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REFRACTIVE SURGERY

Fluid dynamics simulation of aqueous humour in a posterior-chamber phakic intraocular lens with a central perforation

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Abstract

Background A modified implantable collamer lens (ICL) with a central hole (diameter, 0.36 mm), a “Hole-ICL”, was created to improve aqueous humour circulation. The aim of this study was to investigate the fluid dynamic characteristics of aqueous humour in a Hole-ICL using computational fluid dynamics.

Methods Fluid dynamics simulation using an ICL was performed with thermal-hydraulic analysis software FloEFD V5 (Mentor Graphics Corp.). For the simulation, three-dimensional eye models based on a modified Liou–Brennan model eye with conventional ICL (Model ICM, STAAR SURGICAL) and a Hole-ICL were used. Both ICLs were −9.0 diopters (D) and 12.0 mm in length, with an optic of 5.5 mm. The vaulting was 0.50 mm. The quantity of aqueous humour produced by the ciliary body was set at 2.80 μl/min. Flow distribution between the anterior surface of the crystalline lens and the posterior surface of the ICL was also calculated, and trajectory analysis was performed.

Results The flow velocity 0.25 mm in front of the centre of the crystalline lens was 1.52×10^{-1} mm/sec for the Hole-ICL and 1.21×10^{-5} mm/sec for the conventional ICL. Outward flow from the hole in the Hole-ICL was confirmed by trajectory analysis.

Conclusion These results suggest that Hole-ICLs improve the circulation of aqueous humour to the anterior surface of the crystalline lens.

Keywords Fluid dynamics · Phakic IOL · ICL · Hole-ICL · Aqueous humour circulation

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Introduction

Posterior chamber (PC) phakic intraocular lenses (pIOLs) have many advantages for the treatment of refractive error, especially in cases of high and moderate ametropia [1, 2]. Recently, the toric implantable collamer lens (ICL) has been demonstrated to be effective for the correction of high myopic astigmatism [3, 4]. However, cataract development has been noted after PC pIOL implantation [1]. Chen and associates [1] performed a systematic literature review to determine the incidence of cataracts after pIOL implantation, and to identify the predisposing factors for cataract formation. They reported that the incidence of cataract formation was 9.6%, and the analysis of cataract progression in eyes with pre-existing cataracts showed a progression rate of 29.5% after pIOL surgery. One of the causes of secondary cataracts may be a change in the circulation of aqueous humour to the anterior surface of the crystalline lens. Therefore, in 2006, Shimizu created a centrally

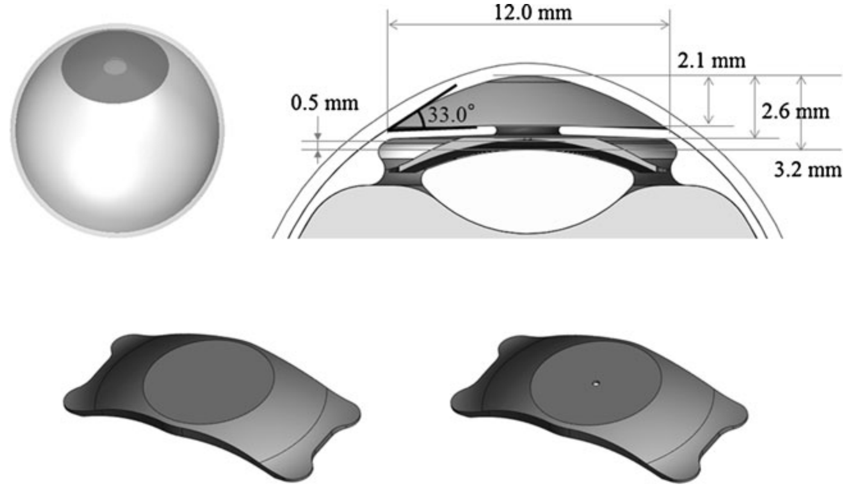


Fig. 1 Three-dimensional models of eyes with ICLs created with FloEFD software. Appearance of the eye model (*top left*) , anterior ocular segment (*top right*), conventional ICL (*bottom left*) , Hole-ICL (*bottom right*)

perforated ICL (i.e., the Hole-ICL) to improve aqueous humour circulation (Shimizu K. Implantable Contact Lens. The 31st Annual Meeting of the Japanese Society of Ophthalmic Surgeons, Yokohama, Japan, 2008). After observing improved aqueous humour circulation in the Hole-ICL, Fujisawa [5] reported that no cataracts were formed when Hole-ICLs were implanted into porcine eyes. That study concluded that the Hole-ICL allowed sufficient flow of aqueous humour, which was distributed over the anterior surface of the crystalline lens through its central hole. In addition, Shiratani and associates [6] suggested the possibility of preventing cataracts with the Hole-ICL using minipigs. However, it is uncertain whether the selected size of the ICL was appropriate, because these studies were performed in porcine eyes, not human eyes. It is known that the ciliary process of the porcine eye is highly developed; it has a large fold, and therefore the ciliary sulcus is deep, the ciliary muscle cells are few in number, and the stroma is thin [5]. Therefore, the circulation of aqueous humour in a porcine eye would be distinct from that in a human eye. Additionally, the theoretical basis for the improvement of aqueous humour circulation around the anterior crystalline lens has never been clarified.

The aim of this study was to investigate the fluid dynamic characteristics of aqueous humour in a Hole-ICL using computational fluid dynamics.

Materials and methods

Computational fluid dynamics simulation of ICL use was performed with the thermal–hydraulic analysis software program FloEFD V5 (Mentor Graphics Corp.), the computational fluid dynamics analysis tool that is commonly embedded in mechanical computer-aided design systems. For the simulation, three-dimensional eye models with conventional ICLs (Model ICM, STAAR SURGICAL) and Hole-ICLs were created (Fig. 1). Both ICLs were −9.0 diopters (D) and 12.0 mm in length, with an optic of 5.5 mm (Fig. 1). The vaulting was 0.50 mm, the pore space between the posterior iris and the ICL was 0.05 mm, and the angulus iridocornealis was 33 degrees. The quantity of aqueous humour produced by the ciliary body was set at 2.80 µl/min, and the inflow and outflow locations are shown in Fig. 2. Outflow locations for aqueous humour were set to involve 10% uveoscleral outflow and 90% trabecular outflow. The solid-state properties of aqueous humour were set in common with those of water; the degree of viscosity of aqueous humour was 7.1917×10^{-4} Pa·s at a temperature of 95 degrees Fahrenheit. The initial pressure was set at 1 atmosphere.

Flow distribution between the anterior surface of the crystalline lens and the posterior surface of the ICL, 0.25 mm from the centre of the crystalline lens, was also calculated (Fig. 3). In addition, trajectory analysis was performed for both ICLs.

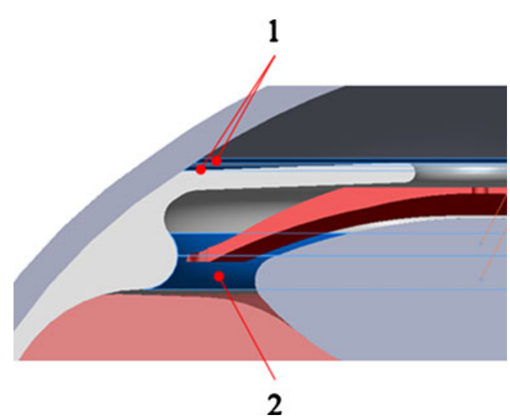


Fig. 2 Locations of aqueous humour inflow and outflow. *1*: location of aqueous humour outflow; *2*: location of aqueous humour inflow

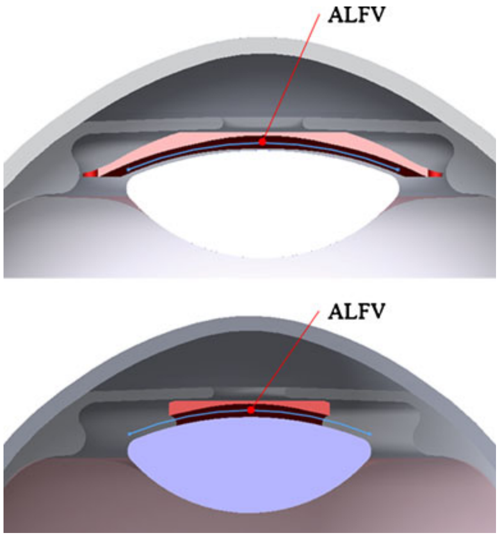


Fig. 3 Analysed lines of flow velocity along the long axis of the cross-sectional surface (*top*) and the short axis of the cross-sectional surface (*bottom*). *ALFV*: analysed line of flow velocity

Results

The flow distribution between the anterior surface of the crystalline lens and the posterior surface of the Hole-ICL was higher than that between the crystalline lens and the conventional ICL (Figs 4 and 5). The difference was particularly striking in the centre (Figs. 6 and 7). For the Hole-ICL, the flow velocity along the short axis was slightly higher than that along the long axis. The flow velocity 0.25 mm in front of the centre of the crystalline lens was 1.52×10^{-1} mm/sec for the Hole-ICL, 1.21×10^{-5} mm/sec for the conventional ICL, and 0.474×10^{-2} mm/sec for the eye without an ICL.

Outward flow from the hole in the Hole-ICL was confirmed by trajectory analysis (Fig. 8).

Discussion

As to the validity of FloEFD software that utilises computational fluid dynamics, the agreement between

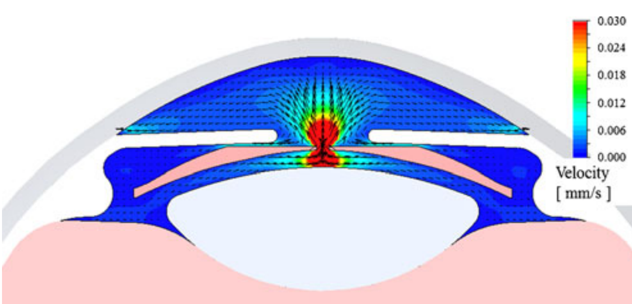


Fig. 4 Flow distribution along the long axis of the cross-sectional surface of the Hole-ICL. The *length of the arrow* corresponds to the flow velocity

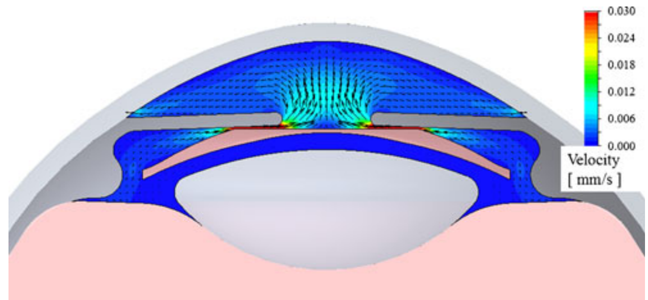


Fig. 5 Flow distribution along the long axis of the cross-sectional surface for the conventional ICL. The *length of the arrow* corresponds to the flow velocity

theory and experimental data was high, as shown in the technical reference (supplementary material). Therefore, we investigated the fluid dynamic characteristics of aqueous humour in a Hole-ICL using this software.

Fujisawa and associates [5] examined the degree of staining on the anterior surface of the crystalline lens by infusing dye into the vitreous humour in the Hole-ICL. The authors suggested that ICL insertion in the porcine eye inhibited the flow of aqueous humour over the anterior crystalline lens surface, not only along its long axis but also across its short axis. These findings are congruent with our results. In the present study, the flow velocity between the anterior surface of the crystalline lens and the posterior surface of the ICL was faster in a Hole-ICL than in a conventional ICL. The flow velocity in the conventional ICL was probably not elevated, because the outflow of the aqueous humour was cut off midstream. However, the quantity of flow in the Hole-ICL was large in a channel running through the hole in the centre, because the distance between the iris and the ICL was narrow. Therefore, the circulation of aqueous humour to the anterior surface of the

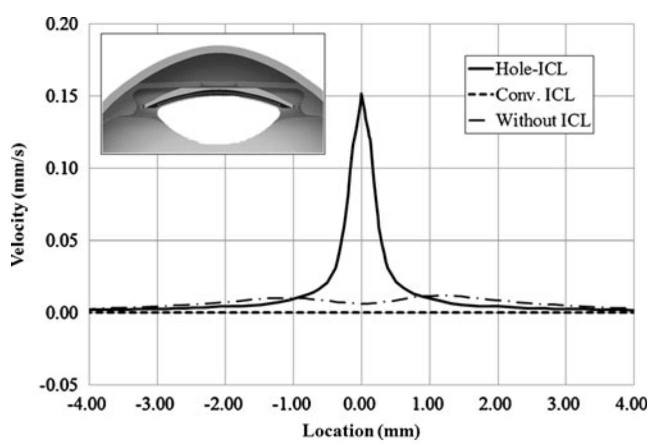


Fig. 6 Comparison of flow velocity along the long axis of the cross-sectional surface of the Hole-ICL, conventional ICL, and the eye without an ICL. The *solid line* represents the flow velocity of the Hole-ICL, and the *dotted line* represents the flow velocity for the conventional ICL

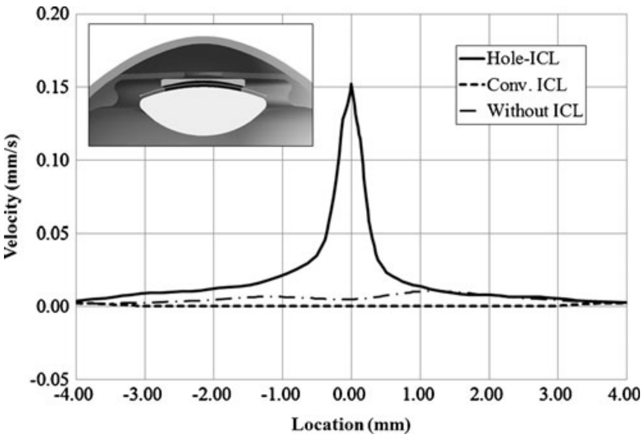


Fig. 7 Comparison of flow velocity along the short axis of the cross-sectional surface in the Hole-ICL, conventional ICL, and the eye without an ICL

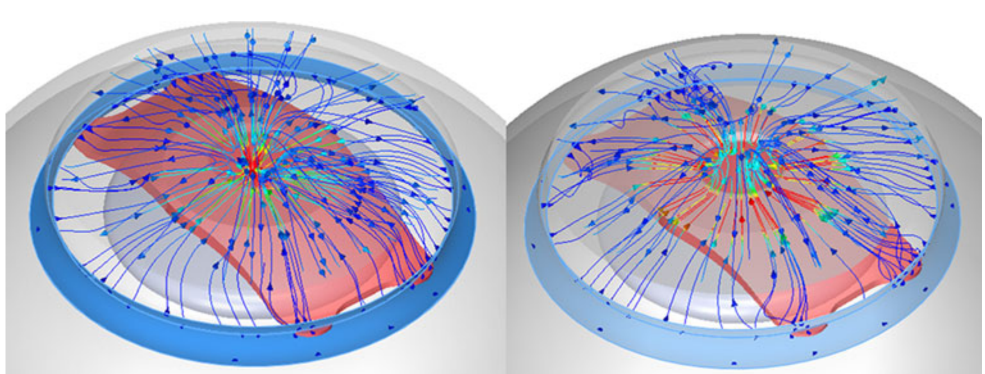
crystalline lens in a Hole-ICL would be higher than that in a conventional ICL.

Several causes of secondary cataracts in patients with conventional ICL have been postulated, including aqueous humour circulation [5, 6], pIOL-crystalline lens contact [7, 8], low vaulting between the ICL and the crystalline lens [9–11], the decreased anterior chamber depth occurring with age [12], myopia [13], and surgical trauma [14]. In particular, Fujisawa et al. [5] and Shiratani et al. [6] performed histopathological studies that revealed the importance of aqueous humour circulation in the vault between the ICL and the crystalline lens in preventing secondary cataracts. They [5, 6] reported that the implantation of conventional-type ICLs into porcine eyes with adequate vaulting was followed in all cases by turbidity appearing as an anterior subcapsular cataract. No turbidity beneath the anterior capsule was reported in any instance in our study, and no eye showed turbidity because the aqueous humour perfusion on the anterior surface of the crystalline lens increased, resulting in adequate provision of the substances needed for crystalline lens metabolism. In this study, increased flow velocity in the vault between the ICL and the crystalline lens would have cataractogenic effects. Furthermore, pIOL-crystalline lens contact and low vaulting are thought to impair aqueous humour circulation. Many surgeons also perform peripheral laser iridotomy (LI) prior to ICL implantation to prevent a pupillary block. LI may cause complications including iritis, intraocular haemorrhage, elevation of intraocular pressure, posterior iris synechia, and corneal decompensation, such as bullous keratopathy. Therefore, although further studies are needed to clarify the effects in vivo, use of the Hole-ICL may improve aqueous humour circulation, preventing secondary cataracts and eliminating the need for LI.

Although the improvement of aqueous humour circulation is promising, there is concern that the optical characteristics of the Hole-ICL deteriorate due to its central hole. The size of the hole affects the trade-off between optical performance and volumetric flow. However, some astronomical telescopes represent cases of an optical system with a centrally perforated lens. A Cassegrain telescope is one such device, having a large, concave paraboloidal primary form with a central hole. Shiratani [6], using ZEMAX optical simulation software, reported that it is desirable that the size of the central hole in the ICL optic be 1.0 mm or less to allow for acceptable image formation. Using ZEMAX software, Uozato and associates [15] and Ohmoto and associates [16] confirmed the optical performance of the Hole-ICL (diameter, 0.36 mm) in an optical bench test and optical simulations. The authors showed that a minimal central hole in an ICL may not have a great impact on optical performance for various ICL powers and effective pupil diameters. Shimizu reported effective treatment results and high safety in an in vivo study of Hole-ICLs (Shimizu K. Topics for New ICL. International Meeting on Advanced Cataract and Refractive Surgery 2009, Seoul, KOREA, September 26, 2009).

With regard to the limitations of the present study, an eye model involving LI was not used in the simulation because we sought to assess the effect of a hole on the fluid dynamic characteristics of aqueous humour alone. The lack of simulated LI may affect the results of this investigation. However, the difference between the eye models with and

Fig. 8 Trajectory analysis in the Hole-ICL (*left*) and conventional ICL (*right*). Representative lines are shown



without LI may have little influence on the relative difference in flow velocity between a Hole-ICL and a conventional ICL, although it may alter each absolute value. In addition, although the flow velocity in the conventional ICL was low in the present study, the flow may be increased in association with the pumping action occurring due to physiological changes in the crystalline lens and/or pupil. Further studies are needed to clarify these effects.

In conclusion, these results suggest that Hole-ICLs improve the circulation of aqueous humour to the anterior surface of the crystalline lens.

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