Calculation of Ophthalmic Viscoelastic Device–Induced Focus Shift During Femtosecond Laser–Assisted Cataract Surgery

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PURPOSE. To assess if a change in refractive index of the anterior chamber during femtosecond laser-assisted cataract surgery can affect the laser beam focus position.

METHODS. The index of refraction and chromatic dispersion of six ophthalmic viscoelastic devices (OVDs) was measured with an Abbe refractometer. Using the Gullstrand eye model, the index values were used to predict the error in the depth of a femtosecond laser cut when the anterior chamber is filled with OVD. Two sources of error produced by the change in refractive index were evaluated: the error in anterior capsule position measured with optical coherence tomography biometry and the shift in femtosecond laser beam focus depth.

RESULTS. The refractive indices of the OVDs measured ranged from 1.335 to 1.341 in the visible light (at 587 nm). The error in depth measurement of the refilled anterior chamber ranged from -5 to $+7$ μm . The OVD produced a shift of the femtosecond laser focus ranging from -1 to $+6$ μm . Replacement of the aqueous humor with OVDs with the densest compound produced a predicted error in cut depth of 13 μm anterior to the expected cut.

CONCLUSIONS. Our calculations show that the change in refractive index due to anterior chamber refilling does not sufficiently shift the laser beam focus position to cause the incomplete capsulotomies reported during femtosecond laser–assisted cataract surgery.

Keywords: femtosecond laser, ophthalmic viscoelastic device, capsulotomy, optical coherence tomography, cataract surgery

Femtosecond laser–assisted cataract surgery is a recent technology that enables surgeons to perform three surgical steps with a femtosecond laser (FS-laser): corneal incisions, capsulotomy, and lens fragmentation.^{1–4} The capsulotomy is achieved by using the laser to perform a cylindrical cut several hundred micrometers in depth through the capsule (Fig. 1). The diameter, thickness, and depth of the cut can be adjusted by the surgeon and can vary between devices. Femtosecond laser–assisted capsulotomy has been previously described as more precise and more reproducible than manual capsulotomy in uncomplicated cases.^{5–7}

However, performing cataract surgery in patients with small pupils caused by pseudoexfoliation, diabetes, α -blocker medication, floppy iris syndrome, and trauma remains challenging.⁸ As in traditional cataract extraction, FS-laser–assisted cataract surgery performed in patients with such conditions can require mechanical dilation using a ring or retractors in order to maintain good dilation throughout the surgery.^{8,9} The mechanical dilation is usually performed under a surgical microscope, prior to the laser procedure. One corneal self-sealing micro-

incision is performed and the anterior chamber is filled with ophthalmic viscoelastic devices (OVDs) in order to maintain its volume and ease the ring insertion. Then the patient is transferred under the FS-laser for performance of the cataract surgery.^{10–12}

It has been suggested that a change in the anterior chamber's refractive index when it is refilled with an OVD could change the geometric properties of the beam and cause the cutting depth range to shift, possibly missing the capsule completely, resulting in incomplete capsulotomies (Fig. 2).¹³ In at least two studies on small-pupil cataract surgery requiring mechanical dilation, authors have recommended modifying the laser settings (increasing the pulse energy or adjusting the depth of the cut) when the anterior chamber is filled with OVDs to account for the difference in refractive index between OVD and aqueous humor.^{12,13}

There are two effects that contribute to the error in capsulotomy depth when OVDs are used:

- The error in measured anterior chamber depth by the onboard optical coherence tomography (OCT): The OCT

FIGURE 1. Default femtosecond laser capsulotomy. The femtosecond laser performs a cylindrical cut (A) through the anterior chamber, anterior capsule (B), and part of the crystalline lens. The figure illustrates the typical depth range of this type of cut. On the *left*, a two-dimensional sagittal view is shown, and on the *right*, that view is rotated to show a three-dimensional representation of the cylindrical cut.

measures optical path length, not physical depth of the anterior chamber. In order to report the physical chamber depth, the machine scales the optical path length by the group refractive index of aqueous humor. When the refractive index of the anterior chamber is modified, the refractive index used for scaling must also be modified accordingly to avoid an error in measurement of the anterior chamber depth; and

- The error in FS-laser beam position: This error is caused by a change in optical refraction of the beam at the interface between the posterior corneal surface and the anterior chamber due to a change in refractive index of the anterior chamber. The change in refractive index is expected to produce a shift of the cut depth position along the axial direction.

In this study, we present measurements of the phase refractive indices of several OVDs and calculations of their corresponding group refractive indices at the wavelengths used in OCT and FS-laser applications. These measurements are used in a model that predicts the effect of a change of refractive index on beam focus position and cut diameter during FS-laser cataract surgery.

METHODS

Refractive Index Measurement

For this analysis, it is necessary to use the group refractive index to account for chromatic dispersion that occurs with broadband light sources such as the ones used for OCT and FS-laser surgery.^{14–16} In the near infrared for the ocular tissues of interest, the group refractive index is always slightly larger than the phase refractive index: For instance, for aqueous humor, the group refractive index at 814 nm is 1.345 as compared to the phase refractive index, which is 1.331.¹⁴ The group refractive indices of OVDs were calculated from measurements of their phase refractive index and dispersion.

The phase refractive indices of six OVDs were measured four times using a refractometer (Abbe-3L Refractometer; RL Instruments, Northbridge, MA, USA) at 37°C with visible light (589.3 nm): VisCoat and ProVisc (Alcon, Fort Worth, TX, USA), Healon 10 (Abbott Medical Optics, Santa Ana, CA, USA), and EyeFill types HD, SC, and C (Croma-Pharma GmbH, Leobendorf, Austria). The chromatic dispersion of each OVD was also recorded by using tables provided by RL Instruments. The dispersion value is used in the method described by Atchison and Smith¹⁷ to calculate group refractive indices of the OVDs

FIGURE 2. Illustration of potential error in femtosecond laser capsulotomy caused by a change in refractive index of the anterior chamber in an extreme case. The cylindrical cut performed by the femtosecond laser (A) is shown shifted into the anterior chamber, and the anterior capsule (B) is not reached by the laser beam. On the *left*, a two-dimensional sagittal view is shown, and on the *right*, that view is rotated to show a three-dimensional representation of the cylindrical cut.

and aqueous humor at wavelengths corresponding to the wavelengths of OCT (830 nm) and FS-laser (1040 nm) used during FS-laser-assisted cataract surgery.^{14–17} These indices were applied to an optical model to predict a combined error in cutting depth of a capsulotomy when the refractive index of the anterior chamber is altered.

Optical Model of the Anterior Chamber Depth Measurement Error

The FS-laser device uses OCT images of the anterior segment to determine the location of the anterior lens capsule. From these images, the optical path length of the anterior chamber is measured and then converted to a measured physical anterior chamber depth by dividing by the group refractive index of the aqueous humor at 830 nm (1.342).¹⁸ The software on the device is not programmed to compensate for a change in refractive index of the media. Therefore, when the anterior chamber is refilled with a medium having a different group refractive index (n_{OVD}) than that of aqueous, the anterior chamber depth (ACD) reported by the OCT does not reflect the real physical anterior chamber depth. The error between real and reported anterior chamber depth is (ΔACD , in mm):

$$\Delta ACD = \left(\frac{n_{OVD}}{1.342} - 1 \right) \times 3.1. \quad (1)$$

A derivation for the equation can be found in the Supplementary Material. This equation was used to determine the error in ACD measured by the OCT for the six OVDs assessed. This equation was also plotted against a range of group refractive indices near that of aqueous humor to assess the sensitivity of the ACD measurement to group refractive index change.

Optical Model of the Femtosecond Laser Beam Focus Shift and Lateral Magnification Error

Calculations were applied to an optical model of the anterior segment based on the Gullstrand eye model¹⁸ in order to simulate ocular conditions during FS-laser-assisted cataract surgery and predict the focus shift caused by the group refractive index change. The optical model uses the following assumptions:

- High-order aberrations are neglected;
- The contents of the anterior chamber are completely replaced by the OVD; and
- The dimensions of the cornea and anterior chamber do not change during the procedure.

The focus shift (ΔFS , in mm) and lateral magnification error (D_{OVD}/D_{AQ}) can be expressed as a function of the group refractive index of the OVD (n_{OVD}) and of the aqueous humor at 1040 nm (1.336), the anterior chamber depth (3.1 mm), and the posterior radius of curvature (6.8 mm)¹⁸:

$$\Delta FS = \frac{n_{OVD}}{\left(\frac{n_{OVD}-1.336}{6.8} \right) + \frac{1.336}{3.1}} - 3.1 \quad (2)$$

$$\frac{D_{OVD}}{D_{AQ}} = \frac{1.336}{\left(\frac{n_{OVD}-1.336}{6.8} \right) + \frac{1.336}{3.1}}, \quad (3)$$

where D_{OVD} and D_{AQ} are the cut diameters with the anterior chamber filled with OVD and aqueous, respectively.

A derivation of both equations can be found in the Supplementary Material. These equations were used to calculate the FS-laser focus shift and magnification error for

TABLE 1. Average Measured Phase Refractive Indices of Four Measurements in the Visible (589 nm) and Calculated Group Refractive Indices of Each OVD at the Relevant Wavelengths (λ) for Both OCT (830 nm) and FS-Laser Light (1040 nm)

OVD	n_p , $\lambda = 589 \text{ nm}$	n_g , $\lambda = 830 \text{ nm}$	n_g , $\lambda = 1040 \text{ nm}$
EyeFill C	1.335	1.339	1.335
EyeFill SC	1.336	1.340	1.335
EyeFill HD	1.336	1.340	1.336
Healon 10	1.335	1.339	1.335
ProVisc	1.335	1.339	1.335
VisCoat	1.342	1.346	1.341
Aqueous humor	1.335	1.342	1.336

For comparison, the phase refractive index (n_p) of aqueous humor at 589 nm and the group refractive indices (n_g) calculated using methods described by Uhlhorn et al.¹⁶ are also provided.

each refractive index measured. Additionally, Equation 2 was plotted for a range of group refractive index values close to that of aqueous humor to assess the effect of refractive index on the change in FS-laser cutting depth. A sensitivity analysis was performed to assess the effect of a change in posterior radius of curvature on the FS-laser beam focus shift.

RESULTS

Refractive Index Measurement

The measured phase refractive indices were consistent with the index of aqueous humor (1.336) except for VisCoat, which has a phase refractive index of 1.342 (see Table 1). The phase refractive index values were measured four times to the third significant digit, and the standard deviations were always zero in the third significant figure and are not reported. The phase refractive index value for the OVDs for visible light ranges from 1.335 to 1.342. The group refractive index value for the OVDs ranges from 1.339 to 1.345 at 830 nm and from 1.335 to 1.341 at 1040 nm.

Anterior Chamber Depth Measurement Error (OCT)

The error in OCT measurement ranges from $-7 \mu\text{m}$ to $+7 \mu\text{m}$. For those OVDs with a refractive index consistent with that of aqueous humor, the error ranged from $-7 \mu\text{m}$ to $-5 \mu\text{m}$ while the error attributed to VisCoat was $+7 \mu\text{m}$. The relationship between these refractive indices and error in OCT measurement is linear (Fig. 3), with a slope of $24 \mu\text{m}$ per 0.01 change in group refractive index.

Femtosecond Laser Beam Focus Shift and Magnification Error

The shift in FS-laser beam focus position ranges from $-1 \mu\text{m}$ to $+6 \mu\text{m}$. We find that the shift in FS-laser beam position with the OVDs of refractive index most similar to that of aqueous humor ranges from -1 to $0 \mu\text{m}$, while the shift due to VisCoat is $+6 \mu\text{m}$. The relationship between the refractive indices and error in FS-laser beam position is approximately linear for values of refractive index close to that of aqueous (Fig. 4), with a slope of $12 \mu\text{m}$ per 0.01 change in refractive index. We also find that the error is relatively insensitive to a change in posterior curvature of the cornea (Fig. 5).

The lateral magnification error due to anterior chamber refilling contributes to a 0.014-mm decrease in capsulotomy

FIGURE 3. Relationship between anterior chamber depth measurement by optical coherence tomography (OCT) and group refractive index of the anterior chamber. The graph shows the change in measured depth of the anterior chamber by OCT when completely refilled with ophthalmic viscoelastic device (OVD) as a function of the group refractive index of that OVD. Ophthalmic viscoelastic devices measured are marked along the line with an X. Aqueous humor is marked as a circle.

diameter when the anterior chamber is refilled with VisCoat or a 0.003-mm increase in diameter for the other OVDs.

Combined Error

The two errors combine additively to produce a larger theoretical capsulotomy cutting depth error that ranges from $-8\ \mu\text{m}$ to $-5\ \mu\text{m}$ for the five OVDs, with refractive indices close to that of aqueous humor and up to $+13\ \mu\text{m}$ for VisCoat (Table 2).

DISCUSSION

The phase refractive indices of six OVDs were measured with an Abbe refractometer. Only one OVD, VisCoat (1.342), was found to be different from aqueous humor (1.336). The disparity in the phase refractive index might be due to the higher density of VisCoat: The active ingredients are present in concentrations of 4% sodium chondroitin and 3% sodium hyaluronate compared to only 1% to 2% sodium hyaluronate in the other OVDs measured.¹⁹

The group refractive index can also be measured more directly using techniques based on OCT.^{16,20} However, the measurement precision afforded by OCT is not sufficient to distinguish the subtle difference between the group refractive indices of each OVD and of aqueous media. The Abbe refractometer was chosen because it provides the required precision.

An on-axis paraxial model was employed to explore how a change in group refractive index of the anterior chamber refilled with an OVD affects the FS-laser beam focus position. We are primarily concerned with whether or not the change in refractive index alone is sufficient to cause a focus shift large enough to result in an incomplete capsulotomy.^{12,13} We find that the change in group refractive index of the anterior chamber has a relatively negligible effect on the cutting depth considering that (1) the thickness of the anterior capsule has

FIGURE 4. Relationship between femtosecond laser beam focus position and group refractive index of the anterior chamber. The graph shows the change in femtosecond laser beam focus position when completely refilled with ophthalmic viscoelastic device (OVD) as a function of the group refractive index of the anterior chamber. Ophthalmic viscoelastic devices measured are marked along the line with an X. Aqueous humor is marked as a circle.

been reported to range from 8 to 20 μm and (2) the safety margins on the lasers are at least one order of magnitude larger than the predicted error.^{21–23} For example, the Catalys (FS-laser from AMO, Santa Ana, CA, USA) has a default capsulotomy depth range of 600 μm that can be adjusted from 200 to 1000 μm .²⁴ The LensX (FS-laser from Alcon) also requires a minimum capsulotomy depth of 200 μm .²⁵ For the Victus device, the capsulotomy thickness is preset to 800 μm , but can be adjusted from 400 to 1500 μm .²⁶ The LensAR device is

FIGURE 5. Relationship between femtosecond laser beam focus position and posterior corneal radius of curvature. The graph shows that the change in femtosecond laser beam focus position is insensitive to a change in posterior corneal radius.

TABLE 2. Predicted Errors Produced by a Change in Group Refractive Index in Both the OCT Measurement and FS-Focus Position After Refilling the Anterior Chamber With Each OVD

OVD	OCT Error, μm	FS-Laser Focus Error, μm	Cutting Depth Error, μm
EyeFill C	−7	−1	−8
EyeFill SC	−7	−1	−8
EyeFill HD	−5	0	−5
Healon 10	−7	−1	−8
ProVisc	−7	−1	−8
VisCoat	7	6	13

preset to 400 μm but can be increased up to 1500 μm .²⁷ The largest shift in cutting depth calculated was 13 μm (Table 2, VisCoat), which is not sufficient to miss the anterior capsule during capsulotomy. To cause the cut to shift outside the safety margins, a focus shift of at least 100 μm is required, which would require an OVD with a group refractive index of 1.417 at 1040 nm according to our optical model. Even refilling the anterior chamber with pure silicone oil (group refractive index ~ 1.403) would not cause this large an error.²⁸ Additionally, we assessed how a change in group refractive index of the anterior chamber affects the diameter of the capsulotomy and found the effect to be negligible over the range of group refractive indices used. At most, the diameter decreases from 8 to 7.986 mm, a change that is smaller than the precision of these devices (0.1 mm).

The optical model considers an on-axis paraxial approximation of the anterior segment and assumes that the cornea retains a curvature consistent with natural conditions. In the presence of applanation, corneal dimensions may change. Some commercially available FS-laser platforms require the use of a proprietary elastomeric interface to applanate the cornea, or use a liquid optic interface enabling the FS-laser procedure without corneal applanation.²⁹ From the derivation in the Supplementary Material and Figure 5, we find that changes in the anterior and posterior corneal shape do not contribute to the shift. The change in corneal shape can therefore be ignored for the purpose of this study.

Due to the model's paraxial nature, other optical effects due to lens tilt, two- and three- dimensional corneal warping, and higher-order aberrations are not considered but could be investigated with a higher-order model. However, since corneal curvature has a minimal effect, it is predicted that a higher-order model will not result in a larger predicted error. The model also assumes a constant anterior chamber depth with OVD refilling. Changes in the geometry of the anterior chamber could occur due to refilling; however, the OCT measurement of the anterior chamber is performed after refilling and would thus measure and correct for any change in anterior chamber depth due to refilling.

In order to prevent incomplete FS-laser capsulotomies after anterior chamber refilling, authors have recommended increasing the laser power, elevating the capsulotomy depth range, or increasing the energy per pulse.^{12,13} However, no clinical outcomes are provided to support that an increase in power or geometry improves the efficacy of FS-laser capsulotomies in the presence of OVD.^{12,13} Our refractive index measurements together with the optical model show that the incomplete capsulotomies that have been observed during FS-laser-assisted cataract surgery cannot be attributed to differences in refractive index between OVD and aqueous.¹³ Given the safety margins used by the laser systems, the focus shift produced by the OVD is too small to have an effect on the laser

TABLE 3. Predicted Capsulotomy Diameter Due to Lateral Magnification After Refilling the Anterior Chamber With Each (8-mm-Diameter Capsulotomy Is Assumed)

OVD	Theoretical FS-Laser Cut Diameter, mm, After Refilling the AC With OVD
EyeFill C	8.003
EyeFill SC	8.003
EyeFill HD	8.000
Healon 10	8.003
ProVisc	8.003
VisCoat	7.986

AC, anterior chamber.

cut. From a purely optical perspective, there is therefore no benefit gained by adjusting the geometrical parameter of the cut.¹³

Other factors that could lead to the imperfect capsulotomy include the presence of small air bubbles in the OVD, which could cause a nonuniform transmission of the FS-laser beam. The presence of a bubble with a diameter of the same order of magnitude as that of the laser cavitation bubble could disrupt the path of the beam.³⁰ The difference in viscosity and thermodynamic properties caused by the anterior chamber refilling may also cause a change in energy required for cavitation. However, it remains unclear if an increase in threshold energy is required to compensate for these differences. Lens tilt due to the insertion of mechanical pupil dilation devices (iris retractors, Malyugin ring, and so on) could also affect the position of the capsulotomy depth.³¹ Some of these effects can be mitigated through the laser control software: The surgeon is currently able to adjust the margins and position of the capsulotomy as well as compensate for some degree of tilt.

In summary, our calculations show that the change in refractive index due to anterior chamber refilling does not sufficiently shift the laser beam focus position to cause the incomplete capsulotomies reported during femtosecond laser-assisted cataract surgery in patients with small pupils that require mechanical dilation. Laboratory experiments and prospective randomized clinical studies are necessary to better define and understand the effect of OVDs on the FS-laser cut and identify the conditions under which incomplete capsulotomies occur.

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