Emulsification of Silicone Oil and Eye Movements

Yau Kei Chan,1 Chiu On Ng,2 Paul C. Knox,3 Michael J. Garvey,4 Rachel L. Williams,5 and David Wong1,5

PURPOSE. Emulsification is an inherent problem of silicone oil used in vitreoretinal surgery. It has been shown that silicone oil can be made more resistant to emulsification and easier to inject by adding high-molecular-weight components (5% or 10% 423-kDa polydimethylsiloxane [PDMS]) to normal 1000 mPa · s silicone oil. The authors hypothesize that this might also reduce the movement of oil within an eye.

METHODS. A model eye chamber made of surface-modified poly(methyl methacrylate) was driven by a computer and a stepper motor to mimic saccadic eye movement. Seven silicone oils with different shear and extensional viscosities were tested. Two sets of eye movements were used: (amplitude 9°, angular velocity 390°/s, duration 50 ms) and (amplitude 90°, angular velocity 360°/s, duration 300 ms). The movements were captured and analyzed by video recording.

RESULTS. The angular velocity of an oil bubble relative to the eye chamber appears to form an exponential relationship with its shear viscosity. Depending on the thickness of the film of aqueous between the eye wall and the oil bubble, the shear rate was estimated to be between 6 and 14 × 10⁴ s⁻¹. The addition of 10% of 423-kDa PDMS to 1000 mPa · s silicone oil significantly reduced the peak relative velocity compared with the base oil of 1000 mPa · s but not 5000 mPa · s.

CONCLUSIONS. The addition of high molecular components to a base oil increases its extensional and shear viscosity. Although the extensional viscosity affected the ease with which the oil could be injected, the results showed that it was the shear viscosity that determined the relative velocity between the oil and the wall of the vitreous cavity, and thus the propensity to emulsify. (Invest Ophthalmol Vis Sci. 2011;52:9721–9727) DOI:10.1167/iovs.11-8586

Emulsification is an inherent problem with long-term silicone oil tamponade and is associated with other complications such as glaucoma, inflammation, and proliferative vitreoretinopathy.1 Recent in vitro experiments have shown that the addition of a high-molecular-weight component (HMWC) (5% or 10% 423-kDa polydimethylsiloxane [PDMS]) to 1000 mPa · s silicone oil made the resultant blend as resistant to emulsification as did 5000 mPa · s silicone oil.2 We have also shown that compared with oils with similar shear viscosities, oil blends with high molecular additives are significantly quicker to inject.3

By adding HMWCs, the extensional viscosities of the oil blends were increased at high strain rates. The extensional viscosity of silicone oil is believed to be important in determining its readiness to breaking off and form droplets.4 At present, we do not know what amount of shear stress occurs during normal saccadic eye movements at the oil-aqueous interface. To the best of our knowledge, no one has studied the movement of a silicone oil bubble inside an eye or estimated the shear forces that might cause emulsification.

We devised a model eye chamber that can mimic eye movements to estimate the shear rates to which the different oils and oil blends are subjected. Physicists refer to the viscosity of a fluid as its ability to diffuse momentum.5 Emulsification of silicone oil inside an eye would depend on eye movement generating the shear, which in turn depends on the relative velocities between the oil and the wall of the vitreous cavity. When the eye rotates, the oil inside would also move, but to varying degrees dependent on its ability to diffuse the momentum—in other words, its viscosity. One could imagine the oil bubble as being made up of layers, each moving with a different velocity. The layer closest to the retina would move almost at the same velocity as that of the eye, whereas a layer of oil further away would move slower because of inertia. Thus, there would be a gradient of velocities within the oil. Low-viscosity oil will have a sharp gradient and high-viscosity oils will have a gentle gradient. In these circumstances, the addition of high-molecular-weight PDMS, in which the large polymer molecules could span the layers, might lead to a reduction in the gradient. If that was the case, the shear rate might be reduced because the relative velocity at the interface between the oil and the eye might also be reduced. Thus, our hypothesis is that the addition of high molecular components reduces the relative velocity between the oil and the wall of the vitreous cavity. To test this hypothesis we devised the following experiments.

MATERIALS AND METHODS

Seven silicone oils were tested in this study, all of which were kindly donated (Fluoron GmbH, Ulm, Germany). Their compositions and both the labeled and the actual measured shear viscosities are listed in Table 1. There was a silicone oil with very low viscosity of around 5 mPa · s (Siluron 2000), a blend made by adding 5% of the 423-kDa PDMS to a base oil of 1000 mPa · s. The additive 423-kDa PDMS has a shear viscosity of 1,000,000 mPa · s. Siluron 2000 had a shear viscosity of around 2000 mPa · s. It was designed to be more resistant to emulsification due to the fact that it had a high extensional viscosity under high shear strain. Blend A was made by mixing 55% 1000 mPa · s with 45% 5000 mPa · s silicone oil. It also had a shear viscosity of around 2000 mPa · s. Because Blend A did not have the HMWC, its extensional viscosity under shear strain would be roughly midway between its com-

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TABLE 1. Compositions and the Physical Properties of Various Silicone Oils

<table>
<thead>
<tr>
<th>Silicone Oil</th>
<th>Composition</th>
<th>Shear Viscosity at 25°C/mPa · s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone oil, 5 mPa · s</td>
<td>Cannot be provided by manufacturer</td>
<td>5</td>
</tr>
<tr>
<td>Silicone oil, 1000 mPa · s</td>
<td>PDMS 1000 mPa · s (37 kDa)</td>
<td>1,030</td>
</tr>
<tr>
<td>Blend A</td>
<td>55% Silicone oil 1000 mPa · s + 5% PDMS 1000 mPa · s</td>
<td>2,141</td>
</tr>
<tr>
<td>Siluron 2000</td>
<td>95% Silicone oil 1000 mPa · s + 5% high-molecular-weight PDMS (422 kDa), 1,000,000 mPa · s</td>
<td>2,189</td>
</tr>
<tr>
<td>Silicone oil, 5000 mPa · s</td>
<td>PDMS 5000 mPa · s (65 kDa)</td>
<td>4,910</td>
</tr>
<tr>
<td>Blend B</td>
<td>90% Silicone oil 1000 mPa · s + 10% high-molecular-weight PDMS (425 kDa, 1,000,000 mPa · s)</td>
<td>5,090</td>
</tr>
<tr>
<td>Silicone oil, 12,500 mPa · s</td>
<td>Cannot be provided by manufacturer</td>
<td>12,500</td>
</tr>
</tbody>
</table>

* Data were provided by Nadine Hagedorn (from Fluoron, GmbH, Ulm, Germany), using an oscillation rheology method. kDa, kilodalton; PDMS, polydimethylsiloxane.

ponents 1000 and 5000 mPa · s base oils. Blend B was made by adding 10% of the 423 kDa PDMS to a base oil of 1000 mPa · s. Finally, an oil with shear viscosity 12,500 mPa · s was also included in this study. The extensional viscosities of all the oils under different shear strain rates have been previously published.

These oils were chosen to test our hypothesis in two ways. First, we wanted to determine whether adding the HMWC decreased the shear rate. We will be comparing silicone oil 1000 mPa · s with and without HMWC. However, we appreciate that adding the HMWC increased not only the extensional viscosity but also the shear viscosity of the resultant blend. Second, therefore, we wanted to test if oils with the same shear viscosity but with different extensional viscosity would behave differently. We compared Siluron 2000 with Blend A, both with similar shear viscosity of around 2000 mPa · s and, likewise, Blend B with silicone oil 5000 mPa · s.

**Procedures**

**Eye Chamber.** The eye chambers that we used were described previously. Briefly, the eye model chambers were cylindrical, with an internal diameter of 20 mm, a length of 20 mm, and a volume of approximately 6.3 mL. The chambers were made of poly(methyl methacrylate). We rendered the surface hydrophilic by coating it with protein. This was achieved by using 0.1 g/mL nonfat milk powder (Carnation; Nestlé, Vevey, Switzerland) in 1 × PBS; the protein was allowed to adsorb for 1 hour. Each silicone oil (5 mL) was injected into the chambers and the remaining space topped up with PBS colored with trypan blue. We took great care to ensure that the chamber contained no air bubbles.

**Simulation of Eye Movements.** We developed a mechanical system to generate motion. The system consists of a stepper motor (C4/MD2 Step Motor System, Arrick Robotics, Tyler, TX), a shaft encoder (Baumer Electric AG, Frauenfeld, Switzerland), and a data acquisition device (National Instruments Corp., Austin, TX). An adapter was fashioned to affix the eye model chamber to the shaft of the stepper motor. The motion was therefore rotational and in one plane only. A computer and a dedicated program were used to control the stepper motor. It was possible using the software to send instructions to execute repetitive motions. The shaft encoder enabled us to record the angular displacement, velocity, and acceleration of the actual motion being executed.

The most frequent human saccades have amplitudes below 15°, with a maximum angular velocity from 300 to 400°/s and a duration of approximately 50 ms. With our mechanical system, we instructed the system to execute two different sets of motion: (amplitude 9°, angular velocity 300°/s, duration 50 ms) and (amplitude 90°, angular velocity 560°/s, duration 300 ms), with the aim of mimicking the stereotyped velocity profiles observed in healthy, adult humans.

**Measurements of Angular Displacement and Angular Velocity to Estimate Shear Rate.** A digital camera that took 30 frames/s was used to capture the motion of the eye chamber and the oil contained within. We recorded the maximum angular displacements of the oil bubble (Fig. 1) and calculated the relative velocity between the wall of the model eye chamber and the oil bubble. The shear rate was dependent on this relative velocity and the thickness of the aqueous film between the oil bubble and the chamber wall such that shear rate = v/b, where v is the relative velocity between the eye chamber wall and the oil bubble and b is the thickness of the aqueous film between them.

An image analysis program, ImageJ software (developed by Wayne Rasband, National Institutes of Health, Bethesda, MD; available at http://rsb.info.nih.gov/ij/index.html), was used to analyze the photographs to measure the angular displacement (Fig. 1) and the velocity of the bubble and the eye chamber.

**Statistical Method.** Unpaired t-tests were performed using commercial software (GraphPad Prism; GraphPad Software, Inc., San Diego, CA). Values of P < 0.05 were considered to be statistically significant. In the experiments with 9° movement, n = 15. In the a, b.

**FIGURE 1.** The measurement method of the maximum angular displacement. (a) The tamponade at rest. (b) The tamponade at its maximum displacement. The line in each figure indicates the chord of the tamponade. By measuring the slope of the chord in (b), the maximum angular displacement could be obtained. The aqueous was colored by trypan blue and a black background was used to enhance the contrast between the tamponade and the aqueous phase. The red mark on the chamber indicates the position of the eye model chamber.
experiments with 90° movement, \( n = 8 \). All values in the graphs are shown as mean ± SD.

**RESULTS**

First Set of Motion: Amplitude of 9°, Velocity of 390°/s, and Duration of 50 ms

The angular displacement versus time and angular velocity versus time profiles of the simulated saccadic eye movement are presented in Figures 2a and 2b. The shape of these plots resembled those of human saccades data that were obtained from a healthy adult executing saccades of a similar amplitude, recorded using infrared oculography (Figs. 2c, 2d). Within the limitation of the stepper motor, this was the best simulation that we could achieve.

**Maximum Angular Displacement.** Silicone oil 12,500 mPa·s had the largest, whereas 5 mPa·s oil had the smallest angular displacement (Fig. 3a). There seemed to be an exponential relationship between the shear viscosity of the oil and its angular displacement (Fig. 3b). There was a significant difference between the maximum displacements of the two oils with the HMWC when compared with base silicone oil 1000 mPa·s. The maximum displacement of Blend B was statistically greater than that of 5000 mPa·s oil (\( P = 0.0355 \)), whereas the maximum displacement of Siluron 2000 was not statistically different from that of Blend A (\( P = 0.919 \)).

**Angular Velocity.** The duration of motion was 50 ms. We could not reliably measure the angular velocity of the oils using our camera because it captured only 1 frame per 33 ms.

Second Set of Motion: Amplitude of 90°, Velocity of 360°/s, and Duration of 0.3 s

**Maximum displacements.** The results turned out to be similar to those stated earlier (Fig. 4a). Silicone oils with additives had significantly higher maximum angular displacements than those of the base oil 1000 mPa·s. There was no statistical difference between the maximum angular displacements of 5000 mPa·s oil and Blend B (\( P = 0.4864 \)) or between that of Siluron 2000 and Blend A (\( P = 0.7973 \)). When we plotted the...
maximum angular displacements against the shear viscosity of the oils, we found a relationship that was exponential (Fig. 4b).

Angular Velocities. Figure 5a shows a plot of the angular velocities of the eye chamber and the oil bubbles. The velocity of the chamber was set to reach 360°/s in approximately 0.03 s. This velocity was maintained for 0.23 s, and the chamber came to a stop in approximately 0.03 s. The plots of angular velocities for all the oils showed a rise and a fall. The velocity was highest for the silicone oil 12,500 mPa·s and lowest for silicone oil 5 mPa·s. The angular velocity of silicone oil 1000 mPa·s was lower than that of Blend A, Siluron 2000, 5000 mPa·s oil, and Blend B. There was little difference that separated the angular velocity of any of the latter four oils.

Figure 5b gives the plot for the relative angular velocities of different oils. With the exception of the silicone oil 5 mPa·s, all the plots showed two peaks. The first peak occurred just after the eye chamber reached its peak velocity and the second peak occurred after the eye chamber started to slow to a stop. The plots illustrate the different ability of oils to diffuse momentum. Silicone oil 5 mPa·s had the highest relative angular velocity when the chamber was moving and the lowest when the chamber was stopping, whereas silicone oil 12,500 mPa·s had the lowest relative velocity when the chamber was moving and the highest when the chamber was stopping. Silicone oil 1000 mPa·s behaved in a fashion between these two extremes. There was little to separate the velocities of the four oils: Blend A, Siluron 2000, silicone oil 5000 mPa·s, and Blend B. Figure 6a shows the peak relative angular velocities of the different oils; the plot in Figure 6b shows an exponential relationship between the peak relative velocity and the shear viscosity.

DISCUSSION

Emulsification of silicone oil observed in patients is a dispersion of oil droplets in an aqueous setting. In the anterior chamber, these droplets can be seen by gonioscopy and, if extensive, can manifest as an “inverted hypopyon.” The inner surface of the eye wall is made up of the retina and the crystalline lens anteriorly. Depending on the thoroughness of the vitrectomy, there might be a variable amount of cortical vitreous attached to the retina and to the lens posteriorly. We have demonstrated in the past that the vitreoretinal surface was hydrophilic and we have also shown that its surface property could be mimicked by protein-coated PMMA. We justified the use of our eye model chamber made of this material in a number of previous static studies. Being hydrophilic, the vitreoretinal surface should not make direct contact with an intraocular oil bubble. Instead, there should be a thin aqueous layer interposed between the oil and the retina. Using optical coherence tomography, Winter et al. measured the thickness of the aqueous film between a bubble of perfluorocarbon liquid and the retina to be between 5 and 10 μm. We envisaged that emulsification of silicone oil occurs because of the shear stress applied across a similarly thin aqueous film. Although there is no published value on the actual thickness of this film, this information is nonetheless important because the shear stress is determined by it, such that the thinner this aqueous film, the greater the shear stress. In this study, we attempted, using a dynamic model, to study the shear rate. Our hypothesis is that the addition of high-molecular-weight additives would reduce the relative velocity between the eye chamber and the oil and therefore would also reduce the shear rate. By implication, the energy available for dispersion of silicone oil would also be diminished.

Rheologists describe viscosity as a measure of the ability to diffuse momentum; a liquid with high shear viscosity is more able to diffuse momentum than one with low shear viscosity. In the dynamic study with 90° motion, 5 mPa·s silicone oil clearly demonstrated this phenomenon. It seemed to remain more still (because of inertia) when the chamber rotated. It was also quicker to stop moving when the chamber stopped (Fig. 5). Low shear viscosity oils had low angular displacement with simulated saccadic movement. With silicone oil 12,500 mPa·s the reverse was demonstrated: it had the highest angular displacement with saccadic movement; it tended to move more with the eye chamber; it also carried on moving once the chamber stopped. In terms of absolute velocities, the trend was clear; the higher-viscosity oils had higher angular velocity and vice versa.

However, in terms of shear rate, it was the relative velocity between the oil and eye chamber that mattered. For a given thickness of aqueous film, the peak relative velocity reflected the maximum shear rate. The addition of 10% of 423-kDa PDMS significantly reduced the peak relative velocities compared with that of 1000 mPa·s oil. Our hypothesis is therefore supported. The addition of 5% of 423-kDa HMWC also reduced the peak relative velocities but not significantly so. The experiment demonstrated a general trend: the higher the shear viscosity, the lower the peak relative velocity. The 5 mPa·s oil had the highest peak relative velocity; silicone oil 125,000 mPa·s had the lowest with silicone oil 1000 mPa·s somewhere in between the two extremes. Comparing oils with a similar shear viscosity, we found that Blend A had a significantly higher peak relative velocity than that of Siluron 2000. This could be explained by the fact that Blend A had a significantly lower shear viscosity than that of Siluron 2000. There was no significant difference between silicone oil 5000 mPa·s and Blend B. In terms of peak relative velocity (that determines the shear stress) it was the shear viscosity that was the main difference that separated the angular velocity of any of the different oils; the plot in Figure 6b shows an exponential relationship between the peak relative velocity and the shear viscosity.
determining factor. Adding HMWC succeeded in increasing only the shear viscosity. Comparing oils with similar shear viscosity but different extensional viscosity revealed that increasing extensional viscosity did not succeed in reducing the peak relative velocity.

Previous studies on silicone oil emulsification relied on the use of large mechanical forces and the vigorous motion generated by vibrators or rotary devices.\textsuperscript{4,18} They have shown that 5000 mPa \textperiodcentered s silicone oil was more stable and less likely to emulsify compared with 1000 mPa \textperiodcentered s.\textsuperscript{19–21} It has always been puzzling to us how emulsification could happen in the human eye given that such violent movements do not occur. Our study tried to mimic human eye movements in terms of amplitude, velocity, and duration. One weakness of the study is that we could not find a reliable way to measure the thickness of the aqueous film. Our study has shown for the first time that the peak relative velocity of the oils closely approximated that of the peak velocity of the eye chamber. In other words, if the peak velocity of the eye chamber was 360°/s, then all the oils attained relative angular rotation velocities of between 310 and 340°/s. All oils irrespective of their shear viscosity had significant inertia such that with the mimicked movement of 90°, when the chamber reached maximum angular velocity, the oils remained more or less stationary. This is the single most important finding. Because the oil remained stationary while the eye chamber moved, relative movement occurred that gave rise to shear stress at the interface between the chamber and the oil. One could estimate the shear rate by making some assumptions for the thickness of the aqueous film. If we take the figure of 10 \textmu m\textsuperscript{17} and assume the peak relative velocity to be between 310 and 340°/s and the diameter of the eye to be 2.3 cm, then the maximum shear rate would be between 6200 and 6800 s\textsuperscript{−1}. The difference in the shear rate between 5 and 12,500 mPa \textperiodcentered s silicone oil would be as little as 10%. It is surprising to us that such a little difference in shear rate could account for such a difference in propensity to emulsify.

To prevent emulsification several strategies have been used. The usual strategy has been to use oils with higher shear viscosity, that is, 5000 mPa \textperiodcentered s or above. As we have shown, using higher-viscosity oil would reduce the peak relative veloc-

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**FIGURE 5.** (a) Angular velocity of eye chamber and different oils with 90° motion. (b) Angular velocity of oil relative to the eye chamber with 90° motion.
Addition of 5% and 10% 423-kDa PDMS to 1000 mPa\(\text{s}\) silicone oil should make it more difficult for droplets to form. The molecules line up, thus making the blends quicker to apply, and we have been able to measure the relative angular velocity. The movement of oil bubbles inside a model eye chamber asked whether the addition of high molecular components would prevent emulsification. We have been able to measure the relative angular velocity and, thus, the shear rate and the energy available to disperse the silicone oil. Once droplets break off from the main body of silicone oil, there also must be surfactants available to stabilize the silicone oil. Once droplets break off from the main body of silicone oil, there also must be surfactants available to stabilize the small droplets; otherwise, surface energy would drive them to coalesce back into larger bubbles. It has been shown that blood products could stabilize dispersed droplets. Therefore, the extent of any inflammation and the breakdown of the blood–ocular barrier might be relevant. Thus, there are individual patient’s parameters that might be confounding factors for emulsification. To date, there is no randomized clinical trial to show that 5000 mPa\(\text{s}\) oil is more resistant to emulsification than 1000 mPa\(\text{s}\) oil and there is no consensus among vitreoretinal surgeons as to which viscosity should be chosen. Although clinical studies comparing silicone oils of different viscosities emphasized the differences in anatomic outcome, they did not look specifically at emulsification. The only consensus thus far has been to use highly “purified” oils with the lower molecular weights removed because they do tend to cause emulsification.

Although it seems preferable to use high-viscosity oils to prevent emulsification, there are also compelling reasons to choose less viscous oils. With the advent of smaller-gauge vitrectomy, surgeons want oils that are easier to inject and choose less viscous oils. With the advent of smaller-gauge vitrectomy, surgeons want oils that are easier to inject and extract through smaller-bore instruments. The new proposed strategy to prevent emulsification is to add HMWC to 1000 mPa\(\text{s}\) silicone oil. This increases the extensional viscosity, which should make it more difficult for droplets to form. The addition of 5% and 10% 423-kDa PDMS to 1000 mPa\(\text{s}\) oil gives the blend a shear viscosity close to 2000 and 5000 mPa\(\text{s}\), respectively. Yet during injection, when shear stress was applied, the molecules line up, thus making the blends quicker to inject. Our research question is therefore very timely. We asked whether the addition of high molecular components could also reduce the shear rate. We have shown, for the first time, the movement of oil bubbles inside a model eye chamber and we have been able to measure the relative angular velocity. Simplistically, it could be said that oils with higher shear viscosity tended to move with the eye chamber and, therefore, tended to exhibit less relative movement or shear stress. This could be one explanation of why oils with higher viscosity have lower propensity to emulsify. The addition of HMWC did reduce the peak velocity, although this might simply be due to the increase in corresponding shear viscosity.

**CONCLUSION: WHICH OIL SHOULD WE CHOOSE?**

We conclude from our study that the shear viscosity was the main factor that determined the maximum shear rate. From the plot between shear viscosity and peak relative velocity, it could be seen that 5000 mPa\(\text{s}\) oil was already on the steep part of the exponential curve (Fig. 6b). This suggests using oils of higher shear viscosity might not be that much more effective at reducing shear rate. There was no significant difference in the peak relative velocity between the 12,500 and 5000 mPa\(\text{s}\) oils, whereas there was a significant difference between the 5000 and 1000 mPa\(\text{s}\) oils. This finding concurred with other in vitro studies. If we were indeed to choose oils with a shear viscosity of around 5000 mPa\(\text{s}\), it might be preferable to choose an oil blend of 10% 423-kDa PDMS in 1000 mPa\(\text{s}\) oil rather than a normal 5000 mPa\(\text{s}\). The case of injecting the former over the latter is sufficient to make it more attractive to some surgeons.

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**References**


