Removal of Silicone Oil From Intraocular Lens Using Novel Surgical Materials

Eleftherios I. Paschalis, Dean Eliott, and Demetrios G. Vavvas

Department of Ophthalmology, Boston Keratoprosthesis Laboratory and Angiogenesis Laboratory, Massachusetts Eye and Ear Infirmary and Schepens Eye Research Institute, Harvard Medical School, Boston, MA

Correspondence: Eleftherios I. Paschalis, Department of Ophthalmology, Boston Keratoprosthesis Laboratory, Massachusetts Eye and Ear Infirmary and Schepens Eye Research Institute, Harvard Medical School, Boston, MA 02114, USA; e-mail: eleftherios_paschalis@meei.harvard.edu

Demetrios G. Vavvas, Department of Ophthalmology, Angiogenesis Laboratory, Massachusetts Eye and Ear Infirmary and Schepens Eye Research Institute, Harvard Medical School, Boston, MA 02114, USA; e-mail: demetrios_vavvas@meei.harvard.edu

Received: 27 March 2014
Accepted: 18 June 2014
Published: 12 September 2014

Keywords: silicone oil; vitrectomy; retinal detachment; IOL; tamponade; ALD; PDMS; lithography; superhydrophobicity; oleophilicity

Citation: Paschalis EI, Eliott D, Vavvas DG. Removal of silicone oil from intraocular lenses (IOL) during vitreoretinal surgery. Transl Vis Sci Tech. 2014; 3(5):4, http://tvstjournal.org/doi/full/10.1167/tvst.3.5.4, doi:10.1167/tvst.3.5.4

Introduction

Silicone oil (SiO) adherence on intraocular lenses (IOL) is a well-known complication of vitreoretinal surgery. Remnants of SiO in the eye can form droplets, strongly adherent to the surface of the IOL, that cause visual acuity reduction and induction of high order refractive aberrations, monocular diplopia, glare, and halos. Removal of such droplets is technically challenging due to the strong hydrophobic interaction between the oil and the lens. This complication is more frequent with hydrophobic IOLs, including silicone and polymethylmethacrylate IOLs.

Over the past years, several methods have been advocated to remove SiO from IOLs using solvents or viscoelastics. However, solvents may cause tissue toxicity, and viscoelastic compounds often result in inadequate removal. Currently, the surgical explanation and replacement of the IOL is the mainstay of treatment, but it is associated with increase in surgical time, complication rate, and cost.
The purpose of this paper is to delineate the physical mechanisms underlying this complication and to develop novel materials that can safely and effectively remove SiO from the surface of IOLs.

Materials and Methods

Hydrophobic/Oleophilic Materials Created

Three different materials were designed and fabricated, exhibiting low surface energies and adequate critical surface tension. The first two materials were fabricated using biocompatible polydimethylsiloxane (PDMS), modified by either soft lithography or inverse three-dimensional (3D) fabrication, while the third material was fabricated using the United States Food and Drug Administration (FDA)–approved surgical Weck-Cel, precisely modified using atomic layer deposition (ALD) of alumina (Al2O3). All materials exhibited enhanced hydrophobic properties.

1. PDMS surface patterning was performed using standard soft lithography techniques (supplemental methods). The objective was to create a PDMS surface with high-aspect ratio (AR) micropillars with nanoroughness on their surface with minimum surface energy (Fig. 1A–D);

2. 3D porous PDMS block was fabricated using water-soluble sucrose microparticles as a negative template (supplemental methods). The size of the particles determined the diameter of the cavitation within the block (Fig. 1E–G). Sucrose was chosen due to its excellent biocompatibility, water solubility, and low cost. The resulting microporous PDMS was sectioned to smaller segments (3 × 0.5 × 3 mm; length × width × height) for surgical use. Structural analysis was performed using nondestructive 3D x-ray microcomputed tomography (microCT; X-Tek HMXST225; Nikon Metrology Inc., Brighton, MI). X-rays were generated using a molybdenum target exposed to 70 KV and 140 μA, and x-ray scans were radial. 3D image rendering was used for image reconstruction (VGStudio Max 2.2, Heidelberg, Germany). Using nondestructive x-ray micro-CT imaging, we were able to visualize the porosity of the 3D PDMS (Fig. 1H). The analysis showed presence of polydispersed porosity, from 100 to 300 μm in diameter. Due to the rough surface of the 3D porous PDMS, its hydrophobicity and oleophilicity were further enhanced; and

3. Surgical cellulose Weck-Cel was purchased from BVI (Beaver Visitec International, Waltham, MA). Hydrophilic Weck-Cel was converted to hydrophobic using atomic layer deposition (ALD) of Al2O3 (supplemental methods). This modification provided hydrophobic/oleophilic properties to Weck-Cel (Fig. 1I–L).

Hydrophobicity/Oleophilicity Assessment

Hydrophobicity/oleophilicity was determined by using static contact angle (CA) measurements with 10 μL deionized (DI) water or SiO in room temperature. Hydrophobicity describes the ability of a surface to repel water and oleophilicity the ability to bind hydrocarbons or SiO. Experimentally, this is assessed by placing a water or SiO droplet on the surface of the
from the PDMS surface:
\[
AR = \frac{(L_{ll'} + L_{ll''})/2}{L_{ww'}} 
\]  

In Vitro Assessment

SiO removal from IOLs was performed in vitro as follows: five IOLs (two silicone and three acrylic) were submerged in medical grade SiO (SILIKON1000; Alcon Laboratories, Fort Worth, TX) for 3 days. They were then removed, and excess oil was removed by balanced salt solution (BSS) irrigation. The IOLs were then placed in a glass beaker (100 mL BSS) for 30 minutes until SiO droplet formation occurred on the IOL surface. SiO removal was then performed using the fabricated materials. SiO removal was assessed based on previously described methods.6

Ex Vivo Assessment

Pars plana lensectomy and vitrectomy in explanted porcine eyes was performed using the 23-G transconjunctival Accurus vitreotome from Alcon. An acrylic IOL (AcrySof IQ Aspheric; Alcon) was implanted in the anterior chamber (AC) of the eye, and the posterior segment was filled with SiO 1000 centistoke (Silicon 1000; Alcon). The oil was left for several minutes and was subsequently removed and exchanged for BSS (Alcon). Triple irrigation/aspiration cycles were performed to thoroughly remove the SiO. Droplets of SiO remnants formed on the posterior surface of the IOL and the AC, which were removed using a 2-mm wide 3D porous PDMS material.

Results

In Vitro Assessment of Hydrophobicity/Oleophilicity

Static CA measurements of water or oil were used to determine the hydrophobicity or oleophilicity of surface.

Provided that SiO and IOL interaction is a highly hydrophobic phenomenon, introducing a more hydrophobic material than the IOL itself can challenge this interaction and preferentially remove the SiO from the surface of the IOL.

Three hydrophobic materials (3D porous PDMS, ALD modified Weck-Cel, and micropatterned PDMS) were created as described in methods and supplemental data and shown in Figure 1. Static CA measurements of the three materials were performed using 10 μL of water. The 3D porous PDMS and
ALD modified Weck-Cel exhibited CA of 155° and 131°, respectively (Fig. 2B–D). Increased hydrophobicity/oleophilicity of PDMS was achieved by generating a pillar structure on its surface (Fig. 2A, 2B), while reducing the pillar size of the pillar structure resulted to increase hydrophobicity. Pillar sizes between 10 and 40 μm provided superhydrophobic properties, with static water CAs greater than 160°, whereas the 80- and 120-μm pillar size exhibited water CA of 145° and 136°, respectively. Dynamic CA measurements using vertical pulling showed a significant 7% reduction in water elongation for each step of pillar size reduction (120, 80, 40, 20, 10 μm) demonstrating reduction in water adsorption. The AR of a vertically pulled water droplet was 1:1 for the 10-μm, 1:12 for the 40-μm, 1:35 for the 80-μm, and 1:33 for the 120-μm pillar size (Fig. 2E–H), with the 10-μm pillar size exhibiting the lowest water adsorption.

Table. Contact Angle Measurements in Air With 10 μL of PDMS Si Oil Droplets Resting the Surface of Micropatterned PDMS, 3D Porous PDMS, and ALD-Modified Weck-Cel

<table>
<thead>
<tr>
<th>CA Measurements Using 10 μL of Si Oil</th>
<th>Micropatterned PDMS (Spreading)</th>
<th>3-D Porous PDMS (Absorption)</th>
<th>ALD Modified Weck-Cel (Absorption)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0 sec</td>
<td>52°</td>
<td>51°</td>
<td>56°</td>
</tr>
<tr>
<td>t = 30 sec</td>
<td>49°</td>
<td>45°</td>
<td>46°</td>
</tr>
<tr>
<td>t = 60 sec</td>
<td>29°</td>
<td>39°</td>
<td>12°</td>
</tr>
<tr>
<td>t = 120 sec</td>
<td>12°</td>
<td>0°</td>
<td>0°</td>
</tr>
</tbody>
</table>

Both the 3D porous PDMS and the ALD modified Weck-Cel achieve complete oil absorption within 2 minutes from the exposure to Si oil, while the micropatterned PDMS continued the spreading of the Si oil thereafter.

Figure 3. SiO absorption by materials. Spreading of a 10-μL droplet of SiO on the surface of the micropatterned PDMS in air (A). The micropatterned PDMS resulted in a 358% increase in spreading area as compared with SiO deposited on the surface of nonpatterned PDMS (B). Complete spreading was achieved within 120 seconds following SiO exposure and resulted to a contact angle of 12° (oleophilic) (C–F). The 3D porous PDMS (G–J) and the ALD-modified Weck-Cel (K–N) resulted to complete SiO absorption.

Figure 4. SiO and water interaction with modified Weck-Cel. ALD-modified Weck-Cel (A) absorbed SiO at the same rate as the standard nonmodified commercial Weck-Cel (B). However, water was absorbed with the ALD modified Weck-Cel was inhibited (C) as compared with the nonmodified Weck-Cel (D). SiO (10-μL droplet) spreading on the micropatterned PDMS covered 358% more area than the nonpatterned PDMS (Fig. 3A–F). SiO CA measurements on 3D porous PDMS and ALD modified Weck-Cel was approximately 0 due to oil absorption (Fig. 3G–N). The absorption and spreading rates are presented in Table 1.

Comparing SiO absorption rate between standard and ALD-modified Weck-Cel, similar rates were recorded (Fig. 4A, 4B). However, the ALD modified Weck-Cel remained dry when submerged in water compared with standard Weck-Cel that rapidly absorbed water and expanded its volume (Figs. 1J–L, 4C, 4D).

SiO Removal In Vitro

SiO removal from acrylic and silicone IOLs was performed in vitro (Fig. 5I:5A, 5II:5A). The 3D porous PDMS and ALD modified Weck-Cel were employed first to remove the bulk of the SiO (Fig. 5I:5C, 5D, and 5II:5C, 5D). Small remnants of SiO on the IOL were removed using the micropatterned
PDMS, which is more effective due to its super hydrophobicity (Fig. 5III:5A–D). SiO removal and polishing of the IOL was accomplished in approximately 2 minutes (Supplemental Video V1). Technical difficulty of performing maneuvers shown in the video within a real eye would require experienced surgeons.

SiO Removal Ex Vivo

SiO removal was performed ex vivo using a porcine eye. A 23-G transconjunctival pars plana vitrectomy, pars plana lensectomy, and acrylic IOL implantation (in AC) were performed. SiO infusion was performed after fluid-air exchange. The oil was left for several minutes, then was subsequently removed and exchanged for BSS. Three irrigation/aspiration cycles were performed to thoroughly remove the oil. Nevertheless, remnants of SiO droplets formed on the posterior surface of the IOL and several droplets remained in the AC. The 3D porous PDMS material (3-mm wide stick) was used to remove SiO droplets from the surface of an acrylic IOL implanted in the anterior chamber of the eye (Fig. 6). SiO removal was accomplished in approximately 30 seconds. Floating oil droplets in the anterior chamber and on the posterior surface of the cornea were easily removed without complications.

Discussion

Previous attempts to remove SiO from IOLs have been very difficult due to the strong hydrophobic interaction between the SiO and the IOLs. The use of fluorinated solvents7 to remove SiO can have toxic effects intraocularly, since they do not remove SiO, but rather form a solution that is dispersed in the eye. Viscoclastic substances on the other hand, such as Healon, are nontoxic intraocularly, but have limited success in previous attempts.1,6

Achieving SiO removal from IOLs requires good understanding of the physical interactions that take place between SiO and IOL material as described by thermodynamics. In general, the degree of mixing of two fluids is favored by entropy, but also depends on
the enthalpies of mixing. Thus, two nonpolar substances may not mix when the enthalpic disadvantage outweighs the entropic advantage of mixing, as described in the following formula:

\[ \Delta G_{\text{mixing}} = \Delta H_{\text{mixing}} - T \Delta S_{\text{mixing}} \]  

Where \( \Delta H_{\text{mixing}} = 2 \Delta H_{a-b} - \Delta H_{a-a} - \Delta H_{b-b}, \) and \( a \) and \( b \) are the two fluids.

However, the inability of hydrophobic compounds to mix with water cannot be explained by the low enthalpic and high entropic behavior of such systems. In hydrophobic interactions, entropy favors demixing instead of mixing, which is a consequence of the conformational entropy of water molecules. Hydrogen molecules have the freedom to make bonds with their nearest neighbors. Replacing one water molecule with a molecule of a hydrophobic solvent reduces the conformational entropy from six possible bonds to three. Thus, this 50% reduction in the conformational entropy of the system results in energy penalty that favors demixing. Therefore, clustering of SiO in water is not due to molecular attraction, but rather an attempt to minimize the conformational entropy loss by surface minimization.

Based on this physical analysis, we fabricated new surgical materials to remove SiO in aqueous environments. Several micro engineering techniques were employed to accomplish this task, including soft lithography and ALD, resulting to the fabrication of three different materials characterized by enhanced hydrophobicity and oleophilicity. By measuring the liquid/vapor interface that meets the solid surface, we determined the hydrophobic/hydrophilic behavior of each material. Likewise, the Cassie-Baxter state was assessed using CA and AR measurements. The Cassie-Baxter state describes the ability of a surface to prohibit water molecules from penetrating into the grooves. This allows effortless spreading of SiO in aqueous environments. The dynamic CA and AR measurements showed that the micropatterned PDMS possess such properties.

In this work, PDMS and Weck-Cel were modified to exhibit oleophilic and hydrophobic properties. Both materials are biocompatible and FDA approved for surgical use. In particular, PDMS is used for the packaging of implantable biomedical microdevices and sensors for fabrication of implantable glaucoma valves, for designing drug-eluting scaffolds and epiretinal implantable electrodes, and in the synthesis of new composite injectable cement. Similarly, atomic layer deposition of Al2O3 is used as a coating technique in bio-micro-electromechanical sensors (MEMS) and other devices that come into contact with biological media, scaffold for osteointegration, and bone prosthesis. It is reported to be as biocompatible as glass, with good bone tissue compatibility. Weck-Cel sponges are the standard in eye surgical fluid control, made of highly absorbent, natural cellulose material, and are biocompatible and safe for use in delicate surgical areas. All these properties led us to consider these materials and techniques suitable for surgical use. However, appropriate sterilization is required to ensure the safety of the procedure. Ideally, PDMS should be sterilized by heat (dry or steam) and ALD modified Weck-Cel by gamma-irradiation. Further work is necessary to assess these possibilities.

All materials demonstrated the ability to absorb SiO. The ALD modified Weck-Cel absorbed SiO faster than the 3D porous PDMS, however the 3D porous PDMS has logistical advantages: it is an FDA-approved material, currently used for retinal tamponade, its fabrication is simple and inexpensive, and it can be fabricated in large scale. These properties led us to consider that the 3D porous PDMS material may be a more feasible, not only for clinical use, but also for industrial applications, such as oil retrieval from the sea. Both the 3D porous PDMS and the ALD modified Weck-Cel showed increased capacity to remove bulk quantities of SiO, however the superhydrophobic properties of the micropatterned PDMS provided detailed removal of even strongly adherent SiO remnants. This suggests that these materials should be used synergistically to obtain optimal surgical results.

Our preliminary results suggest that in situ surgical removal of SiO from IOLs is feasible using the described materials. Even though our procedure requires enlargement of the pars plana incision, it is still significantly less invasive compared with the alternative surgical exchange of the IOL. Future developments in our designs include the optimization of the materials for use through a 20- or 23-G vitrectomy port. Since PDMS polymer is already approved for intraocular use, toxicity is not an important concern for this design. However, the use of ALD to modify Weck-Cel is a new technique which requires full toxicological investigation prior to human application.

**Conclusion**

In conclusion, this work suggests that SiO attachment on the surface of IOLs is a highly hydrophobic
A phenomenon that can be addressed by fabricating materials that provide more favorable interactions to SiO. Preliminary in vitro and ex vivo results are promising and currently more thorough clinical investigation of these materials is underway.

Acknowledgments

The authors thank Miriam Englander and Susan Cardoza for their contribution to this work with regards to syntax and grammatical revisions.

Supported by the Boston Keratoprosthesis (BK-Pro) Fund, the Eleanor and Miles Shore fund, the Research to Prevent Blindness, Inc., the Yeatts Family Foundation, the 2013 Macula Society Research Grant award, the RPB Physician Scientist Award, and the Lions unrestricted fund to MEEI.

Disclosure: D. Eliott, None; E. I. Paschalis, None; D. G. Vavvas, None

References