2 Calculating the permittivity

A material is classified as 'dielectric' if it has the ability to store energy when an external field is applied. The permittivity is the value that shows the amount of energy that can be stored in the sample and is denoted in Farad per meter (F/m). In other words, this value defines the capacitance of the sample.
The absolute permittivity ϵ is divided into the constant vacuum permittivity $\epsilon_0 = 8.85pF/m$, and the relative permittivity ϵ_r which is dependant of the material.
The capacitance (C) of a capacitor is calculated (Equation 5.1) easily when the dimensions(Area A, length d) of the capacitor and absolute permittivity (ϵ) of the dielectric are known.

$$C = \frac{A\epsilon}{d} \tag{5.1}$$

In the opposite way, the permittivity ϵ is calculated when the dimensions are known and the capacitance is measured.

There are several ways to measure the (absolute) permittivity of an unknown material. In this project, the **Parallel Plate Capacitor** is chosen because of simplicity.
To use this method, a capacitor needs to be build where the dielectric contains the sample only and no other unwanted substances like air,dust...

A basic capacitor is build with aluminium tape that is taped on top and bottom of the sample with the exact area of the sample. preferably a circular or rectangular shape is used to calculate the area. Also, a relatively large area is preferred for the dielectric to mitigate the fringing effects of the capacitor. The rule of thumb is that Fringing is ignored when the ratio length/area is less than 50. Noise will be present because of the amateuristic approach at building this device, for example the tape uses adhesive that is latex based and adds to the permittivity measurements.

the permittivity is complex, which means it has a real and imaginary component that is dependant on frequency/conductivity.

$$\hat{\epsilon} = \epsilon' - j\epsilon" = \epsilon' - j\frac{\sigma}{\omega} \tag{5.2}$$

The Magnitude of the permittivity is dependant on frequency so a Voltage Network Analyser can be used to sweep through all frequencies. The same measurement process as the impedance is used to create the permittivity graph.

5.1.3 Calculating the conductivity

The conductivity σ of the sample is calculated using Equation 5.3 and shows the linear relation between resistance and conductivity. Conductivity depends on the dimensions (Area A, Length L) and the resistance. The conductivity is acquired from the real part from the impedance measurement and can be tuned using various filler materials inside the creation of the phantom such as sodium chloride NaCl.

$$\sigma = \frac{L}{RA} \tag{5.3}$$

The final value is denoted in Siemens per meter (S/m) and shows how good a material can conduct current at certain frequencies. This value is also necessary to compute the complex permittivity.

Chapter 6

Results

Chapter 7

Discussion

Chapter 8

Conclusion

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Appendices