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Mechanical Adaptive Silicone Composites for UV-triggered Facilitated Cochlear-Implant Removal

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Abstract: The removal of the cochlear implant (CI), which in some cases is without alternative, is still an act of simple pulling, not only causing harm for the patient by damaging tissue but also making reimplantation more difficult. For that reason, it is necessary to develop mechanisms to make an explantation easier. To overcome this problem adaption of the mechanical properties by light-degradable periodic mesoporous organosilica (PMO) can be one solution. By introducing PMO nanoparticles into the CI's silicone matrix, the particles act as a stiffening agent, which can be degraded by irradiation with UV light. Using this mechanism, the silicone becomes softer, thus making explantation easier and safer for patients. Here first results, concerning the creation of a silicone composite material with light-sensitive adaptive mechanical properties are reported.

Keywords: cochlear implant, silicone composites, organosilica, PMO, UV-light

1 Introduction

Cochlear Implants (CI) are the gold standard to give people with sensorineural hearing loss, a new sense of hearing. While the CI is continuously being optimized to show favorable interactions with its surroundings and to improve hearing impressions, there are cases where the implant has to be removed. Reasons for a removal can be an untreatable infection, a defective device, or also the improvement of the current technology.[1] Due to the on growth of fibrous tissue, the removal of an implant can damage surrounding tissue structures, causing

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trauma for the patient but also leading to complications at reimplantation.[2] For that reason, a new material concept of using light-degradable PMO nanoparticles [3] which are integrated into silicone and act as strengthening filler particles, is developed. Silica particles have not only shown to be biocompatible, but are also widely used to adjust the properties of silicones by having strong interaction with the polymer chains.[4] Silanol groups on the surface of the silica make it possible to form hydrogen-bonding with the silicone resulting in higher strength. The interaction depends on the size of the filler particles. As shown in literature smaller particles have a stronger effect on the silicone, because of higher interaction surfaces.[5] While the PMOs indeed show similar surface chemistry like silica, the hydrophobicity can vary with the introduced moiety, which might alter the interaction with the silicone. Due to silanol groups on the surface, post-synthetic modification is feasible, which makes PMOs a highly versatile filler material. Through introduction of a light-sensitive moiety (see Figure 1) into the silica, degradation of the nanoparticles via light becomes accessible.

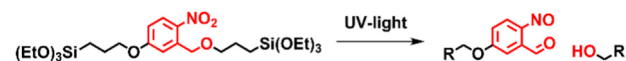


Figure 1: Bisilane containing a Norrish type moiety (red), which enables bond cleavage at irradiation of UV-light.

By degrading the strengthening filler particles, the silicone composite should become softer, and thus the removal of the CI should be easier and less harmful for the patient. Figure 2 shows the concept behind the research.

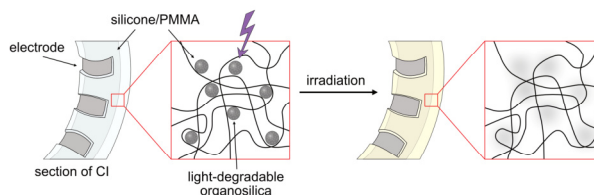


Figure 2: Concept for softening polymer composites by light-induced degradation of filler nanoparticles. Before irradiation the organosilica provide reinforcing properties to the silicone.

2 Materials and Methods

All chemicals were used without further purification. 5-Hydroxy-2-nitrobenzyl (97%), sodium hydride (90%), dimethylformamide (DMF, anhydrous), allyl bromide (97%), toluene (anhydrous), triethoxysilane (99%), Karstedt's catalyst (in xylene, Pt-2%), cyclohexane ($\geq 99.7\%$), ethyl acetate (99.8%), sodium chloride, sodium carbonate ($\geq 99.8\%$), magnesium sulfate ($\geq 99.5\%$), silica gel (60-200 μm), cetyltrimethylammonium bromide (CTAB, $\geq 98\%$), ammonium hydroxide solution (28-30 % NH_3 in water), tetraethyl orthosilicate (TEOS, $\geq 99\%$), were purchased from Sigma-Aldrich Corporation (München, Germany). The silicone Sylgard™ 184 was purchased from DOW® (Wiesbaden, Germany).

2.1 Synthesis of Bivinyli-intermediate

For the synthesis of the PMO, the precursor had to be synthesized first. Apart from scaling up, the synthesis reported by DE COLA et al. [1], has been adapted.

In the first step, a bivinyli-intermediate is synthesized as follows. Under N_2 -inert gas, 4 g of 5-hydroxy-2-nitro benzyl alcohol was dissolved in 40 mL of anhydrous DMF. After cooling the flask with an ice bath, 1.25 g sodium hydride was added in three portions. In the following, 4.68 mL allyl bromide was added. After 1 h of stirring, the ice bath was removed and stirred at room temperature for one more hour. The reaction was quenched with 20 mL water. The aqueous phase was extracted three times with ethyl acetate. For purification of the organic phase, the solution is firstly washed with saturated sodium carbonate solution and secondly with brine. After drying over magnesium sulfate the solvent is evaporated under reduced pressure. Finally, the crude oil was purified via flash column chromatography with cyclohexane:ethyl acetate (4:1, v:v).

2.2 Synthesis of Bissilane-Precursor

In the second step, the bissilane precursor has been synthesized. Under N_2 -inert gas, 3 g of the bivinyli intermediate was solved in 27 mL toluene. Further, 6.10 mL triethoxysilane is added, followed by 0.450 mL Karstedt's catalyst. The solution is heated up to 50 °C and stirred for 12 h, before adding another 0.36 mL Karstedt's catalyst. After another 12 h of stirring, the solvent is evaporated under reduced pressure. The crude oil was purified via flash column chromatography with cyclohexane:ethyl acetate (7:1,v:v).

2.3 Synthesis of Light-degradable Organosilica Nanoparticles

The particles were prepared using a modified STOEBER-synthesis. While using the approach of DE COLA et al. [1], the amount of ammonia and concentrations of the bissilane and TEOS for scale-up has been adjusted. In a typical synthesis 0.4 g CTAB is dissolved in a mixture of ethanol:water (1:2;v:v). As a catalyst, 0.32 mL 28-30 wt% ammonia is added. In a separate vial, 0.8 g of the synthesized bissilane is mixed with 0.691 mL of TEOS in 1.5 mL ethanol. The silane-mixture is then poured into the prepared CTAB-solution and stirred for 16 h at room temperature. The particles were washed with water (1:1;v:v) and ethanol before drying under vacuum. Transmission electron microscopy (TEM) was measured on a Tecnai G2 F20 TMP from FEI Company (Hillsboro, USA).

2.4 Manufacturing of Mechanical Adaptive Composites

To incorporate the particles into the silicon, the organosilica was sieved with a 200- μm -sieve to prevent bigger agglomerates. The particles were then transferred to the silicone oil. The mixture was then mixed with the SpeedMixer™ (DAC 150 SP) on setting 1, as shown in Table 1. Afterwards, the curing agent was added and the mixture was mixed again, with setting 2.

Table 1: Mixing protocol for incorporating the particles (setting 1) and the curing agent (setting 2).

Setting 1		Setting 2	
Revolution / rpm	Time / s	Revolution / rpm	Time / s
1500	15	3500	25
2000	30	2500	20
2500	15	2000	30
3000	10	-	-
3500	30	-	-

The composite was then poured into the desired shape. To extract any trapped air bubbles, the specimen was treated with vacuum (5×10^{-2} bar) for 30 minutes at room temperature. Prior to closing the mold with the negative mold, the silicone was placed in an oven at 80 °C for 45 minutes, as a pre-curing step. This prevents new air bubbles to form when pressing the negative mold on top. After closing, the specimens were kept at 80 °C for 24 h. For dynamic mechanical measurements (DMA) a cylinder with 20 mm in diameter and 1 mm in height

was used. DMA was measured in a plate-to-plate geometry on a MCR302 type rheometer from Anton Paar (Graz, Austria)

3 Results and Discussion

The synthesized PMO nanoparticles, as shown in the TEM images in Figure 3 on the left side, are spherically shaped with a mean diameter of 130 nm (SD = 20 nm).

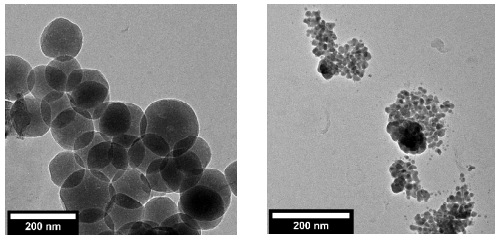


Figure 3: Left: TEM image of the synthesized spherical organosilica nanoparticles. Right: Organosilica after irradiation for 6 h in ethanol:water (5:1,v:v) at 325 nm. The particles are fractured into smaller segments, proving its disintegrating properties. Scale bar: 200 nm.

Thermogravimetric (TG) measurements showed, that around 30 % of the particles consist of the integrated light-sensitive bissilane. Furthermore, the particles showed disintegrating properties, when irradiated in an ethanol-water solution as shown in Figure 3 on the right side. By comparing the particles before and after irradiation with UV-light at 325 nm, a shift from 320 nm to 380 nm is observed, as reported in literature [3] as well, which is evoked due to the change of the π -system of the bissilane.

In the next step, the particles have been integrated into transparent and biocompatible silicone to determine their impact on the mechanical properties. The particles could be distributed well in the silicone as shown in Figure 4.

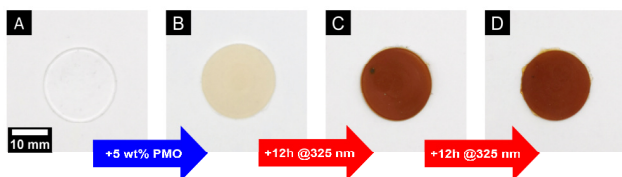


Figure 4: Photographs of silicone specimen in front of a white background. A: transparent silicone without organosilica particles. B: Silicone composite with 5 wt% of organosilica incorporated. A homogeneous distribution is observed. C, D: Silicone composite with 5 wt% of organosilica incorporated after irradiation with 325 nm for 12/24 h at each site. The shift in colour from yellowish to brownish indicates the bond cleavage.

After irradiating the composites, the shift in colour from yellowish to brown was observed, which could also be observed for the pure particles. By measuring the penetration depth of

the brown colour over the cross-section of the specimen, it was estimated that the light reaches around 0.4 mm into the composite at 5 wt%. For that reason, composites with a cylindrical height of 1 mm were produced. The cross-section of such irradiated specimen can be seen in Figure 5.

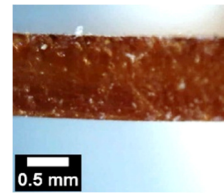


Figure 5: Cross-section of 5 wt% composite irradiated at 325 nm with app. 20 mW/cm² for 12 h. The specimen is irradiated over the entire cross-section.

To measure the rheologic properties of the composites DMA was performed using an amplitude sweep. In Figure 6 measurements for the various specimen are shown.

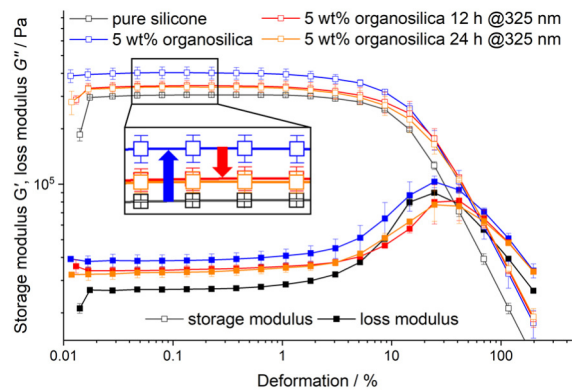


Figure 6: DMA of the pure silicone and the non-irradiated and irradiated 5wt%-composites. The storage modulus of the non-irradiated composites is higher compared to the irradiated specimen, indicating a softening effect. Blue Arrow: Effect of addition of particles. Red Arrow: Effect of irradiation of composites.

While the linear viscoelastic (LVE) range for the pure silicone ranges around 0.30 MPa, it increases with the incorporation of 5 wt% particles to a value of 0.40 MPa indicating a higher capacity to store energy through deformation (see Figure 4, blue arrow). After 12 h of irradiation, the LVE drops to a value of 0.35 MPa, indicating decreased structural support by the filler particles. Irradiation for further 12 h did not show a higher effect on the storage modulus. Until now, we could not find similar materials in literature to compare to. We will therefore work on the determination of the optimal mechanical properties of the composites for im- and explantation and how they can be achieved.

4 Conclusion

In summary, we achieved the first proof of our material concept by showing that it is possible to alter the mechanical properties of silicone by light-sensitive degrading incorporated filler particles. Nevertheless, the effects are still rather small. To increase the effect further research on the properties of the PMO nanoparticles, different filler mass percentages and different silicones will be done.

To reach a higher effect on the softening of the silicone it would be possible to use even smaller filler particles. Smaller particles should be degraded more easily due to the higher surface-to-volume ratio. One more possible improvement for the system would be to increase the amount of light-sensitive moiety in the silica. By doing so, more positions for bond cleavage would be accessible leading to stronger degradation of the particles. This should also lead to higher effects on the silicone.

At this stage of the research, it is difficult to estimate which kind of viscosity is necessary to achieve easier CI removal. For that, we are looking into possibilities to simulate the process with a model. Using the model, silicone with different viscosity could be tested to find the ideal range of viscosity, which we need to aim for.

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Author Statement

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