Heart phantom with electrical properties of heart muscle tissue

Abstract: The weakened heart is supported by a left ventricular assist device (LVAD) to supply the heart muscle with oxygenated blood. In case the heart muscle recovers during LVAD therapy, the patient has to be weaned from the device. To date, there is no adequate method to detect heart muscle recovery in LVAD therapy. In order to establish a novel method based on the measurement of electric conductivity, this study presents a silicone model of a ventricle mock-up to simulate the electrical properties of cardiac muscle tissue. Previous studies have shown that the electrical properties of myocardial tissue change during ischemia, so that these changes are a possible estimate for measuring the condition of myocardial tissue. To this purpose, this study presents a casting process for a ventricle model and describes the materials used to imitate the electrical properties of the heart muscle to obtain conductive material. Initial results showed that the higher the carbon concentration in the silicone, the higher the conductivity of the silicone samples. The measurements were performed at different frequencies and the samples were analyzed for homogenization.

Keywords: Silicone conductivity, LVAD, Electrical properties myocardium

1 Introduction

Cardiovascular disease remains the leading cause of death in developed countries. Due to diseases such as hypertension, atherosclerosis or other genetic risk factors and an unhealthy lifestyle in an ageing society, more than 400 million people worldwide suffered from heart disease in 2015, resulting in the deaths of approximately 18 million people [1]. Reduced perfusion of myocardial tissue caused by e.g. obstruction in the coronary arteries reduces the pumping performance of the heart. In severe cases LVAD Therapy can be used to sufficiently supply affected myocardial tissue with oxygenated blood to help the heart muscle to recover. In order to adapt to individual needs of the patient, so-called physiological control strategies are currently being developed [2, 3]. In the context of physiological control, parameters that indicate the state of heart are needed. Often information about pressure, cardiac output and volume, if available, is used. Schäfer et al. showed that heart tissue changes its electrical properties during ischemia [4]. A control parameter derived from these observations to quantify the state of recovery of heart muscle would be beneficial to develop therapy protocols leading to weaning of the LVAD from the patient.

In this paper, in order to model the electrical behaviour of physiological and pathological heart muscle tissue a ventricle mock-up from silicone has been cast. Different concentrations and types of carbon structures have been added to manipulate the conductivity of silicone. These samples were then analysed.

2 Methods and Materials

2.1 Ventricle casting procedure

To establish measurement techniques to determine the state of heart tissue, an anatomical mock-up of the left ventricle has been cast. For this purpose, data from computer tomographic images (CT-images, taken from [5]) is used to construct two shells building a casting mould for a silicone ventricle. To keep complexity to a minimum, the atria and supply vessels were...
removed from the data. The simplified 3D model is shown in Fig. 1. Since the heart is a hollow organ, a casting mould for the blood cavity was constructed by scaling the model from the heart muscle to an end-diastolic volume of 120 ml. Resulting, that the outer ventricle mould had to be scaled in such a way that the wall thickness of the later silicone phantom corresponds to physiological myocardial thickness’s of approx. 8-10 mm on average. The casting moulds were manufactured from Polylactide (PLA), a red standard filament (thickness: 1.75 mm, layer thickness: 0.2 mm), by a 3D-printer.

Due to the fact that the inner blood cavity (core) had to be removed from the heart after completion of the subsequent silicone casting of the heart muscle, it was necessary to develop a soluble interior. The choice was to produce a heat-soluble core of paraffin wax so that the finished ventricle can be boiled in a water bath and the wax rinses out. With this procedure it is ensured that the ventricle is hollow. Wooden sticks are fixing the paraffin wax core during the curing process of the silicone. Fig. 2 a) displays the casting mould including the paraffin wax core which was used to cast the silicone ventricle mock-up (Fig. 2 b), c).

### 2.2 Silicone conductivity variation

In the experiments silicone with a shore scale of A00 was used (SILIKONFABRIK.DE, Ahrensburg, Germany). To simulate the elastic properties of the heart ventricle, the established relationship observed by Gent et al. [6] between the modulus of elasticity $E$ and the shore scale $A$ was used to approximately meet the elastic behaviour of the heart muscle. Depending on timing in the cardiac cycle the ventricle has an elasticity modulus between 20 kPa and 280 kPa. Tab. 1 demonstrates exemplary values of the shore scale compared with the elasticity modulus. It can be seen that the selected silicone has on average the elastic properties similar to heart muscle tissue.

Silicone is an insulator. Hence, to model the electric properties of the myocardium, it is necessary to add particles into the liquid silicone. In this paper two carbon materials with different textures have been used. First, carbon black powder VUL-CANR XC72 from Cabot Corporation (Boston, USA) was analyzed and second, carbon cutlets with an average length of 3 mm were tested. The higher the concentration of the fill material in the silicone, the more conductive the product becomes. But the higher the concentration, the more difficult the mixing and casting process becomes, as the mixture becomes very viscous.

The limit above which a strong increase in electrical conductivity can be detected when measuring the silicone samples is called the percolation limit. In first experiments with concentrations of carbon black powder based on the publication of Sethi et al.[7], it was not possible to reach the percolation limit and cure the silicone mixture at the same time. For this reason, we decided to test the mixture of carbon black powder and the carbon cutlets instead of mixing only carbon black powder with silicone. Therefore, 1 parts per hundred rubber (phr) of carbon black powder was added to different concentrations of carbon cutlet.

Electrical conductivity of the samples was measured with a precision LCR-Meter E4980A from Keysight (Santa Rosa, USA). In order to be able to generate comparability between the silicone samples, they have been cast in a consistent geometry. All samples were poured into a tube made of hard plastic with a diameter of 28 mm. After vacuumizing and curing of the samples, the tube was cut to short pieces of about a length of 150 mm. Circular copper circuit boards have been used to connect the silicone samples to the LCR-meter for impedance measurement. A weight of 35.6 g has been added on top of the electrodes and sample in order to achieve the same surface pressure on every sample and additionally to fix the electrodes to ensure a maximized contact area.

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**Tab. 1:** Exemplary the dependency between shore scale and modulus of elasticity, taken from [6]

<table>
<thead>
<tr>
<th>Shore scale</th>
<th>Approx. $E$ in kPa</th>
</tr>
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<tbody>
<tr>
<td>Shore A00</td>
<td>100</td>
</tr>
<tr>
<td>Shore A13</td>
<td>500</td>
</tr>
<tr>
<td>Shore A33</td>
<td>1500</td>
</tr>
</tbody>
</table>

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**Fig. 3:** Measurement setup of the silicone samples.
Experiments have been done with 10 samples of silicone/carbon mixtures. The measurement setup is depicted in Fig. 3.

### 3 Results

The resulting measurements showed that a purely ohmic behaviour could be observed for all silicone mixtures, since a negligible small phase value was measured with the LCR-meter. The left side of Fig. 4 shows experiments with the mixture of exclusively carbon cutlets. In the right, the measurements of mixtures with carbon black powder and carbon cutlets are depicted. It can clearly be seen that with higher concentrations of carbon material the conductivity increases. Comparing the two mixtures it can also be seen that mixing the carbon cutlets with the powder obviously leads to a rise in conductivity. We observed that conductivity of the samples remains almost constant over frequency. With the given measurement setup the values of the impedance measurements of each sample were reproducible (error bars in the plots). Only at 20 Hz there was a transient phenomenon noticed, that can be explained by a settling process in the LCR-meter.

In Fig. 4 on the left side, the same concentration of carbon cutlets have been mixed for 2 samples (1 phr (I) and 1 phr(II)). It is striking that for the two samples with the same concentration a deviation of approx. 19 % in conductivity has been measured. If we have a look at the microscope image from Fig. 5a) this deviation can be explained by the fact that it is generally very difficult to produce an exactly reproducible product when mixing conductive silicone. There are three areas visible that differentiate in the amount of carbon cutlets. The area depicted as 1 (Fig. 5a) ) almost does not contain any carbon cutlets at all while in area 2 there is an agglomeration of carbon cutlets. However, area 3 appears to have a network structure of carbon cutlets. Above all, the homogeneous distribution of carbon material in the silicone has proved to be a major difficulty. The microscopic analysis of the silicone samples mixed with carbon cutlets and carbon black powder (Fig. 5b)) lead to the con-
Fig. 6: Conductivities of different silicone samples with different concentrations in carbon material at 50 kHz.

clusion that here homogenisation of the carbon was improved. The sample with a concentration of 1 phr carbon cutlets has been cut in half and their conductivity for both was measured. The error in conductivity between the 1 phr and 1 phr (half) samples is in average only 10%.

A non-linear increase in conductivity, starting at a carbon concentration of 0.9 phr, was observed at all frequencies in the silicone samples with carbon cutlets and carbon black powder. This could be explained by the effect that additional carbon powder bridges free spaces between the carbon cutlets and hence lead to a higher conductivity. Referring to Fig. 6 in the graph with only carbon cutlets the ascent of the curve is less steep. This was analogically observed at all measuring frequencies.

4 Discussion and Conclusion

This study is an approach to model the electrical behaviour of a heart’s ventricle. The results show that the higher a concentration in carbon material, the higher the conductivity. Myocardial tissue varies its conductivity between 0.05 – 0.3 S/m, which can be reached by a very low concentration of carbon cutlets and carbon black powder (e.g. 0.7 phr). An example for a ventricle mock-up from silicone and carbon can be seen in Fig. 2c). Although the results show clear dependencies of the amount of carbon to conductivity there are some shortcomings which need to be improved. The process of homogenization is very difficult, so that methods to homogenize the carbon in the silicone would improve the reproducibility. The elastic behaviour should be studied in more detail since in future the cast ventricle mock-up will be used in a test bench to also mimic the volumetric changes in the left ventricle. Additionally, changes in permittivity of silicone ventricle mock-ups are planned to be simulated, so that also the capacitive parts of muscle tissue are taken into consideration.

In conclusion, the study shows that electrical properties of myocardial tissue, concerning passive conductivity, can approximately be modelled. Hence, be a future perspective to develop measurement techniques to derive parameters which quantify the state of heart muscle. This would be of major importance in LVAD therapy and patient’s individual recovery.

Author Statement

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References