Injectable accommodative lenses, a preclinical study
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Chapter 7

Changes in Spherical Aberration After Lens Refilling With a Silicone Oil.
Abstract

Purpose: Accommodation can possibly be restored to presbyopic human eyes by refilling the lens capsular bag with a soft polymer. The optical changes after refilling of the capsular bag were studied in a pig eye model.

Methods: Ten isolated pig lenses were used. The optical power and spherical aberration were measured with a scanning laser ray-tracing technique. From digitized lens contour photography the optical power and spherical aberration were calculated by mathematical ray-tracing. After refilling with a silicon oil, the measurements were repeated. Both the influence of the change of a gradient into a homogeneous refractive index and the influence of the changes in lens contours on lens power and spherical aberration were determined.

Results: After refilling the lens power was lower (49.9±1.5D vs 36.8±1.5D, p<0.001) and a change in spherical aberration occurred (-3.6D vs 7.9D, p<0.001). Substitution of a gradient by a homogeneous refractive index using the same lens contours resulted in a change of spherical aberration (–3.6±2.0D to 11.0±2.1D, p<0.001). The change in lens contours with equal homogeneous refractive index did not result in a change in spherical aberration (p=0.08).

Conclusions: The lower lens power after refilling is due to the lower refractive index of the refill material. After refilling an increase of spherical aberration occurred, caused by the change of gradient into homogeneous refractive index. Spherical aberration was not influenced when the lens curvatures changed after refilling. The influence of refilling on spherical aberration of human lenses has to be studied.
Introduction

Surgical restoration of accommodation after the onset of presbyopia has received considerable attention. However, to our knowledge there is no procedure yet published which results in a refractive change of the human eye as measured by a refractometer in excess of 1 diopter. Usually, presbyopes need reading glasses with a power of 2 to 3 diopters, so an accommodative amplitude of 1 diopter is insufficient for reading.

According to the classical Helmholtz theory of accommodation, the emmetropic eye is focused for distance when the ciliary muscle is relaxed. In this condition the zonular fibers, which attach to the periphery of the lens, are under a resting tension to maintain the lens in a flattened state. With accommodation the ciliary muscle contracts, causing a reduction of the ciliary body diameter and a release of tension of the zonular fibers. This action allows young lenses to regain their unstretched shape which is characterized by an increase in the anterior and posterior lens curvature. This results in an increase in lens power and objects near to the eye are focused on the retina. All the structures involved in accommodation (lens capsule, lens nucleus and cortex, zonula, ciliary muscle and choroid) show age-related changes that may explain the onset of presbyopia at the approximate age of 45 years. However, many investigators consider hardening of the lens nucleus and cortex to be the most important factor that causes presbyopia. It seems to provide a logical explanation, because the lens changes its shape during accommodation. Pau and Kranz described a simultaneous increase of lens sclerosis and a decrease of accommodative ability. Fisher, by placing lenses on a rapidly rotating table, demonstrated that older lenses are more resistant to deformation than younger lenses. Glasser and Cambell established that older lenses, when exposed to equatorial stretching forces, show less change in focal length than younger lenses. If the lens nucleus and cortex are responsible for presbyopia, replacement of the hardened lens substance by a suitable soft, transparent polymer may restore the accommodative range.

Kessler was the first to describe a surgical method to replace the contents of the capsular bag of the crystalline lens by a soft refill material. He removed the lens cortex and nucleus through a small capsulorrhexis and then injected a flexible
polymer into the bag. He prevented leakage of the polymer from the capsular bag by using a plug. In vitro studies of refilled human eyes and in vivo studies of non-human primate eyes found accommodative changes in the refilled lenses, indicating the potential of this procedure. When the natural lens content is replaced by a silicon polymer, this influences the optical properties of the lens. First, the gradient refractive index which exists in the natural lens is changed to a homogenous refractive index. An optical analysis by Smith showed that the gradient refractive index is responsible for the negative spherical aberration of the crystalline lens. Thus, it can be expected that refilling the capsular bag will result in a more positive spherical aberration. In a study by Koopmans et al refilled ex vivo human lenses predominantly showed positive or zero spherical aberration, but never negative spherical aberration which was seen in natural human lenses. This supports the prediction that the optical properties will change due to refilling. However, in the study by Koopmans et al spherical aberration was not quantified. A second optical factor which changes after lens refilling and which could influence spherical aberration is the curvature of the surfaces of the refilled lens. It is not clear yet how the lens curvature changes after refilling the lens capsule. The lens curvature is influenced by the amount of material that is injected in the capsular bag. In order to make a useful comparison between optical properties of natural lenses and refilled lenses it seems logical to compare natural lenses with refilled lenses which have been filled to a level such that the original lens dimensions are reestablished. In this study we established the amount of spherical aberration before and after lens refilling and determined whether a change of spherical aberration was caused by a change of lens curvature or caused by the change from a gradient refractive index to a homogenous refractive index. Therefore, we measured the optical properties of ten pig lenses before and after lens refilling. Because several measurements and associated manipulation were needed for one lens, the use of lenses from a species with a sturdy lens capsule such as a pig was advantageous. Furthermore, pig eyes were easily available. Lens thickness was a parameter that could be measured and influenced during the surgery so the lenses were refilled to a predetermined thickness similar to the thickness of the natural lens.
Materials and Methods

Ten eyes of 6-month-old pigs were obtained from the local slaughterhouse. The eyes were kept in a saline solution consisting of 8 g/l NaCl, 0.4 g/l KCl, 1 g/l glucose, 2.38 g/l HEPES and 0.1 g/l Na$_2$HPO$_4$ and stored in a refrigerator at 5° Celsius until the experiments started within 24 hours after enucleation.

Measurement of Natural Lens Thickness

When the natural lens is taken from its position inside the eye, it is possible that the lens thickness is altered. Therefore, the natural lens thickness was measured in 4 conditions:

1. The eye was positioned in a cup with the cornea facing upwards. Extraocular muscles and conjunctiva were removed with scissors. During the experiments the tissues were regularly wetted with saline. To measure the thickness of the lens a 10-MHz ultrasound A-scan probe (A-5500, Sonomed, Lake Success, NY) was used. The probe was manually held perpendicular to the cornea, until maximum echographic signal peaks of the anterior and posterior surface of the lens were obtained. Three measurements were taken and the mean thickness was used.

2. Using a surgical microscope, a paracentesis was made in the cornea and an anterior chamber maintainer (Becton Dickinson, Oxford, UK) connected to an infusion bottle was inserted in the eye. A physiological intraocular pressure of 8 mmHg for a living pig was simulated by hanging the bottle of the saline infusion at 11 cm above the eye$^{12}$. In this situation, the thickness of the lens was measured again with the A-scan.

3. Following this, the cornea and the iris were removed. Then the ciliary body was separated from the anterior sclera by blunt dissection. The anterior sclera was cut away to expose the ciliary body and the anterior choroid. Again, the thickness of the lens was measured with A-scan.

4. Next, the lens-zonula-ciliary body apparatus was mounted in a plastic ring. This plastic ring with an inner diameter of 33 mm was placed around the exposed choroid. The plastic ring, which was described before$^6$, served to mount the lens. Four sutures (8-0 virgin silk) were knotted to the ciliary body at the 12, 3, 6 and 9 o’ clock position and threaded through 4 corresponding holes in the ring. The sutures were then
immobilized by small plugs into the holes of the ring. The tension on the sutures was individually adjusted to make sure that the ciliary body remained unstretched, but the sutures were not loose either. After applying the sutures, a circumferential cut was made through the choroid in the region of the ora serrata to separate the anterior segment tissue from the posterior segment of the eye. The anterior segment tissue comprised the ciliary body and the ciliary muscle, the lens and the zonular complex. The plastic ring with the anterior segment was lifted carefully and remaining vitreous adhesions to the posterior segment were cut. The posterior segment was left in its place in the cup as a support. After the vitreous cuts, the anterior segment was placed back on the posterior segment in the cup and submerged in saline. Finally, the lens thickness was measured again with A-scan ultrasonography.

A sonic speed of 1704 m/s was used for the pig lenses. This value was determined from the mean thickness of the lenses calculated from lens contour photography and the mean thickness of the lenses as measured by A-scan ultrasonography at room temperature.

**Measurement of Focal Length**

A scanning laser instrument was used to measure the focal length of the lens (figure 1a). The ring containing the tissue was mounted vertically in a holder which was placed in a rectangular glass tank measuring 24 x 10 x 10 cm and filled with saline, with the anterior surface of the lens facing the laser beam. In this way, we assumed that the optical axis of the lens was horizontal and parallel to the incident laser beams. The position of the optical axis was defined by the laser beam that passed through the lens undeviated. The saline solution was lightly clouded with coffee creamer to visualize the laser beam passing through the solution. The lens was vertically scanned with a 5-mW HeNe laser beam (633 nm; model 1125; JDS Uniphase, Manteca, CA) with a diameter of 0.81 mm, by shifting the vertical position of a mirror on a X-Y stage (model UTM25PP1HL; Newport, Irvine, CA), driven by a computer controlled stepper motor (model MM3300; Newport). This stepper motor allowed the laser beam to be moved and positioned with an accuracy of approximately 12 µm. The horizontal and vertical displacement of the glass tank could be adjusted manually to make the laser coincide with the optical axis of the lens by estimation. A video camera (model XC77; Sony, Tokyo, Japan) viewed the
glass chamber from the side. The laser beam was clearly visible in the lightly clouded saline solution. The laser beam position was recorded by the camera and displayed on a computer screen.

The incident and exiting pathways of the laser beam passing through the lens were digitized with image-processing software (Optimas, ver. 6.5; Media Cybernetics, Silver Spring, MD). This program calculated the positions of the incident and exiting pathways of the laser beam and the slopes of the beams. Whenever the slopes and the vertical displacements of the incident and exiting beams were similar, the laser beam was deemed to coincide with the optical axis of the lens. During vertical lens scanning, the camera recorded the incident and exiting laser beams in the vertical meridional plane. The recorded beam paths were reconstructed to calculate the lens power. Each vertical lens scan covered a distance of 6 mm in 51 discrete steps, from 3 mm above the optical axis and 3 mm below the optical axis. For each lens, 2 scans of the natural lens and 2 scans of the refilled lens were performed. This procedure is called “scanning laser ray-tracing” (SLRT).

**Figure 1a.** Layout of the scanning laser setup to measure the focal length and spherical aberration of the lens.
Figure 1b. Layout of the contour photography setup to assess anterior and posterior radii of the lens.

**Measurement of Anterior and Posterior Radius**

The anterior and posterior radii of the lens were assessed by digital lens contour photography. A rectangular glass tank with a volume of 10 x 5 x 5 cm was filled with the saline solution. The glass tank was placed on a revolving stand equipped with a circular scale in 1 degree steps. A monochrome video camera (CV-M50, JAI, Yokohama, Japan) equipped with a macro lens (Cosmicar 75 mm, Pentax, Hamburg, Germany) was installed 30 cm in front of the glass tank. The video images were fed to a personal computer. The pixel to millimeter conversion was calculated from a picture of a steel calibration ball of 0.5 inch diameter, placed in the glass tank at the position where the pig lens was photographed. Two adjacent inferior sutures were loosened from the plastic ring while the top of the lens remained attached to the other two sutures, still attached to the plastic ring. The ring was placed flat on top of the
glass tank, so that the lens was hanging freely and vertical in the saline on the two sutures (figure 1b). In this way, the optical axis was directed horizontally. The optical axis was positioned perpendicular to the axis of the camera as judged by observation. A picture was taken and the area within the lens contour was determined with image processing software (Optimas, Media Cybernetics, Silver Spring, MD). The lens was rotated in small steps until the area within the lens contour as seen by the camera reached a minimum. We assumed that in this position the optical axis of the lens was perpendicular to the camera axis. Then four pictures of the lens were taken. Between every picture the glass tank with the lens was rotated 180 degrees so each side of the lens was photographed twice. The digital image files were processed with custom written image processing software (using Matlab v6.0, Natich, Ma). After detection of the lens contour, a circle was fitted to the anterior and posterior lens surface to determine the radius of curvature.

**Lens Refilling: The Surgical Procedure**

After SLRT and lens contour photography, the two detached sutures were reattached to the plastic ring, again without excess tension or slack. The plastic ring was repositioned on the cup on the remnants of the bulbus which functioned as a support to the lens in the ring. Under the surgical microscope the anterior capsule was punctured with a 27-gauge needle. With appropriate forceps a minicircular capsulorrhexis of 1 to 1.5 mm was created in the periphery of the lens. The lens substance was aspirated manually with an 18-gauge cannula connected to a 10 mL syringe by an extension tube. A 2.7 mm diameter silicone plug was inserted into the capsular bag to prevent leakage. A silicone oil (AMO, Groningen, The Netherlands) was injected into the capsular bag with a 5 mL syringe with a 25-gauge cannula. Before injection the oil was briefly exposed to vacuum to remove any air bubbles. The lens capsule was refilled to the thickness of the natural lens in the plastic ring, within a range of ± 0.1 mm, which is the accuracy of A-scan ultrasonography. To do this, the capsular bag was refilled to the desired thickness by estimation. Then the lens thickness was measured. At this time, A-scan sonic velocity was set at 1066 m/s. We had established this sonic speed in the silicone oil by measuring a 10 mm cylinder of material by A-scan at room temperature. When the lens was too thin, the cannula was reintroduced and more material was added. When the lens was too
thick, oil was removed by gently depressing the silicone plug, so oil could escape. Excess oil was removed from the surface of the lens by flushing with saline. During refilling and removing oil from the surface of the lens, care was taken not to inject air bubbles or saline into the capsule.

After the refill procedure, SLRT and lens contour photography of the refilled lens was repeated as described for the natural pig lens.

Silicone oil

A silicone oil with a refractive index of 1.42 and a viscosity of 1750 cP was used to refill the lens capsule (AMO, Groningen, the Netherlands). Usually, polymerizing materials are used for refilling of the lens capsule\textsuperscript{5,6,8,10}. We used a non-polymerizing silicone oil in order to be able to repeat our measurements at various degrees of lens refill without introducing a bias due to an ongoing polymerization process.
Analysis of the Data

Refractive power of the lens

In order to determine the refractive power of the natural and refilled lenses, the focal length of the lens was calculated by computer software (Matlab ver. 6.0; Natich, MA) from the SLRT data. The intersection points of the incident and exiting beams were calculated for each of the 51 beam pairs. Intersection points with coordinates in excess of 3 SD from the average intersection point were eliminated from the data set. A straight vertical line was fitted through the remaining points and was assumed to represent the principal plane of the lens. The optical axis of the lens was defined as the beam passing through the lens with the smallest slope difference between incident and exiting beam. The focal point of the lens was located by a fitting procedure. We calculated the angles between the exiting beams and the radii of a circle (centered on the optical axis) at the intersections of the light rays with the perimeter of the circle. In conjunction with the fitting procedure, the center of the circle was shifted along the optical axis until the squared sum of these angles reached its minimum. The position of the center of the circle then represented the focal point of the lens. The distance between the principal plane and the center of the circle, by definition, was the focal length. From this, the refractive power of the lens was calculated.
Figure 2. Reconstruction of a scan of a natural pig lens. Vertical line at the origin of the horizontal axis: primary plane of the lens; circles: horizontal position where each exiting beam intersects with the optical axis; and the vertical position, where the incident beam meets the lens. A fourth-order polynomial was fitted to these points in order to determine the spherical aberration.

Spherical Aberration

Spherical aberration was determined by fitting fourth-order polynomials to the intersections of the exiting beams with the optical axis as a function of scan diameter (figure 2). The difference between the average lens power at 3 mm above and below the optical axis and at the center of the lens gives the extent of the spherical aberration of the lens in diopters. The lens power at the center of the lens was obtained from the solution of the polynomial at zero (i.e., at the optical axis).
Mathematical Ray-tracing

To determine the influence of the contour changes of the lens and the change from a gradient refractive index to a homogenous refractive index on refractive power and spherical aberration, we used mathematical ray-trace software (Matlab ver. 6.0; Natich, MA). The program fitted a 10th order polynomial to the lens contour data from the lens contour pictures and calculated the refraction of 51 parallel light rays evenly distributed over a 6 mm aperture through the contour. From these data the focal length and spherical aberration were calculated similar to the SLRT method. This method was called “mathematical ray-tracing” (MRT).

To make a comparison between the data obtained by MRT and SLRT in natural pig eyes, the equivalent refractive index of the natural pig lens was needed. The equivalent refractive index was established as the refractive index at which the mean refractive power in MRT in natural lenses equaled that of the mean refractive power obtained with the SLRT method. This equivalent refractive index of 1.4686 was used for subsequent calculations.

Statistical analysis

To make comparisons between the conditions the two-sided Student’s T-test was used.
Results

All lenses were refilled successfully to the thickness of the natural lenses as measured in condition 4 within a deviation of plus or minus 0.1 mm, as measured by A-scan ultrasonography (table 1). The silicon oil did not leak from the capsule after refilling and during the measurements.

<table>
<thead>
<tr>
<th>Lens nr</th>
<th>Natural lens (mm)</th>
<th>Refilled lens (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>2</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>3</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>7.0</td>
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<tr>
<td>5</td>
<td>7.4</td>
<td>7.3</td>
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<tr>
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<td>7.2</td>
<td>7.2</td>
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<tr>
<td>9</td>
<td>7.4</td>
<td>7.2</td>
</tr>
<tr>
<td>10</td>
<td>7.4</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 1. Thickness of the natural lens in condition 4 and of the refilled lens.

<table>
<thead>
<tr>
<th>Natural pig lens</th>
<th>SLRT*</th>
<th>MRT†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refilled pig lens</td>
<td>B</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 2. Identification of the data sets.
* SLRT = Scanning Laser Ray-Tracing
† MRT = Mathematical Ray-Tracing

The data sets were named as indicated in table 2 to facilitate identification of the groups.
Four comparisons were made from this table and are displayed in the following figures:

A compared to B (figure 3). This comparison shows the differences in refractive power and spherical aberration in the natural and refilled lenses, as measured with SLRT. The natural lenses have a mean refractive power of 49.9±1.5D and a negative spherical aberration of −3.6±2.0D. The refilled lenses have a lower mean refractive power of 36.8±1.5D and a positive spherical aberration of 7.9±2.3D. The differences in power and spherical aberration are significant \((p<0.001)\). Figure 3. Data set A compared to B. Difference in refractive power and spherical aberration in natural and refilled lenses, as measured with Scanning Laser Ray-Tracing. The mean refractive power of natural lenses is higher than in refilled lenses. The sign of the mean spherical aberration changes from negative in natural lenses towards positive after refilling.

B compared to D (figure 4). This comparison shows that there are no differences in refractive power and spherical aberration as assessed with SLRT and MRT. The refractive index in MRT is set to 1.42. The power and spherical aberration between the two groups do not show significant differences \((p=0.89\) and \(p=0.42\) respectively), as expected.
Figure 4. Data set B compared to D. Comparison between Scanning Laser Ray-Trace and Mathematical Ray-Trace through the photographed lens contour in the refilled lenses. With the refractive index set to 1.42 in the Mathematical Ray-Trace, which is the refractive index of the silicone oil, differences in refractive power and spherical aberration are not significant.

A compared to C (figure 5). This comparison shows the influence on the spherical aberration when a gradient refractive index is substituted by a homogeneous refractive index. The equivalent refractive index of the natural pig lens (1.4686) which was used in MRT was calculated by equalizing the refractive power (49.9D) in MRT to the refractive power in SLRT. The calculated spherical aberration determined with the use of homogeneous refractive index with the natural lens contours is +11.0±2.1D. The spherical aberration in the natural lens with a gradient refractive index is -3.6±2.0D. The difference is significant (p<0.001).
C compared to D (figure 6). To show the influence of the contour changes after refilling the lens on the refractive power and spherical aberration the same equivalent refractive index of 1.4686 is used in the calculations in both lenses. The mean refractive power of the refilled lenses is 5.2D higher than the mean refractive power of the natural lenses (p<0.001). The mean spherical aberration of the refilled lenses is not significantly different from the spherical aberration of the natural lens contour (p=0.08).

**Figure 5.** Data set A compared to C. A Scanning Laser Ray-Trace through the natural pig lens is compared with a Mathematical Ray-Trace through the photographed lens contours of the natural pig lens. This shows the influence on spherical aberration when the gradient refractive index in natural lenses is substituted by a homogeneous refractive index. A calculated equivalent refractive index of 1.4686 was used in the Mathematical Ray-Trace. The calculated spherical aberration of the lens with a homogeneous refractive index was significantly more positive than the spherical aberration in the natural eye with a gradient refractive index.
Figure 6. Data set C compared to D. A Mathematical Ray-Trace through the photographed lens contours before and after refilling was performed. The same equivalent refractive index was used in both lenses to show the influence of the contour changes of the lens on the refractive power and spherical aberration after refilling. The mean refractive power increases after refilling. The mean spherical aberration doesn't change significantly.

Figure 7 shows the radii of the anterior and posterior surface of the lens before and after refilling. Before refilling the mean anterior radius was 7.08±0.35mm and the mean posterior radius was 5.08±0.14mm. After refilling the mean anterior radius was 6.30±0.15mm and the mean posterior radius was 4.77±0.16mm. The differences in the anterior and posterior radii after refilling are both statistically significant (p<0.001). After lens refilling the radius of the anterior and posterior surface are smaller.
Figure 7. Radii, as determined from lens contour photographs before and after refilling the lens capsule. After refilling, the radii of the anterior and posterior surfaces of the lens are smaller.

Figure 8 shows the thickness of the lenses during the different stages through the experiment. The mean thickness of the lenses in the untouched eye is 7.4±0.1mm. When the eye is pressurized, the mean thickness of the lenses is 7.0±0.1mm. After removing the cornea and the scleral ring, the mean thickness of the lenses is 7.3±0.1mm. Attached in the plastic ring, the mean thickness of the lenses is 7.4±0.1mm.
Figure 8. Natural lens thickness in the consecutive stages of preparation of the pig eyes during the experiment.
Discussion

These experiments show that refilling of the pig lens capsule with this silicone oil results in significant changes in the optical properties of the lens. First, the lens power (figure 3) and the lens radii of the refilled lens (figure 7) are lower than those of the natural lens. One would expect a higher lens power when the sphericity of the lens increases. This contradictory relationship can be explained by the lower refractive index of the refill material than the equivalent refractive index of the pig lens. The material used in these experiments was made with the intention to refill human lenses, which have a lower equivalent refractive index than pigs.

Secondly, there is a change of the sign of the spherical aberration of the lens from negative (-3.6D) into positive (7.9D) as shown in figure 3. This change can be explained by the fact that the gradient refractive index in the natural lens is replaced with a homogenous refractive index in the refilled lens. Figure 5 shows that even if the lens contours are identical a change from a gradient refractive index to a homogeneous refractive index results in a significant increase in spherical aberration.

The sphericity of the lens contours increases after refilling (figure 7). This could also be responsible for the increase in spherical aberration. In figure 6 a comparison was made between conditions of lenses before and after refilling while the same homogenous refractive index was used. The change in lens contour after refilling did not influence the spherical aberration significantly (figure 6).

We should remember that the lenses, in conjunction with these measurements, were removed from the eye. It is quite plausible that this had some influence on our data, especially if we consider that the mean natural lens thickness increases by 0.4mm when removed from the intact pressurized eye and mounted in a plastic ring without stretch (figure 8). We estimated that an increase in lens thickness by 0.4 mm results in a decrease in anterior lens curvature of 11.1 to 7.0 mm (appendix). During accommodation, the posterior capsule surface curvature changes minimally\textsuperscript{24}. This means that our conclusions are based on experiments with pig lenses with experimentally-induced decreased lens curvatures. Under these experimental conditions we found that the change of gradient refractive index to homogeneous refractive index had the largest effect on spherical aberration. The additional changes in lens curvature due to refilling (while the refractive index of the lens does not change) only result in a change of spherical aberration of 0.78 D.
Another consideration is that our conclusions are based on a comparison of a direct measurement of the lens power and spherical aberration (SLRT) with a calculation of the lens power and spherical aberration determined by a mathematical ray-trace (MRT) through the fitted surfaces derived from lens contour photography. The latter method could be sensible to errors resulting from an improper fit. However, in figure 4 a comparison of lens power and spherical aberration was made of refilled pig lenses as measured by both methods (SLRT and MRT). In SLRT the mean power was 36.8D and the mean spherical aberration was 7.9D. In MRT the mean power was 36.7D and the mean spherical aberration was 8.6D. There was no significant difference between both groups. This shows, that the mathematical ray-trace method does not induce significant systematic errors.

In human eyes, spherical aberration and the possibility of correcting it has received considerable attention\textsuperscript{14-18}. It is the largest type of aberration beside sphere and cylinder. Spherical aberration increases the depth of focus, but decreases the modulation transfer at high spatial frequencies at optimum focus\textsuperscript{19}. Correcting spherical aberration in pseudophakic patients by implanting an intraocular lens with an aspheric design results in an increase in contrast sensitivity at optimum focus\textsuperscript{20-22}. These influences of spherical aberration on the optical performance of human eyes make it relevant to predict the effect of lens refilling on this parameter. Since spherical aberration is important for the visual performance of human eyes it is important to be able to predict the effect of lens refilling on this parameter. Based on our experiments and previous studies\textsuperscript{6,7} we may conclude that there will be an increase towards a positive value of spherical aberration but it is not clear whether lens refilling in human eyes will result in such large changes in spherical aberration as in pig eyes. Pig lenses differ considerably from human lenses. Pig lenses are more spherical and thicker than human lenses. It could be that the contribution of the gradient refractive index and the surface curvatures to the total amount of spherical aberration differs between the two species.

Some aspects of human lens refilling can be simulated in model eyes. Norrby\textsuperscript{23} constructed an eye model based on corrected Scheimpflug images of the eye in which the lens was modeled as an optical component with a homogeneous refractive index with two aspheric surfaces. In this model no spherical aberration was found in the unaccommodated situation for a 35 year old eye. This suggests that, contrary to our results in pig lenses, a homogeneous refractive index in a human lens...
does not lead to an unnatural positive spherical aberration. However, no modeling was done comparing the homogeneous refractive index with that of a gradient refractive index in this model. Also, the accuracy of estimation of the asphericity of the lens surfaces from the Scheimpflug images was poor (as stated by Norrby), while the level of aberration is very sensitive to asphericity. Therefore, uncertainty exists as to how accurate the eye model used by Norrby is in predicting the amount of spherical aberration.

In conclusion, we found that refilling of pig lenses with the silicone oil used in these experiments results in an increase of spherical aberration. The change of gradient refractive index to homogeneous refractive index plays an important role. The change in lens curvatures after refilling did not result in an increase of spherical aberration. The influence of lens refilling on spherical aberration of human lenses has to be determined by similar experiments with human eyes.
Appendix

To estimate the effect of a change in lens thickness on the anterior lens radius, the pig lens was represented as an intersection of two spheres. The volume of such an intersection is given by:

\[
\frac{\pi (R+r-d)^2 \left(d^2 + 2dr - 3r^2 + 2dR + 6rR - 3R^2\right)}{12d} \quad (a)
\]

where:

- \( R \) = radius of first sphere.
- \( r \) = radius of second sphere.
- \( d \) = the distance between the centre of the two spheres which is calculated by \( R + r \)-lens thickness.

After changing the lens thickness from 7.0 mm to 7.4 mm the goal seek function in Microsoft Excel was used to find the anterior radius which would result in a lens with the same volume. We assumed that the posterior radius didn’t change with a change in lens thickness.

This estimation showed that a change in lens thickness from 7.0 to 7.4 mm results in a change of the anterior radius from 11.1 to 7.0 mm.

\( a \) from: [http://mathworld.wolfram.com/Sphere-SphereIntersection.html](http://mathworld.wolfram.com/Sphere-SphereIntersection.html)
References


