Numerical Analysis of Aqeous Humor Flow in Healthy and Glaucomatous Eyes using a MIG Stent.

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***Abstract*—Glaucoma is the second leading cause of irreversible blindness worldwide. One of the indicators of eye glaucoma is the increased intraocular pressure which could be caused by the overproduction of aqueous humor or drainage system malfunction.**

To analyze the differences between normal and glaucomatous eyes, SolidWorks was used to construct a 3D model of the eye consisting of structures such as the cornea, sclera, iris, ciliary body, trabecular meshwork (TM), Schlemm canal (SC), as well as a model of the iStent inject micro-stent. Ansys Workbench, utilizing the finite element method, is used to simulate the fluid flow through the normal drainage pathway (CFD Analysis) as well as through the glaucomatous eye. The models of the eye structures and the stent are combined to analyze the biological and biomechanical effects of the stent insertion into the glaucomic eye.

Keywords— Glaucoma, MIGS, Eye model, Finite element analysis, Stent, POAG, Trabecular meshwork, Schlemm canal, Collector channels, modelling.

I. Introduction

Glaucoma is a common eye condition that is responsible for up to 12% of all blindness cases worldwide [1], where the optic nerve, which connects the eye to the brain and supplies visual information to the brain, becomes damaged. The eye continuously secretes a clear fluid called aqueous humor (AH) by the ciliary body, located in the posterior chamber (PC) of the eye behind the iris. The AH circulates from where it's secreted up to the anterior chamber (AC) where approximately 75% leaves through the trabecular meshwork [2] (TM), Schlemm canal (SC) and then collector channels (CC), and the remaining 25% return to the ciliary body from underneath the sclera.

In healthy eyes, the rate of AH drainage balances the secretion rate, meanwhile in glaucomic eyes this balance fails due to either overproduction of aqueous humor or a blockage in the drainage system and both strongly lead to high intraocular pressure. Higher levels of intraocular pressure (IOP), which ranges normally from 10 to 21 mmHg[3], lead to damage to the optic nerve resulting in vision loss which cannot be restored.

There are two main types of glaucoma: primary open-angle glaucoma (POAG) and angle-closed glaucoma. In POAG the angle between cornea and iris is open and the SC is not abstracted by the iris, but the TM is partially blocked, whereas in angle-closed glaucoma there's an acute angle between the cornea and the iris leading to the iris impeding the drainage of AH.

In the following work, SolidWorks and Ansys fluent are used for the modelling and analysis to assess whether the selected micro-stent is of beneficence to the glaucomic eye or not.

II. Background

In 2017, 0.5% Out of the Egyptian population suffered from glaucoma according to Dr. Ahmed Khalil, Vice president of the Egyptian Association of Glaucoma

Glaucoma's main effect is the deterioration of the optic nerve which is irreversible, unfortunately the disease isn't usually detected during its early stages so medications or even surgeries can prevent the optic nerve damage, but it is rather detected when the disease itself has already progressed the IOP has a strong connection. As the IOP increases past 21 mmHg, the stronger a doctor suspects the presence of glaucoma [5].

After diagnosing a patient with glaucoma, the patient starts a journey to stop further optic nerve deterioration and IOP reduction, via different pathways including oral medications and eye drops, surgery, stents, micro-stents.

Treatment start with eye drops that either reduce AH production rate or open the blocked drainage system. If the drops failed to reduce IOP, laser treatments such as laser trabeculoplasty, cyclophotocoagulation and laser iridotomy can be an option, they are either used to damage ciliary body cells or to open holes in the trabecular meshwork.

In case laser treatment also did not work, a surgical procedure called trabeculectomy is performed to open the trabecular meshwork. If the increase in the intraocular pressure continues, Ahmed valve device can be used to drain excess AH[6][7].

An alternative to Trabeculectomy are micro-invasive glaucoma surgeries (MIGS), these procedures are much less invasive than Trabeculectomy. In MIGS, micro-stents are used to facilitate the drainage of the excess fluid resulting in a net reduction of AH accumulation inside the AC, as well as a reduction in the overall IOP.

An example to these stents is iStent inject, whose model is shown in Fig.4, it bypasses the normal AH pathways through the TM, and right into the SC. It is made from titanium coated with heparin. Indicated to be used with adult patients with mild to moderate primary open angle glaucoma[8].

In a study utilizing patients suffering from early open angle glaucoma and cataract [9], a total of 73 eyes were used where 38 eyes were implanted with the iStent device and 35 were implanted with the iStent inject device. At 6 months after surgery, mean IOP reduced by 26.6% in the eyes with iStent inject and over 70% of eyes in both groups became medication-free by 6 months post-implantation.

III. METHODOLOGY

Data Collection

Normal human eye dimensions were obtained from multiple resources including the human eye atlas [4], as well as studies [11] - [21].

None of the previous published eye models contained all the eye structure dimensions used in our study. Thus, a careful thorough comparison between all studies in the literature was performed to select the most accurate, easy to implement eye structure dimensions. Eye structure dimensions selected in our study are presented in table 1.

Tools

A computer with an octa core CPU with 1.80 GHz and 1.99 GHz, a RAM of 12.0 GB in addition to an SSD drive, was used as the main unit for the modelling, as well as the all the analysis on both SolidWorks and Ansys Fluent.

SolidWorks 2019 was used for all 3D modelling purposes including:

- Eye model.
- TM, SC, CC modelling
- iStent inject – stent modelling

Ansys Fluent 2019 R3 and all its sub-tools were used for:

- Flow volume creation
- Mesh generation for flow analytics
- Material properties assigning
- Flow properties analysis
- Mesh generation for structural analytics
- Structural analysis

Eye Model

The human eye was modeled as the first step in this study. An attempt to create an eye model from OCTs was proposed, yet the tissues being focused on in our study are the TM, SC, CC which are extremely small compartments. No scanning technique can segment these structures, thus preventing us from modeling them realistically. Alternatively, 3D modelling of the eye from anatomical data was the best fit.

Eye models' presence on the internet is extremely rare, and if found these are made for educational purposes only, thus several important structures aren't present.

Even though the outer structure of the eye model used in this study was downloaded off the internet, major modifications in the structure sizes were performed to match the actual dimensions of the human eye. SolidWorks was used for the creation and addition of structures such as the TM, SC, CC as shown in Fig.1, as well as the gaps in which they fit in the eye as shown in Fig.2

Stent Model

The iStent inject is the second generation of Glaukos trabecular micro-bypass stents and was FDA approved in 2018. It consists of 3 parts:1. the head that is almost conical in shape with 4 holes on the sides and 1 at the top, 2. the thorax, which was modeled as a cylinder, 3. the flange was modeled as a cylinder with inner radius equivalent to the radius of the thorax to fit them together and finally, all 3 parts are combined in an assembly file to create the final iStent inject model shown in Fig.3

Combing the edited eye model with the TM, SC, CC with the stent model, inserting 2 stents 30° apart from each other yielded the final model shown in Fig.4

Table I: Eye Model Dimensions

Eye part	Our model	Literature value
Eye globe diameter (mm)	20	24 [13],[14]
AC diameter (mm)	13	12 [11]
AC Depth (mm)	2.3	3.2 [11]
Iris thickness (mm)	0.65	0.5 [13]
Distance between iris and lens (mm)	1.6	0.12 [11]
Lens length (mm)	7	8.75 [11]
Lens width (mm)	3.7	3.5 [11]
Sclera thickness (mm)	1	1 [16]
Cornea thickness (mm)	1	0.78 [15]
Cornea radius (mm)	6	5.5 [12]
Ciliary body hight (mm)	0.8	1 [13]
Max Thickness of trabecular meshwork (μm)	130	132 [16]
Schlem's canal thickness (μm)	280	300 [19]
Schlem's canal hight (μm)	28	25 [19]
No. of collector channels	30	30 [18]
Length of collector channels (μm)	230	260 [21]
Diameter of collector channels (μm)	52	52 [21]

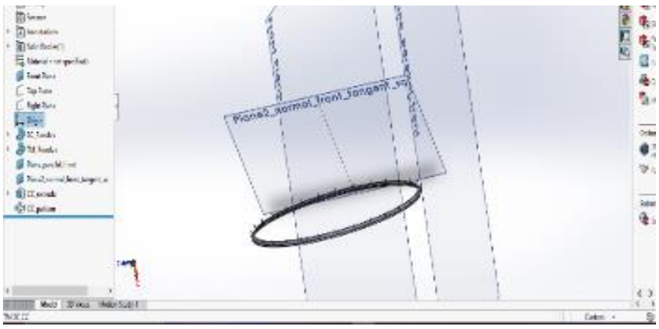

Figure 1 : The TM, SC, CC models

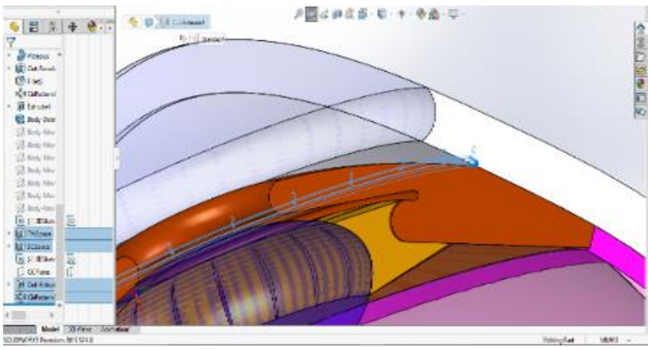

Figure 2 : The 3D model openings

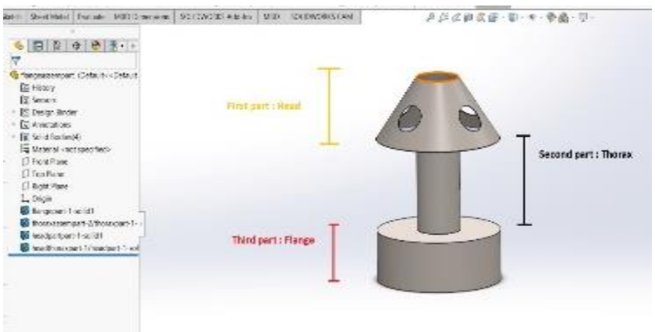

Figure 3: iStent inject model

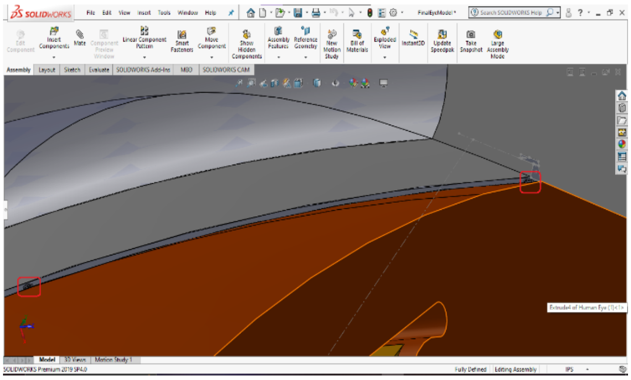

Figure 4: The final eye model with the inserted stents. Stents positioned in the red boxes

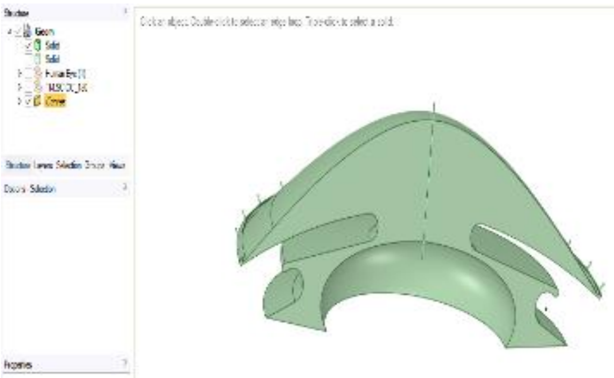

Figure 3 : Flow volume

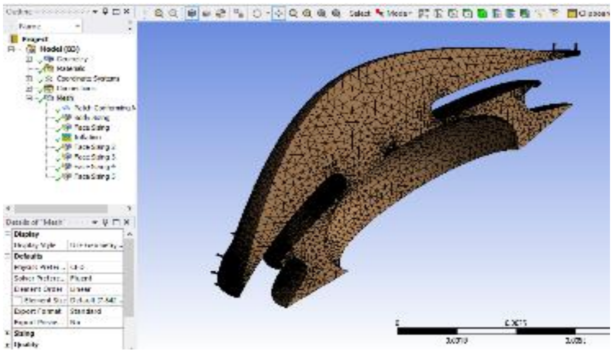

Figure 4 : Meshed eye model

Table 2: mesh characteristics

Body element size (m)	Skewness (max)	Orthogonal quality (min)	Aspect ratio (max)	Inflation layers no.
2e-4	0.91904	8.0957e-2	9.5021	12

Flow volume

The flow volume was created using Ansys Workbench by filling the space where the AH will flow from where it is secreted in the ciliary body all the way up to the TM, the flow volume is shown in Fig.5.

Meshing

Meshing is the step where the solid body is converted into small elements as depicted in Fig.6. Approximately 40 trials [10] have been conducted till the best mesh was achieved with the characteristics shown in table.2

Material properties assignment

Material properties for each structure was assigned according to the literature[11] - [22] . During setting up the mesh and naming the parts of interest, the material properties for TM porosity, inlet flow rate, pressure, and velocity, AH viscosity and density, and outlet pressure are assigned.

IV. RESULTS AND DISCUSSION

The velocity streamlines are depicted in Fig.7 while the pressure contours are shown in Fig.8. The results for the fluid analysis, show resemblance to those expected for the normal eye, with high velocities in extremely curved or narrow spaces and lower velocities near wider spaces. As for the pressure contours, the pressure values are high near the inlet face and the values decreases as the fluid passes through wider spaces as illustrated.

The fluid analysis yields pressure values just as it does yield pressure contour vectors, these values are distributed and mapped on the model as shown in Fig.9.

The wall shear stresses on various parts of the flow volume are then calculated through the static structural analysis and are displayed in Fig.10.

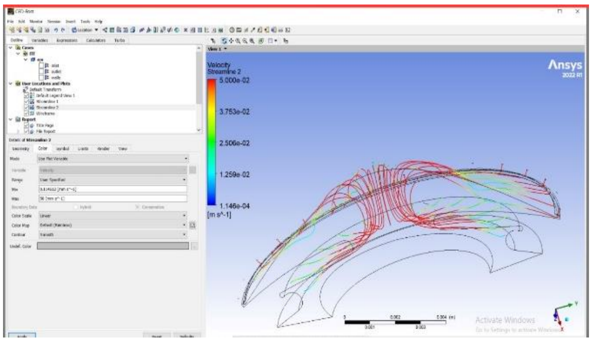

Figure 5 : The velocity streamlines in a cross section of the eye

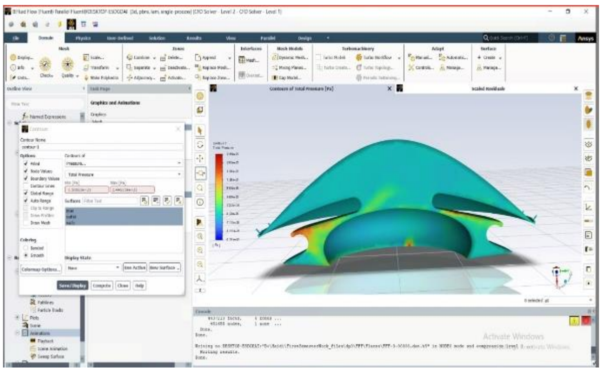

Figure 6 : The pressure contours in a cross section of the eye

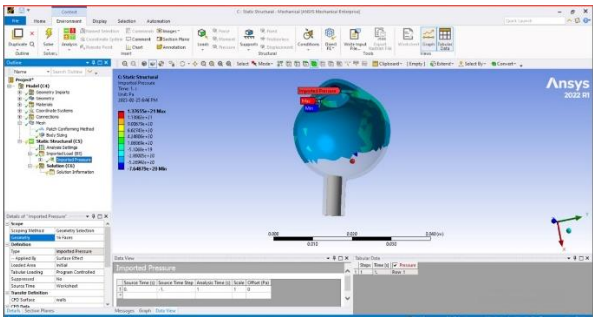

Figure 7 : The pressure distribution from the fluid analysis

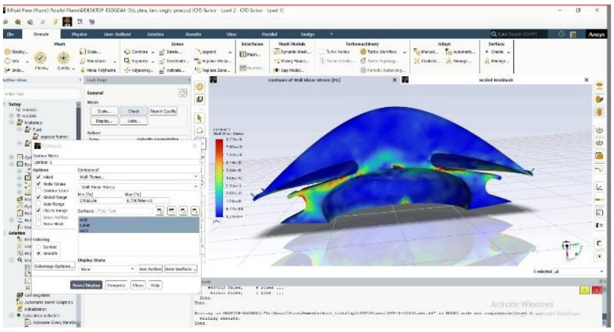

Figure 10: The wall shear stresses from the structural analysis

V. CONCLUSION

Three-dimensional model of the eye with essential structures as well as advanced structures such as the TM, SC, CC was created to study the effects of the increase of IOP due to presence of glaucoma. A flow volume representing the volume where the AH exists was also created to conduct the fluid analysis which yielded results resembling the actual flow in the eye thus indicating the success of the modelling process and the fluid analysis. In addition, the static structural analysis computed the wall shear stresses in the eye. Results showed that the velocity of the AH increases as structures become tortuous or when the space where they move gets narrower suggesting that as the TM collapses in glaucomatous eyes, the velocity will increase, thus causing the pressure to increase significantly.

VI. FUTURE WORK

The fluid as well as the structural analysis are to be repeated for the glaucomatous eye. Afterwards, the effects of glaucoma on the retina and optic nerve deteriorations are to be analyzed and studied.

The other line of work to be followed at the same time is the stent insertion effects analysis. Various modifications to the stent design such as the material from which it is made, the number of stents to be injected into the TM, as well as the dimensions of the different parts composing the stent are to be optimized and analyzed to find best stent design for glaucoma treatment. In addition, the design and 3D printing of a new TM structure may be the basis for a new era in glaucoma treatment.

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