DOI 10.5162/16dss2022/P11

Detecting Cell Growth on Cochlear Implant Stimulation Electrodes by Impedance Spectrometry

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Introduction

The most important way of communication between people is still speaking and hearing. If a person is deaf, this significantly limits his or her ability to communicate. However, if the patient's auditory nerve is still intact and the reason for deafness is damage to the hair cells, a cochlear implant (CI) can bypass them. Thus, the patient gets the possibility to hear again, which can increase the quality of life. [1,2]

Cochlear implants are hearing prostheses used to replace the function of the inner ear. In simplified terms, a CI consists of an external part on the outside of the head and an internal part in the patient's inner ear. An external speech processor records sounds from the environment, converts them into electrical signals, and then transmits them to an electrode array located inside the cochlea in the perilymph-filled scala tympani. Inside the cochlea, the stimulation electrodes of the CI stimulate the spiral ganglion cells of the auditory nerve electrically. [1,3,4]

The functionality of a CI strongly depends on the current that stimulates the spiral ganglion cells, which in turn strongly depends on the electromagnetic properties of the surrounding tissue. A well-known issue of CIs is the growth of cells such as fibrocytes or blood contamination from a damage of the cochlea wall on the stimulation electrodes [5]. When cells grow on the stimulation electrodes, thereby changing the dielectric constant, they weaken the electric field at the auditory nerve and the impedance increases as Bester et al. showed in [5]. Thus, stimulation efficiency of the CI decreases and the patient’s ability to hear deteriorates. However, the degradation of a patient's hearing can also have other reasons, such as an incorrect position of the CI inside the cochlea or a tip fold-over during insertion [6–8]. In case of a degradation of the hearing ability of a patient with CIs, it is important to know the cause at an early stage in order to intervene with an individual treatment. One method to detect cell growth on the stimulation electrodes at an early stage and to differentiate cell growth from other influencing effects is recording the impedance spectra of CI stimulation electrodes [9].

Methods and Materials

The electrode array of a CI can be considered electrically as an RC circuit. In its simplest consideration, two stimulation electrodes form a plate capacitor. The capacitance of this plate capacitor depends on the area *A* of the stimulation electrodes, their distance *d* from each other and the dielectric constant *ε* of the surrounding medium, and thus the geometric and electromagnetic properties of the capacitor.

$$C = \varepsilon \cdot \frac{A}{d}$$

If cell growth occurs on the stimulation electrodes, the properties of the medium between the stimulation electrodes change and thus the dielectric constant *ε* and conductivity *σ* change. This leads to a change in the complex impedance between the two stimulation electrodes. Fig. 1 shows a CI with biofilm on the stimulation electrodes.

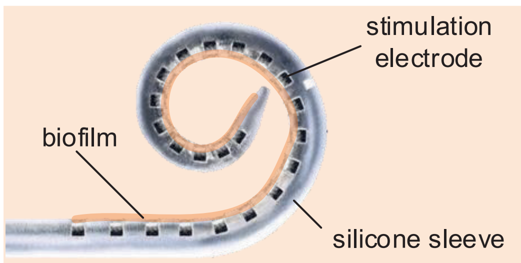

Fig. 1: Cochlea implant with stimulation electrodes. Any cell growth on the stimulation electrodes changes the electrode impedance.

Thus, measuring the impedance of the stimulation electrodes can provide information about the functionality of a CI. The complex impedance $\underline{Z}_m$ of a medium depends on its capacity *C*, the conductance *G* and the electrical excitation frequency *f*.

$$\underline{Z}_m = \frac{1}{G + j2\pi fC}$$

The measurement of the impedance of the stimulation electrodes is already implemented in all CIs available today, but it is usually just used at one frequency [2]. Although this method can detect cell growth on the stimulation electrodes when no other interfering factors are present, it faces limitations when other effects influence the impedance. Specifically, a change in the geometry of the stimulation electrodes [8], e.g. due to curvature of the CI in the cochlea or the distance to the wall of the cochlea [6], can influence the impedance. Therefore, measurements should be made over a certain frequency range in order to differentiate between these effects [9]. In this way, it may be possible to distinguish changes in position of the CI from changes in the dielectric properties of the surrounding medium, depending on the frequency.

In order to develop a suitable spectrometric method, enlarged CI models in the form of flexible printed circuit boards (PCB) were designed first. The advantage of these enlarged implants is that they are significantly less expensive than a commercial CI, easier to manufacture in large quantities – real CIs are manufactured manually – and they are significantly more robust in vivo. The CI models are made of polyimide and have six stimulation electrodes. The stimulation electrodes are made of copper with gold coating. They are 0.50 mm long, 2.00 mm wide, have a height of 18.00 µm and have a center distance of 1.00 mm from each other. An exemplary CI model can be seen in Fig. 2. Although it is an enlarged model of a real CI, this model is suited to test the spectrometric approach.

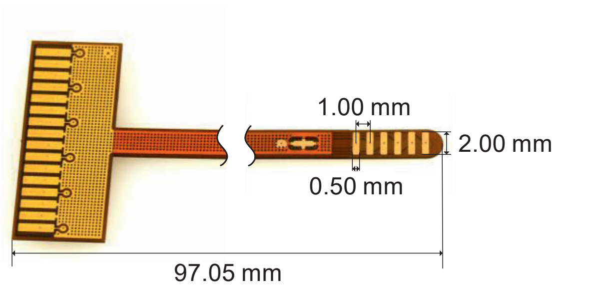

Fig. 2: Enlarged thin film CI model made of flexible PCB with six stimulation electrodes at the tip. The stimulation electrode and all wires are made out of copper with gold coating.

To measure the impedance, the CI model is coupled to an impedance analyzer E4990A from Keysight (voltage: 500 mVrms, frequency range: 20 Hz to 20 MHz), via a self-designed PCB and high-frequency cables from R&S (ZV-Z193 RF cable, frequency range: 0 Hz to 26.5 GHz).

The first measurements were made in solutions of deionized water (DI water) with sodium chloride (NaCl) or potassium chloride (KCl). The influence of saline as a surrounding medium is particularly interesting because the scala tympani, in which the cochlear implant is placed in the patient's inner ear, is filled with perilymph. Perilymph is an electrolyte containing 150 mmol/l sodium ions and just 5 mmol/l potassium ions [10]. Therefore, to a first approximation, it can be replicated by a solution of sodium chloride in DI water. Moreover, since perilymph is the typical ambient medium of CI, these measurements are important to generate 'zero' impedance spectra and validate the measurement method. The measurement setup for determining the impedance of enlarged CI models is shown in Fig. 3.

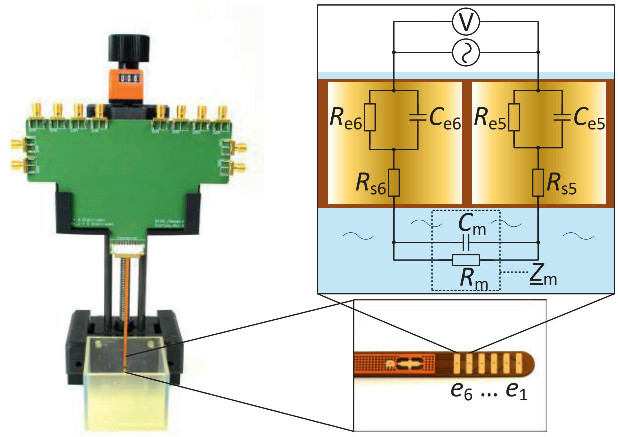

Fig. 3: Measurement setup for determining the inter electrode impedances of the enlarged CI model with associated RC circuit. The electrodes can be considered as leakage resistors R_{e5} and R_{e6} in parallel with capacitors C_{e5} and C_{e6} of a double layer of ions and water molecules in combination with the serial resistors R_{s5} and R_{s6} [3].

The impedance $\underline{Z}$ between two stimulation electrodes depends strongly on the geometry of the CI and its surrounding medium. The stimulation electrodes together with the surrounding medium form an RC circuit, as shown in Fig. 3. In an equivalent circuit, the stimulation electrodes can be considered as leakage resistors R_{e5} and R_{e6}. In parallel, a double layer of ions and water molecules formed at the contact area between each stimulation electrode and the surrounding medium forms the capacitors C_{e5} and C_{e6}. In addition, the contact areas between the stimulation electrodes and the medium form serial resistors R_{s5} and R_{s6}. The stimulation electrodes and the surrounding medium itself form a complex impedance $\underline{Z}_m$, which is the combination of a resistor R_m and a parallel capacitor C_m. [3]

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Results and Discussion

For low frequencies close to DC, capacitors behave like open circuits with infinite resistance. In high frequency ranges, on the other hand, capacitors resemble a short circuit and their impedance approaches zero.

$$\lim_{f\to 0} Z \rightarrow R_{e5} + R_{s5} + R_m + R_{e6} + R_{s6}$$

$$\lim_{f\to \infty} Z \rightarrow R_{s5} + R_{s6} + Z_m$$

In the high frequency range, the impedance of the solution is therefore primarily determined by its conductivity, which mainly depends on the concentration of the salt ions. As shown in Fig. 4, the higher the concentration of salt ions in the solution, the better it conducts electric current and its electrical resistance R_m decreases.

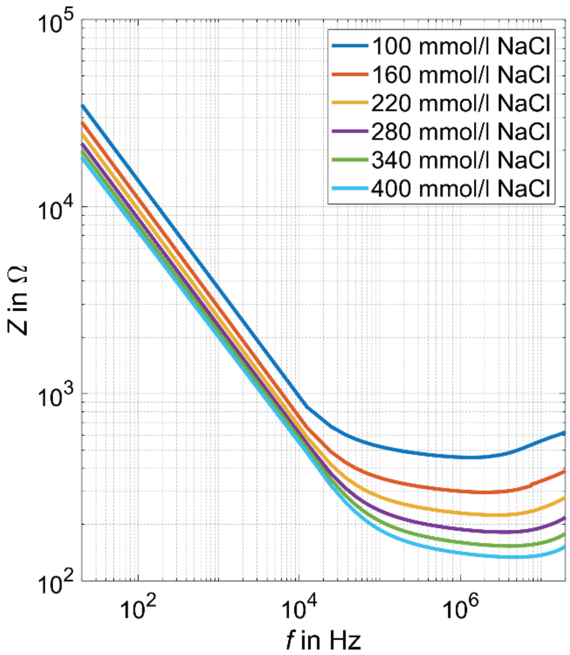

Fig. 4: Absolute value *Z* of the impedance between the stimulation electrodes e_5 and e_6, as a function of the frequency at different NaCl concentrations of the surrounding medium between 100 mmol/l and 400 mmol/l.

Fig. 4 shows the absolute value *Z* of the complex impedance $\underline{Z}$ between the stimulation electrodes e_5 and e_6 of an enlarged CI model in dependence of the frequency in sodium chloride solution with different concentrations. Over the entire frequency spectrum from 20 Hz up to 20 MHz, the impedance decreases with increasing sodium chloride concentration.

The decrease of Z_m with increasing concentration of salt ions is larger at high frequencies and thus confirms that the absolute value of *Z* of the complex impedance $\underline{Z}$ between two stimulation electrodes is a function of the concentration *c* of the salt ions.

$$Z \sim \frac{1}{c} \rightarrow \log_{10} Z \sim -\log_{10} c$$

Fig. 5 shows the absolute value of the complex impedance between the stimulation electrodes e_5 and e_6 of the enlarged CI model as a function of the ion concentration of the surrounding medium at a fixed frequency of 20 MHz. The capacitance of the solution can be considered short-circuited at this frequency, revealing a clear relationship between salt concentration and impedance. With a slope of -1.06 log(Ω)/log(mmol/l) for potassium chloride and -1.01 log(Ω)/log(mmol/l) for sodium chloride, the two salts show similar impedance behavior as a function of the respective salt concentration.

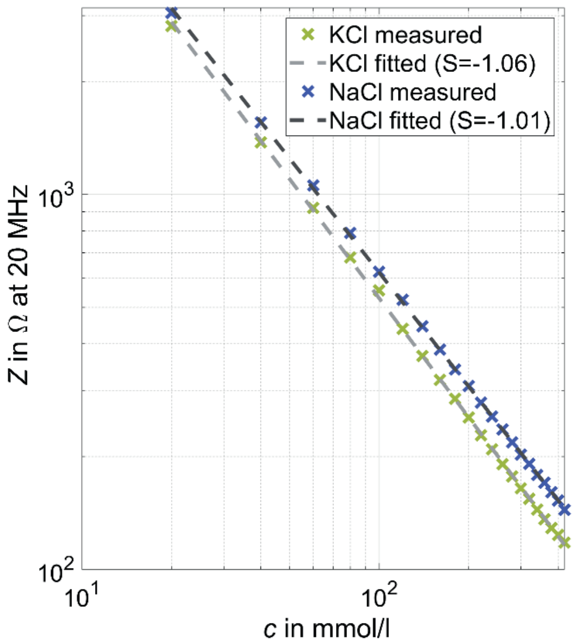

Fig. 5: Absolute value *Z* of the impedance between the stimulation electrodes e_5 and e_6 of the enlarged CI model as a function of the NaCl concentration or KCl concentration of the surrounding medium at a fixed frequency of 20 MHz.

$$Z(c_{NaCl}) \; at \; 20 \; MHz = 64.86 \, \frac{k\Omega \, mol}{m^3} \cdot \frac{1}{c_{NaCl}}$$

$$Z(c_{KCl}) \; at \; 20 \; MHz = 68.39 \, \frac{k\Omega \, mol}{m^3} \cdot \frac{1}{c_{KCl}}$$

Conclusion

This work shows very first measurements with an enlarged cochlear implant (CI) model to motivate the frequency dependent impedance of the stimulation electrodes to be used for investigating the nature of the surrounding medium. The existing stimulation electrodes can serve as sensors to detect changes in the perilymph and thus trigger early treatment, if necessary. This work also serves as the basis for extending the impedance spectrometric method to distinguish between different effects on the electrode impedance such as cell growth and geometry change of the CI in order to treat CI patients in the best possible way.

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Acknowledgement

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB/TRR-298-SIIRI – Project-ID 426335750).