Glaucoma

# Computational Study of Aqueous Humor Dynamics Assessing the Vault and the Pupil Diameter in Two Posterior-Chamber Phakic Lenses

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Submitted: May 10, 2016
Accepted: July 15, 2016

Citation: Fernández-Vigo JI, Macarro-Merino A, Fernández-Francos J, et al. Computational study of aqueous humor dynamics assessing the vault and the pupil diameter in two posterior-chamber phakic lenses. *Invest Ophthalmol Vis Sci*. 2016;57:4625–4631. DOI:10.1167/iovs.16-19900

**Purpose.** To compare the behavior of aqueous humor (AH) and analyze flow differences by comparing the volume and velocity of the flow after two different models of implantable collamer lens (ICL) placement.

**Methods.** Computational fluid dynamics with numerical simulation using Ansys Fluent software was performed to compare the AH flow through a peripheral iridotomy (PI), which is typically performed after implantation of a V4b lens to the central hole of a V4c lens. The volume and flow rate in 24 scenarios were compared according to the type of lens, pupil diameter (PD) (3.5 or 5.5 mm), the vault (100, 350, and 800 μm) and the PI (single or double, 180 or 360 μm).

**Results.** With a standard vault (350 μm) and a PD of 3.5 mm, the volume of AH that flows from the posterior to the anterior chamber through the PI (V4b lens: 73.4% in 360 μm and 17.3% in 180 μm) and for the central hole (V4c lens: 75.7%) is larger than in the case of a PD of 5.5 mm (13.9%, 0.91%, and 15.3% respectively). When the vault is low (100; PD 3.5 mm), the volume of AH that reaches the central hole of the V4c lens is diminished (52.0%), being 5.1% if the pupil is enlarged.

**Conclusions.** AH flow varies depending on the type of ICL implanted, whether it is implanted with an iridotomy or a central hole on the lens, the PD, and the vault.

Keywords: aqueous humor, phakic lens, iridotomy, lens vault, computational modeling

The dynamics of aqueous humor (AH) in the human eye have been studied extensively by various physical methods because of its involvement in the pathophysiology of IOP.[1–6] However, to date, the dynamics of AH have been little studied in relation to the changes that occur after implantation of phakic IOLs. Implanting a phakic lens is an obstacle hindering the passage of AH from the posterior chamber into the anterior chamber through the pupil, forcing the AH to redistribute.

Among phakic lenses, the most widely used is the implantable collamer lens (ICL; STAAR Surgical AG, Nidau, Switzerland),[7,8] which is a posterior-chamber lens for correcting refractive errors. These lenses have certain potential risks, such as ocular hypertension, pupillary block (because of increased contact lens–iris), the reduction of the angle width, and cataracts or endothelial damage.[9–13] Classically, to prevent this circulatory problem of the AH after implantation of the ICL and to prevent those complications, a peripheral iridotomy (PI) was performed.

A new model of the ICL has been commercialized. It features the V4c lens with a central hole or Aquaport, allowing passage of the AH from the posterior to the anterior chamber and directly through it, eliminating the need to perform a PI and its potential complications.[14,15] The ICL has proven to be an effective and safe lens[14–17]; nevertheless, despite the new lens design, certain potential complications still exist.[18–20] Aqueous humor plays a key role in the origin of the complications related directly to ocular hypertension and indirectly in the development of cataracts. The latter could arise not only from a possible mechanical contact between the posterior side of the lens and the anterior side of the crystalline, but also because of the decreased circulation of the AH in the anterior side of the crystalline induced by the presence of ICL, which could contribute to its appearance and modify its metabolism.

One of the first models simulating the dynamics of AH after ICL implantation was done by Kawamorita et al.,[21] suggesting that the central-hole ICL improves circulation of AH on the anterior surface of the crystalline lens. Repetto et al.[22] analyzed the changes occurring in the cornea and iris because of the effects on intraocular AH flow after iris-fixated phakic lens placement in the anterior chamber. Further, Yamamoto et al.[23] showed that the flow of AH through a PI is influenced by the pupil diameter (PD), and analyzed the possible effects on the endothelium.





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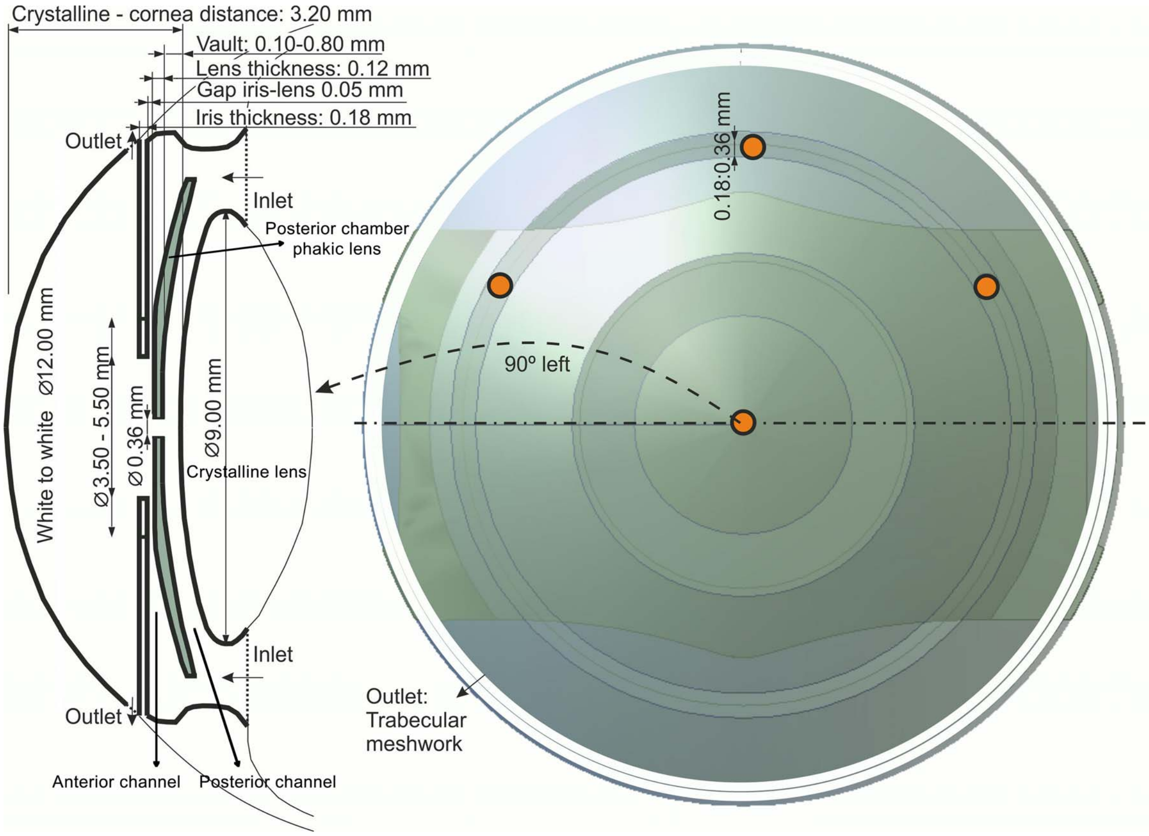


**Figure 1.** Standard measurements of a human eye used to perform the simulation.

However, the changes in the circulation of AH in the presence of a phakic lens in its passage from the posterior to the anterior chamber remains poorly understood, and there are no studies comparing the dynamics of AH in both ICL models, V4b (iridotomy) and V4c (central hole), taking into account important parameters, such as the PD, the vault of the lens, and the size and number of the PI, its analysis was the purpose of the present study.

## Methods

For the simulation an ICL (STAAR Surgical AG), a foldable phakic lens of collamer, a biocompatible, flexible, and absorbent material with a convex–concave central optical zone was studied. This lens should be placed in the posterior chamber between the iris and crystalline lens, with the support of the haptics in the ciliary sulcus. Figure 1 shows the standard measurements of the anterior segment of the human eye that were used for the simulation. This figure shows the division into two channels of the posterior chamber after implantation of the ICL: an anterior channel formed by the posterior surface of the iris and the anterior side of the ICL lens, and a posterior channel formed between the posterior side of the ICL and the anterior side of the crystalline lens.

Two types of ICL lens, the V4b and V4c, were studied. The difference between them is a 360-μm hole located in the center of the optics, the KS-Aquaport (STAAR Surgical AG) in the V4c. This hole allows the flow of AH to facilitate the transition from the posterior chamber into the anterior chamber, avoiding the need for a PI for the same circulatory purpose in the V4b model. In the V4b model, two sizes of single PI were simulated, located at 12 hours (180 and 360 μm), and a double iridotomy (180 μm both), located at 10 and 2 hours (Fig. 1).[24] Indications, surgical technique, and morphology of both lens models are identical. To perform the simulation, we used a rigid lens of 11 spherical diopters (Table 1).

A three-dimensional full study based on computational fluid dynamics (CFD) was performed with Ansys Fluent software (v6.3.26; Ansys, Inc., Canonsburg, PA, USA). Cases were run in a steady mode with laminar flow, using as inlet condition a constant flow rate of 2 μL/min ($3.34 \times 10^{-8}$ kg/s) of AH and, as outlet condition, a gauge pressure of 15 mm Hg (20 hPa). No-slip boundary conditions were prescribed at the solid surfaces. The fluid is Newtonian and incompressible. The flow was removed at the trabecular meshwork at the same rate as production. In this study, the thermal convection caused by the difference between the temperatures of the surface of the cornea and the rest of the chamber wall was considered as responsible for the flow in the anterior chamber, establishing a temperature of the iris and crystalline of 37°C, and of the cornea at 34°C. Buoyancy effects due to temperature gradients were modeled with Boussinesq approximation. It was assumed that the density of the fluid changes with temperature according to the equation: $\rho = \rho_0[1 - \beta(T - T_0)]$.[9] A grid dependence analysis was carried out before performing the final calculations. For this purpose, three grids of coarse, medium, and fine size cells were built, using the static pressure at a fixed point as the reference variable. Variations below 1% were observed when the results for the fine and coarse grids were compared with the medium ($7.5 \times 10^5$), the latter finally used in this study. With regard to the elimination of the AH, although it is known that there is a double track, we only took into account the trabecular pathway because it is the main pathway, which accounts for 90% of the elimination of the AH, and did not analyze the uveoscleral pathway.[25] We established



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**Table 1.** Parameters Used for the Numerical Simulation With Standard Values of an Adult Human Eye and the Measurements of the ICL

| Standard Values for a Human Eye | |
|---|---|
| **Parameter** | **Value** |
| Anterior chamber diameter, mm | 12 |
| Anterior chamber depth, mm | 3.2 |
| Crystalline diameter, mm | 9 |
| Crystalline thickness, mm | 4 |
| Iris thickness, mm | 0.18 |
| Iridotomy, μm | 180; 360 |
| Distance between iris and crystalline, mm | 0.93 |
| Distance between iris and lens, mm | 0.12 |
| Lens length, mm | 8.75 |
| Lens width, mm | 3.5 |
| Lens thickness, mm | 0.12 |
| Vault: distance between crystalline and ICL lens, μm | 100; 350; 800 |
| Linear expansion coefficient of aqueous humor b, $K^{-1}$ | 0.0003 |
| Density of AH $\rho_0$, $kg/m^3$ | 998.2 |
| Dynamic viscosity of AH μ, Pa·s | 0.001 |
| Gravitational acceleration g, $m/s^2$ | 9.81 |
| Thermal conductivity K, W/m·K | 0.6 |
| Specific heat $C_p$, J/kg·K | 4182 |
| Inlet area, $mm^2$ | 42.39 |
| Outlet area, $mm^2$ | 86.75 |

an iridocorneal angle width of 30 degrees,[17] modifying the angle using the software to adjust to the vault studied. Although the eye is substantially symmetrical about its axis, the force of gravity breaks this symmetry, so that the resulting flow is three dimensional, also taking into account the gravitational effect on the simulation. Standard values of the adult human eye used in the simulation are shown in Table 1.

The volume and flow rate of the AH crossing ducts (iridotomy or central hole) to pass from the posterior to the anterior chamber were compared in 24 scenarios, depending on the type of lens (V4b with variable size and number of PI or V4c with central hole), PD (3.5 or 5.5 mm), and the vault (distance between the anterior side of the crystalline lens and the posterior surface of the ICL), simulating a vault considered low (100 μm), standard (350 μm), and large (800 μm).

To illustrate the movement of AH, the trajectory analysis is shown in Figure 2, which represents the flow streamlines colored by residence time, which is the time since its formation in the ciliary body to disposal through the trabecular meshwork.[26] In Figure 3, the flow velocity rates of AH to pass through the ducts are shown. The Supplementary Figure shows the representation of the velocity rates in the horizontal plane.

## Results

The results are shown in terms of the parameters evaluated, focusing at first on the type of lens, comparing the ICL model with the central hole (V4c) versus PI (V4b).

The percentage of AH flowing through the central hole of the V4c ICL (75.7%) is similar to flow in the large PI (360 μm; 73.4%) on a 3.5-mm PD. The flow in both ducts of 360 μm (V4c with central hole and V4b with iridotomy) is much larger compared with the PI of 180 μm (17.3%) and the double PI (31.6%). These percentages are drastically reduced to 15.5%, 13.9%, 0.91%, and 2.0% respectively, when the pupil is enlarged to 5.5 mm. This decrease occurs because when the PD increases, the contact between the posterior side of the iris and the anterior side of the ICL is reduced, thereby decreasing the resistance in the anterior channel, which facilitates most of the AH volume to pass to the anterior chamber directly through the pupil.

The results described are applicable for a standard vault of 350 μm; however, if there is a high vault (800 μm), the results are similar. The circulating AH is 77.3% through the central hole, 75.1% through the large PI (360 μm), 18.1% through the small PI (180 μm), and 31.5% through the double PI for a 3.5-mm pupil. If the pupil increases to 5.5 mm, then the percentage of AH that passes through the ducts is reduced to 32.8%, 28.1%, 1.6%, and 3.1%, respectively. This is again because the iris–ICL contact is less and therefore there is less resistant to the flow through the anterior channel.

On the contrary, if there is a low vault (100 μm) with a 3.5-mm pupil, results somewhat differ. The percentage of AH flowing through the central hole is substantially lower (52%) compared with that through the large PI, which remains similar to the above values (73%).

This could be because at low vault, the percentage of AH that passes through the ICL rear is less because of the increased resistance resulting from the large narrowing present in this space. Further, the resistance in the anterior channel is lower respectively, so that the AH tends to flow through this channel. Iridotomy, however, is virtually independent of changes in the channel resistance, and remains equally accessible to the AH. If in this situation (low vault) the pupil enlarges to 5.5 mm, the percentages are greatly reduced from 52.0% to 5.0% through the central hole, 73.9% to 12.1% through the large PI, and 19.7% to 0.8% in the small one, decreasing from 30.6% to 1.6% in the double PI. Again, this is due to the reduced resistance in the anterior channel.

In contrast to V4c, in which the vault significantly affects the volume of AH that flows through the ducts, in the case of V4b, regardless of the vault, the percentage of volume passing through the PI in both cases, large (vault 100, 73.8%; vault 350, 73.4%; vault 800, 75.2%) or small PI (vault 100, 19.7%; vault 350, 17.3%; vault 800, 18.1%) is practically identical with a PD of 3.5 mm. However, the PD itself also would be an influential factor in this type of lens, if the pupil is 5.5 mm, because of the values referred to descend until 12.1%, 13.9%, and 28.2% in the large PI, and to 0.8%, 0.9%, and 1.6%, respectively, in the small PI (Table 2).

In Figure 2, the 24 simulated situations are represented and explained, showing the streamlines, colored by residence time of the AH, depending on the type of lens, PI, PD, and vault. In the central-hole lens (first row, A–F), when there is a low vault (A and B), the residence time in the anterior chamber is greater if the pupil is larger (B). In C and D, in which there is a standard vault, circulation and filling the anterior chamber are more homogeneous; however, there is more circulation in the anterior crystalline lens in the situation shown C than in D, because of smaller PD (75.5% vs. 15.5%, respectively, Table 2). E and F show a high vault, in which a greater circulation can be observed on the anterior crystalline lens and through the central hole than in situations with a low vault (Table 2), but in F, because of a larger PD, an increased residence time in the anterior chamber was observed. In the rest of the rows (G–X), the V4b lens with different iridotomies is shown. It could be observed that a large volume of AH passes through the iridotomy and goes directly toward the trabecular meshwork, thus having less circulation in the anterior chamber than in the central hole lens. If there is an increased pupil size, the circulation occurs more homogeneously, being especially more remarkable in the 360-μm (G–L) than in the 180-μm iridotomy (M–R). The circulation of AH in the 180-μm double iridotomy (S–X) is more similar to the single 180-μm iridotomy than the 360-μm iridotomy.

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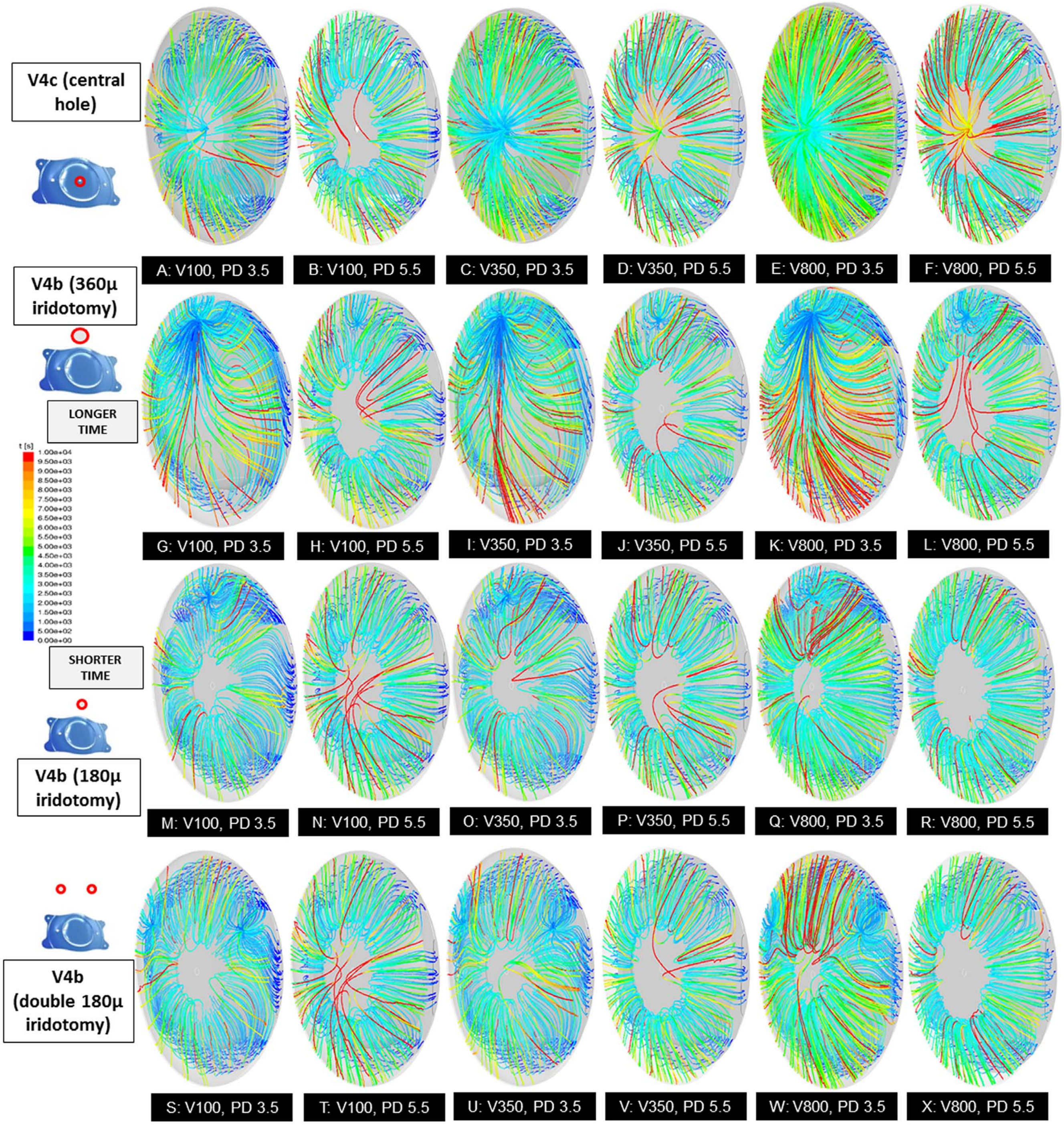


**Figure 2.** The 24 situations are represented showing the residence time of the AH depending on the type of lens implanted (V4c with a central hole versus V4b with an iridotomy), PD (3.5–5.5 mm), and vault (V: 100, 350, 800). It is represented with stream lines of trajectory analysis using a time-color scale.

Figure 3 shows the velocity of AH as it passes through the central hole and through the PI. For the V4c (upper row) at equal vault, flow velocity is much higher in all cases if the pupil is smaller. However, in all cases, this increased flow velocity is dissipated in the anterior chamber and this aqueous stream does not affect the endothelium. In addition, with a high vault, there is more circulation in the anterior crystalline lens. The inferior row represents the lens V4b (360-µm iridotomy). Increasing the velocity of the flow through the iridotomy could cause a stream of AH that alters the peripheral endothelium. Moreover, with a larger PD, the percentage of AH flowing through the pupil is larger and the velocity of the peripheral stream of AH is lower.

## Discussion

In the present study, using a computational simulation of the flow of AH in the presence of two phakic lens models, it was noted that the flow rate and residence times of the AH vary by

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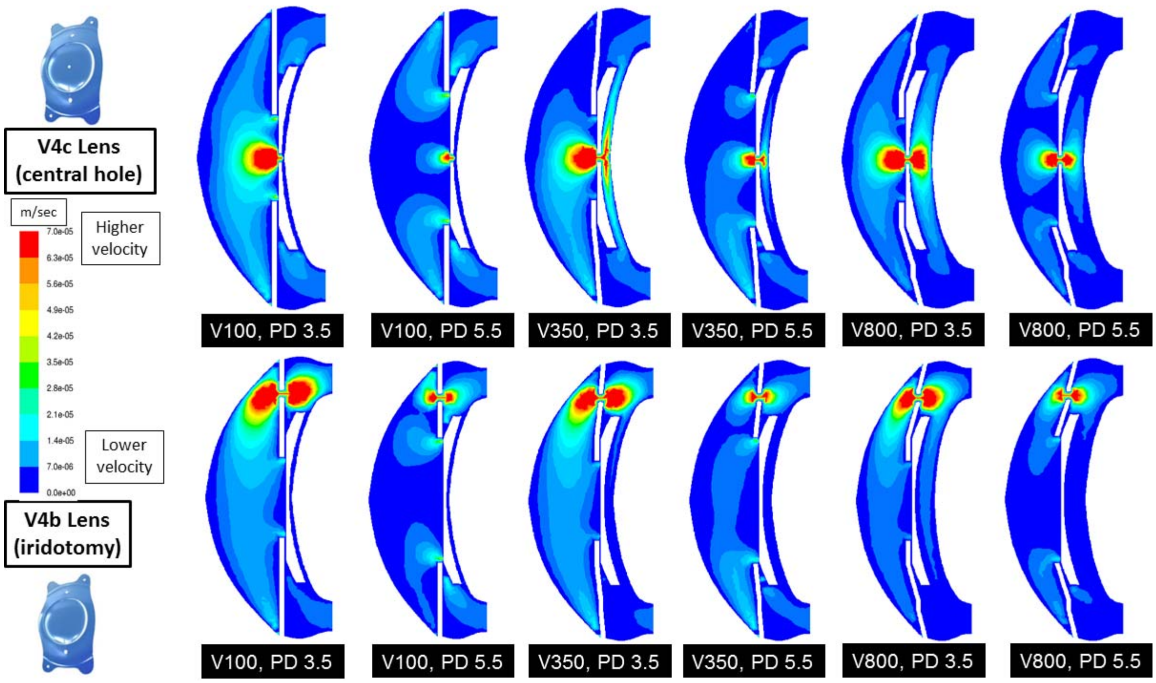


**Figure 3.** Representation of the AH velocity passing through the central hole and through the iridotomy in the vertical plane, according to the type of lens (V4c with central hole and V4b with 360-μm iridotomy), PD (3.5–5.5 mm), and vault (V, 100, 350, 800).

the model of lens implanted, the V4b with the required PI and V4c with the central hole, and by the PD and the vault.

The volume of AH passing from the posterior to the anterior chamber is similar in both types of lenses (V4c with central hole of 360 μm and V4b with a 360 μm PI), so both solutions

**Table 2.** Results of AH Velocity and Volume in the 24 Scenarios Studied, According to the PD, the Vault, and the Type of Lens Implanted: V4b With Variable Size and Number of Iridotomies, or V4c With Central Hole

| PD, mm | Vault, μm | Type of Lens | Velocity, mm/s | Volume, mL/min | % of AH |
|---|---|---|---|---|---|
| 3.5 | 100 | V4c (central hole) | $1.79^{-01}$ | $2.89^{-04}$ | 52.01 |
| | | V4b (one iridotomy, 360) | $2.54^{-01}$ | $4.11^{-04}$ | 73.86 |
| | | V4b (one iridotomy, 180) | $6.78^{-02}$ | $1.10^{-04}$ | 19.73 |
| | | V4b (double iridotomy, 180) | $5.21^{-02}$ | $1.69^{-04}$ | 30.33 |
| | 350 | V4c (central hole) | $2.60^{-01}$ | $4.21^{-04}$ | 75.72 |
| | | V4b (one iridotomy, 360) | $2.52^{-01}$ | $4.08^{-04}$ | 73.36 |
| | | V4b (one iridotomy, 180) | $5.95^{-01}$ | $9.64^{-05}$ | 17.32 |
| | | V4b (double iridotomy, 180) | $2.71^{-03}$ | $8.78^{-06}$ | 31.58 |
| | 800 | V4c (central hole) | $2.66^{-01}$ | $4.31^{-04}$ | 77.35 |
| | | V4b (one iridotomy, 360) | $2.58^{-01}$ | $4.18^{-04}$ | 75.17 |
| | | V4b (one iridotomy, 180) | $6.23^{-02}$ | $1.01^{-04}$ | 18.14 |
| | | V4b (double iridotomy, 180) | $5.41^{-02}$ | $1.75^{-04}$ | 31.51 |
| 5.5 | 100 | V4c (central hole) | $1.75^{-02}$ | $2.83^{-05}$ | 5.09 |
| | | V4b (one iridotomy, 360) | $4.16^{-02}$ | $6.75^{-05}$ | 12.12 |
| | | V4b (one iridotomy, 180) | $2.82^{-03}$ | $4.57^{-06}$ | 0.82 |
| | | V4b (double iridotomy, 180) | $2.71^{-03}$ | $8.78^{-06}$ | 1.58 |
| | 350 | V4c (central hole) | $5.34^{-02}$ | $8.64^{-05}$ | 15.53 |
| | | V4b (one iridotomy, 360) | $4.79^{-02}$ | $7.76^{-05}$ | 13.94 |
| | | V4b (one iridotomy, 180) | $3.12^{-03}$ | $5.05^{-06}$ | 0.91 |
| | | V4b (double iridotomy, 180) | $3.36^{-03}$ | $1.09^{-05}$ | 1.96 |
| | 800 | V4c (central hole) | $1.13^{-01}$ | $1.83^{-04}$ | 32.82 |
| | | V4b (one iridotomy, 360) | $9.68^{-02}$ | $1.57^{-04}$ | 28.17 |
| | | V4b (one iridotomy, 180) | $5.34^{-03}$ | $8.66^{-06}$ | 1.56 |
| | | V4b (double iridotomy, 180) | $5.34^{-03}$ | $1.73^{-05}$ | 3.11 |

seem equally effective in preventing IOP elevations or pupillary block. In a clinical study, Higueras-Estaban et al.[19] also found no difference between these two types of lenses in terms of IOP. As we have seen, the volume that goes through the central hole as large PI was similar (with a standard vault) for a PD of 3.5 mm (75.7% and 73.4%, respectively) and with a PD of 5.5 mm (15.5% and 13.9%, respectively).

On the contrary, if the PI is unique and smaller (180 μm) or double (180 μm each), the values would be much lower, being 17.0% and 31.6% for the PD of 3.5 mm and fall to 0.91% and 1.96%, respectively. Therefore, the size and number of iridotomies significantly determine the circulation of AH flow that goes from the posterior to the anterior chamber. Thereby, Agraval et al.[27] constructed a mathematical model to determine the optimal size of the PI in uveitis, and suggest that at least a 300- to 350-μm PI, greater than the standard Fleck[24] recommendation of 150 to 200 μm, was more adequate.

In this study, the importance of PD was observed. If the pupil is small, the iris–ICL contact and the resistance in the anterior channel (iris–ICL) increase, forcing the AH to seek alternative ways: iridotomy and posterior channel (ICL–crystalline); whereas, if the pupil is enlarged, and consequently the contact resistance is reduced, the flow is facilitated through the pupil. Thus, it was observed that when the PD is greater, AH volume passing through the ducts (PI or central hole) is lower. Yamamoto et al.[23] demonstrated that pupil constriction produces a marked increase in AH flow through the PI against the corneal endothelium, producing a mechanical stress that could lead to the peripheral corneal decompensation that may occur after an iridotomy. In the present work, it was also observed that increasing the flow rate through the iridotomy may affect the peripheral corneal endothelium, especially when it comes to smaller pupils; however, a corresponding increase in flow velocity through the central hole is dissipated in the anterior chamber and does not cause alterations on the endothelium.

Regarding AH circulation in the anterior crystalline lens having a more physiological and homogeneous circulation

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through the central hole of the lens depends on the model of the implanted lens. These results are consistent with the study of Kawamorita et al.,[21] which suggest that the central-hole ICL improves circulation in the front of the crystalline lens. Because the AH has a key role in maintaining the homeostasis of the anterior segment of the eye, particularly in the metabolism of the endothelium and crystalline lens, any change in its correct circulation can produce different alterations. This is important because a smaller volume and less circulatory permanence of AH could be a cause of cataracts. One of the main limitations of the Kawamorita et al.[21] study was that it was not a comparative study with the V4b and the influence of pupil size, aspects that we have assessed in this study.

As for the vault, the enormous importance of pupil size should be noted when a low vault (100 μm) is observed, as in the case of the central-hole lens in which the percentage of AH volume reaching the central hole is 5.1% for larger PD (5.5 mm), being 10 times higher (52.0%) when the pupil is smaller (3.5 mm). Therefore, in the case of a low vault, the situation is much more physiological in patients with smaller pupil size than in those with a large PD because a greater percentage of the AH circulates directly through the pupil without circulating above the anterior crystalline lens, thereby increasing the circulatory disturbances.

The vault is an important parameter,[28–30] and different studies have observed that a low vault (<250 μm) increases the risk of cataract formation,[12,20,29] whereas a high vault (>750 μm) could cause a pupillary block and secondary glaucoma.[31] It has been shown in comparative studies that the vault with the V4c is equivalent to that observed with V4b.[16,19,30] However, contrary to V4c, where the vault substantially affects the flow, through the PI in V4b, the flow is not altered regardless of the vault, being practically independent.

Based on the results of the model, we hypothesize some potential clinical implications. If the pupil is large (5.5 mm), a very low volume would pass through both the small PI (180 μm; <1%) and the double PI (180 μm each, <3.2%), so they appear less effective and recommended solutions to facilitate the passage of AH and to prevent a pupillary block than the realization of a single larger PI (360 μm, 12%–28% depending on the vault). However, if the PD is standard (3.5 mm) doing a small PI (180 μm) may be sufficient for the dynamics of AH (17%–19%) and would be more advisable than to do a large PI (360 μm), because an outsize volume (73%–75%) would pass directly to the trabecular meshwork without recirculating in the anterior chamber. Furthermore, in patients with large PD, a higher vault than the standard could be more physiological, as it would improve the circulation in the anterior crystalline lens. This is because in patients presenting a large pupil (5.5 mm) and an implant of a central-hole lens, the flow through it would be 5% with a low vault (100 μm). It would increase three times (15%) with a standard vault (350 μm) and more than six times (32%) when the vault is high (800 μm). Therefore, the most adverse scenario in which greater AH circulatory disturbances would occur would be the theoretical situation of patients who exhibit low vault with a large PD. Finally, the implantation of the central-hole lens is recommended, because it seems more physiological in terms of AH dynamics for the crystalline lens and for the endothelium than the one that requires the PI.

The main limitation of our work is that it was done on a simulated theoretical model because in the human eye it is difficult to measure some of its properties in vivo, including the distribution and dynamics of AH. Physical and mathematical simulations can improve understanding of ocular physiology and postsurgical changes, bearing in mind that the calculations are performed from a theoretical point of view, with the limitations and differences that this may lead to in practice.[4–6,21,22]

This is the first study in which a simulation model of the AH dynamics comparing the implant of two phakic lens models, V4b with PI and V4c with a central hole, was made that also assesses different vaults and PDs. Future studies may contribute to a better understanding of the changes that occur after implantation of different IOLs and the changes that it produces on the dynamics of AH.

In conclusion, the circulation of AH is influenced by the type of lens implanted, being more physiological in the central-hole model than in the one that requires an iridotomy. In addition, the PD and PI significantly affect the circulation of AH, as well as influencing to a lesser extent the vault of the lens.

## *Acknowledgments*

Disclosure: **J.I. Fernández-Vigo**, None; **A. Macarro-Merino**, None; **J. Fernández-Francos**, None; **L. De-Pablo-Gómez-de-Liaño**, None; **J.M. Martínez-de-la-Casa**, None; **J. García-Feijóo**, None; **J.Á. Fernández-Vigo**, None

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