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Modeling and Simulation of Human Cornea for the Measurement of Intraocular Pressure (IOP) through Eyelid

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Abstract: This article describes a study based on the use of an instrumented form of applanation and indentation tonometry through eyelid. The methods and devices which are available for the measurement of intraocular pressure (IOP) have their own limitations. These cause discomfort to the patients during IOP measurement. Also these methods, used to measure IOP over cornea, need anesthesia. In the present work, an attempt is made to develop a device for the measurement of IOP through eyelid which eliminates the need of anesthesia and enhance the patient's comfort and convenience of the clinician. To represent the results of proposed technique, the human eye modeled with cornea, sclera and also with the eyelid, is used. Furthermore, simulation results of stress values for the range of IOP i.e. 5-40 mm of Hg are presented and discussed comparatively with eyelid and without eyelid i.e. directly 'on cornea' methods.

Keywords: Glaucoma, cornea, sclera, eyelid, intraocular pressure, tonometry.

1 Introduction

The glaucoma has remained the challenging entity in the field of 'eye problems' even today, in spite of all sorts of advances in diagnostics as well as therapeutic modalities have come up. In the developing countries like India, the management of health problems in masses is still attracting issue. Due to this and due to, dearth of expertise in this field, as well as compromising economic conditions in India, the simple, economical devices to meet the demands gained their own importance. In view of this, the attempt of this study enlightened me to proceed. A new technique is proposed to measure intraocular pressure (IOP) through the eyelid. The main advantage offered by this method is the increase in patient's comfort and prevention of corneal infection [Chiu (2005); Piletskii (1998); Nakai, Nagaoka, Yoshizawa et al. (2004)]. In this paper conceptual model of a device for the measurement of IOP through the eyelid is proposed. The modeling and simulation results are presented and discussed subsequently.

The anterior segment of the eye is filled with a clear fluid called aqueous humor (AH). It

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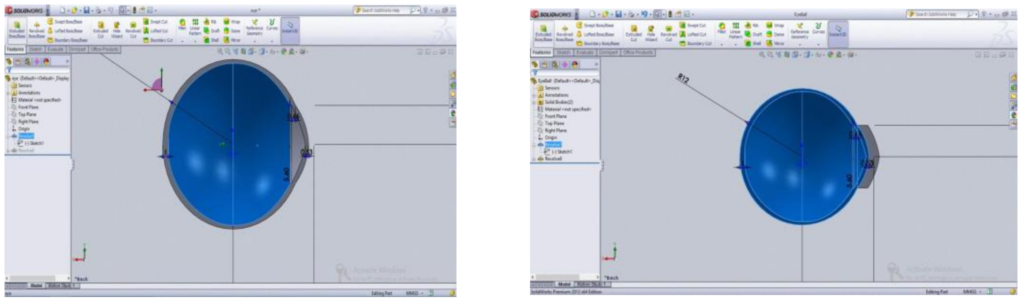
is produced in the posterior chamber in the ciliary body at the rate of 2-3 ul/min. Glaucoma occurs due to the resistance to the aqueous humor out flow, which in turn leads to an increase of IOP [Villamarin, Roy, Hasballa et al. (2012); Ju, Wang, Xie et al. (2005); Pinar-Sueiro, Rodriguez-Puertas and Vecino (2011)]. IOP levels cannot be used to describe glaucomatous pathology fully, but at the same time, its relevance in managing patients with glaucoma should not be underestimated. Out of the various risk factors, known such as age, race, family history, central corneal thickness, ocular perfusion, diabetes and genetics etc., IOP is the only modifiable risk factor [Davey, Nouri and Zaczyk (2013)]. Glaucoma is a progressive disease and can lead to optic nerve neuropathy which damages optic nerve if untreated for a long time [Hitchings (2009)]. Progressive retinal ganglion cell death and visual field loss are associated with it hence it is considered as second leading cause of blindness in the whole world [Ferreira, de Oliveira, da silva et al. (2013); Terminology and Guidelines for Glaucoma, European Glaucoma Society, 4th edition (2016)]. Tonometry is IOP measurement that is most commonly performed on the cornea. It is mainly used to determine the IOP of the eye and diagnose the diseases such as glaucoma [Terminology and Guidelines for Glaucoma, European Glaucoma Society, 4th edition (2016); Polyvas, Peyman and Enikov (2013)].

According to the survey conducted by World Health Organization, the number of glaucomatous patients will increase to 80 million people worldwide by 2020 [Auvray, Rousseau, Lissorgues et al. (2012)]. Meena et al. [Chakrabarti, John and Chakrabarti (2009)] described the evolution of tonometry and the different tonometry principles used in various tonometers since last two centuries [Singh (2014); Yves and Robert (2007)]. Goldmann applanation tonometry (GAT) represents today the reference standard for assessing IOP [Lomoriello, Lombordo, Tranchina et al. (2011)]. Although it is treated as a reference standard there are some inaccuracies in IOP interpretation [Davey, Nouri and Zaczyk (2013); Lomoriello, Lombordo, Tranchina et al. (2011)]. Recent studies showed that IOP varies throughout the day. Steps involved in measurement of IOP by GAT require a skilled technician or expertise of Ophthalmologist [Karani, Tan, Xiong et al. (2014)]. Steve et al. [Liang, Lee and Shields (2009)] explored the need of monitoring IOP and self-tonometry in management of glaucoma. Furthermore, the pressure phosphene tonometer, Ocuton s tonometer and tonopen used in self-assessment of IOP were explained. Presently another method is developed for measurement of IOP by the effect of piezoelectric bimorphs [Tong, Yue and Xia (2012)]. Patrick et al. [Dubois, Zemmouri, Rouland et al. (2007)] invented a new device to measure IOP in which vibrometry by laser interferometry and spectral analysis of mechanical impulse using temporal micro hammer, was used. Peter et al. [Polyvas, Peyman and Enikov (2013)] presented a novel trans-scleral tonometer based on digital palpation tonometry. Dikin et al. [Dikin, Ivanyschev, Kornev et al. (2013)] developed a dynamic tonometer for measuring IOP. It was based on the monitoring of the oscillation period of the dynamic system of tonometer elements and the eye.

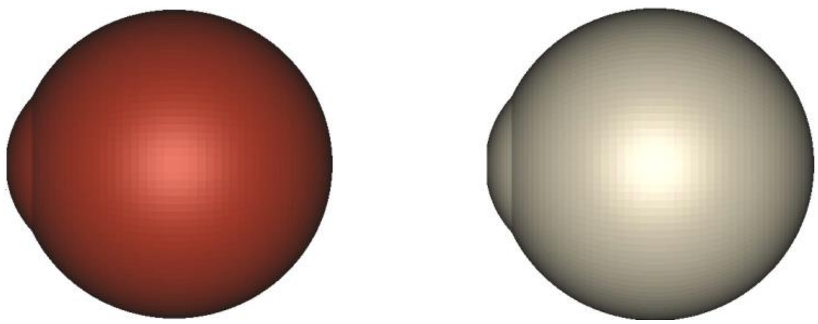
2 Methods and materials

While modeling the human eye, the structure of the eye is considered to be almost spherical. The sclera and the cornea are treated as the main parts of the eye [Bocskai (2009)]. For constructing the model of human eye, varying thickness of sclera was introduced by referring non uniform geometry of the human eye [Woo, Kobayashi and Lawrence (1972); Liu and Roberts (2005)]. To build the model of human eye Solid works v15 was used (Fig. 1 and Fig. 2).



(a) (b)

Figure 1: 2D model of eye created in Solid work v15 (a) without eyelid, (b) with Eyelid



(a) (b)

Figure 2: Solid model of human eye (a) Model representing normal cornea (b) Model representing the applanated cornea

After modeling the human eye in Solid works v15 the models were converted into Standard Tesselation Language (STL) format. The STL file of human eye was imported in to the Catalyst Ex, pre-processing software to link with RP machine. This STL file was then sent to RP machine (uPrint SE, Stratasys Inc., Ontario, CA, USA) to get the acrylonitrile butadiene styrene (ABS) model of the human eye using fused deposition modeling (FDM) method. The prototypes of the complete eyeball with sclera and cornea were developed and section of eyeball too. Another prototype was developed for human eye with eyelid and applanated stage of cornea shown in Fig. 3. As per the expert Ophthalmologist, geometry and sizes were finalized. Finally using Finite Element Analysis mechanical behavior of cornea had been checked.

Figure 3: Prototypes of sclera and cornea

2.1 Indentation depth

Eye patients were examined for the screening of glaucoma using Schiotz tomometry in rural and remote settings [Kok, Berendschot and Hardus (1998)]. In schiotz's tonometry measurement of IOP is made by finding out the indentation depth and the weight applied on the foot plate. Indentation and applanation principles are used in the present study to find out IOP. The measurement of the indentation depth for applanation of cornea was the primary interest. The indentation depth was calculated for the cornea with and without eyelid. Robert [Moses (1971)] had represented the empirical calibration of schiotz's tonometer, the maximum plunger weight being taken as 15 gm.

So the total force exerted on the corneal surface, FC=0.15+0.11=0.26 N

The Normal range for IOP is 16~21 mm of Hg. So, 21 mmHg was taken as the known IOP value for calculation.

$$r_T = \sqrt{(\frac{F_C}{\pi P_t})}$$

Where, Fc force exerted on corneal surface, Pt is the known IOP value and r_T half of the cord.

So, r_T=5.44 mm

Similarly,

$$r_I = \sqrt{(\frac{F_P}{\pi.P_t})} = 4.129\text{mm}$$

Where, r_I is radius of the plunger indentation and F_P applanation force

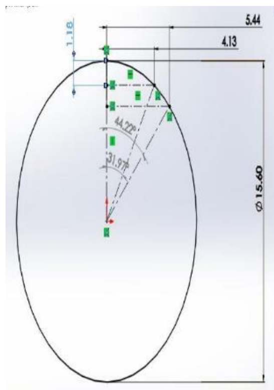
The relation between Radius and Arc Length is given by,

A= r×θ

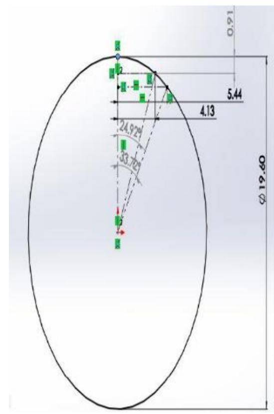
Where A is the Arc length, r is the Radius and θ is the sector angle.

By using solid works v15, the sector angles for the radius r_T and r_I were found out.

Θ_T=44.22 degrees or 0.7717 radian
Θ_I=31.97 degrees or 0.5579 radian



(a)



(b)

Figure 4: Measurement of h_1 (a) without eyelid (b) with eyelid

Arc radius, A_T=6.082 mm

Arc length, A_I=4.396 mm

Slant height of the cone frustum formed by the plunger indentation,

$S=C-p-A_T+A_I$

Where, S is surface tension, p radius of plunger base, A_T arc length corresponding to arc F_T, A_I arc length corresponding to arc F_I.

In this case corneal arc, C=A_T

So, $S=-p+A_I$

Slant Height, S=-1.53+4.396=2.866 mm

$l_2=r_I-p$

l_2=4.129-1.53=2.599 mm

And,

$$l_1 = \sqrt{s^2 - l_2^2} = 1.207mm$$

Where, l_1 and l_2 are sides of right angle triangle Sl_1l_2 shown in Fig. 4 (a).

In this case, h_2=0 and $h_1$is found from the Fig. 4 (a)

And, h_1=1.18 mm

Where, h1 is the height of foot plate arc, h_2 height of concavity.

So, the Indentation Depth, $I_C=h_1+l_1$=1.18+1.207=2.387 mm

If IOP is to measure over the eyelid, Indentation depth can be similarly found out using Fig. 4 (b). Considering the average thickness of the eyelid as approximately 2 mm,

h_1=0.91 mm (From Fig. 4 (b))

$$l_1 = \sqrt{s^2 - l_2^2} = 0.839mm$$

So, the Indentation Depth, $IE=h1+l1$=0.91+0.839=1.749 mm

The total indentation depth over the eye lid is $IC+IE$=4.136 mm

2.2 Development of device

A conceptual model of the device to measure the IOP through eyelid is shown in Fig. 5. For construction of the model Solid work v15 was used. Fig. 5 shows a sectional view of the device which comprises an outer casing, the plunger attached with a rod and a compression spring. The plunger is modeled with a flat circular cross section of a constant diameter of 3.06 mm [Terminology and Guidelines for Glaucoma, European Glaucoma Society, 4th edition (2016)]. A mass spring model of the cornea was developed to investigate the factors influencing corneal shape. Change in cornea shape was computed respectively with finite element model, mass spring model and finally IOP and external pressure were simulated [Xie, Wang, Ju et al. (2008)]. Venketesh et al. [Sathyanarayanan, Mahadas and Hung (2013)] developed a homeomorphic model of the human eye wherein mass-spring-damper (MSD) model was used to investigate forces and displacement throughout. In the proposed model of our device, the applanation pressure required to flatten the cornea, can be calculated by using the stiffness and the displacement of the compression spring used. The indentation depth can be recorded by the displacement of the plunger. The spring used has wire diameter 0.25 mm, no. of coils 15, pitch 1 mm and stiffness of the spring 0.05178 N/mm [Shigely and Mischke (2006)].

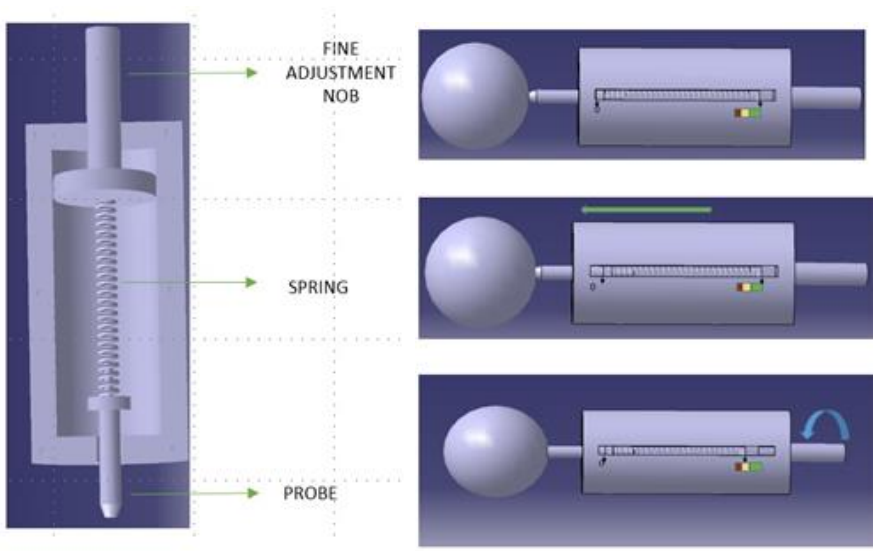


Figure 5: CAD model of the proposed device

2.3 Finite element analysis

A linear Finite Element (FE) analysis was carried out using ANSYS 15.0 workbench. The values of IOP for cornea with and without eyelid have evaluated. The normal range of IOP is 16-21 mm of Hg, above 21 mm of Hg is treated as elevated IOP. Therefore, for analysis the range of IOP was selected 5-40 mm of Hg [Nakai, Nagaoka, Yoshizawa et al. (2004); Tong, Yue and Xia (2012)]. For assessing mechanical behavior of cornea finite element method (FEM) had been used [Nejad, Foster and Gongal (2014)]. The eyeball, which is bounded by thin shell, is considered almost spherical in shape [Bauer, Lyubimov and Tovstik (2005)]. It consists of two parts, sclera and cornea with different mechanical properties [Esposito, Clemente, Bonora et al. (2015); Xing and Wei (2014)].

A finite deformation, hyper elastic, orthotropic material model based on CAD models, having 3357 nodes and 1735 elements were developed. The eye models were imported in ANSYS as igs format file to reduce data loss. Suitable constraint was applied on the eye model by fixing the sclera. The varying thickness of outer shell of the eye was incorporated and the aqueous, vitreous and fatty tissues were modeled similar to soft human tissue [Power, Stitzel, West et al. (2014)].

The material properties, Young's modulus 0.19 Mpa and 98.97 Mpa were used for cornea and eyelid. The mean eyelid pressure on cornea was considered 4.1 mm of Hg and average eyelid thickness was introduced 2 mm [Schutte, van den Bedem, van Keulen et al. (2006); Ljubimova (2009)]. Poisson's ratio used for cornea was 0.420, sclera 0.470 and eyelid 0.4945 [Schutte, van den Bedem, van Keulen et al. (2006); Ljubimova (2009)]. Corneal hysteresis for normal eye of 10.24 and the scleral rigidity ranged from 0.0017-0.0022 was selected [Pierscionek, Asejczyk-widika and Schachar (2007); Deol, Taylor and Radeliffe (2015)]. The different pressures are applied normal to the surface of cornea and eyelid (Fig. 6). Tab. 1 represents the IOP in mm of Hg, Pascal and pressure required to applanate the cornea through eyelid. Tab. 2 represents the indentation depth for different IOPs. The material properties of aluminum alloy and stainless steel were collected from software library.

Pressure exerted on cornea by the eyelid=4.1 mm of Hg or 546.621 Pa

Area of contact, A=7.35 mm^2

Equivalent pressure needed to flatten the cornea over eyelid=$IOP(Pa)$-$Eyelid\ pressure$ (Pa).

So, Force needed to flatten the Cornea over eyelid=Applied Pressure/Area of Contact.

Table 1: Pressure in mmHg and its equivalent in Pascal, also Equivalent pressure required to flatten the cornea through eyelid [Liu and Roberts (2005)]

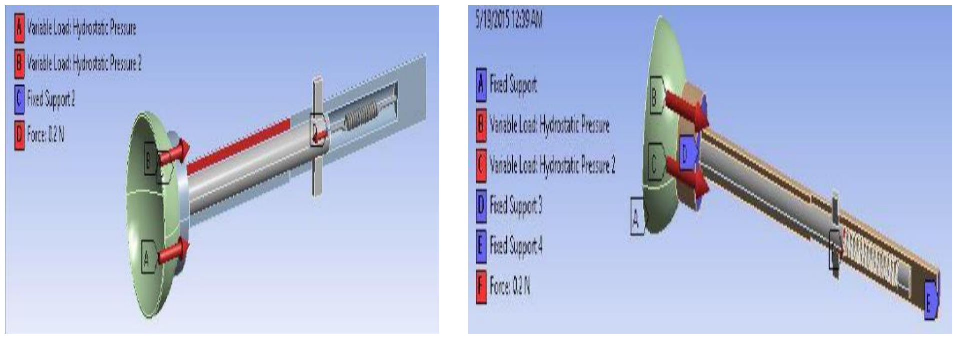
Sr. No.	IOP in mm of Hg	Equivalent Pressure in Pascal	Pressure required for flattening the cornea through eyelid (IOP-eyelid Press) Pa
1	05	666.611	120.040
2	06	799.934	253.313
3	07	933.256	386.635
4	08	1066.578	519.957
5	09	1199.901	653.280

6	10	1333.223	786.602
7	11	1466.545	919.924
8	12	1599.868	1053.247
9	13	1733.190	1186.569
10	14	1866.513	1319.892
11	15	1999.835	1453.214
12	16	2133.157	1586.536
13	17	2266.480	1719.859
14	18	2399.802	1853.181
15	19	2533.124	1986.503
16	20	2666.447	2119.826
17	21	2799.769	2253.148
18	22	2933.091	2386.470
19	23	3066.414	2519.793
20	24	3199.736	2653.115
21	25	3333.059	2786.438
22	26	3466.381	2919.760
23	27	3599.703	3053.082
24	28	3733.026	3186.405
25	29	3866.348	3319.727
26	30	3999.670	3453.049
27	31	4132.993	3586.372
28	32	4266.315	3719.694
29	33	4399.637	3853.016
30	34	4532.960	3986.339
31	35	4666.282	4119.661
32	36	4799.604	4252.983
33	37	4932.927	4386.306
34	38	5066.249	4519.628
35	39	5199.572	4652.951
36	40	5332.894	4786.273

Table 2: IOP and equivalent indentation depth with and without eyelid [Moses (1971)]

Sr. No.	IOP in mm of Hg	Indentation depth, y in mm (without eyelid)	Indentation depth, y in mm (with eyelid)
1	05	3.54	5.76
2	06	3.46	5.62
3	07	3.38	5.50
4	08	3.30	5.39
5	09	3.23	5.27
6	10	3.15	5.18
7	11	3.08	5.10
8	12	3.00	4.98
9	13	2.93	4.84
10	14	2.85	4.72
11	15	2.78	4.60
12	16	2.70	4.52
13	17	2.60	4.46
14	18	2.53	4.32
15	19	2.45	4.20
16	20	2.36	4.08
17	21	2.28	3.94
18	22	2.21	3.82
19	23	2.13	3.68
20	24	2.06	3.56
21	25	1.98	3.44
22	26	1.90	3.30
23	27	1.82	3.18
24	28	1.75	3.06
25	29	1.67	2.92
26	30	1.59	2.80
27	31	1.52	2.66
28	32	1.44	2.56
29	33	1.37	2.42
30	34	1.30	2.30
31	35	1.22	2.16
32	36	1.15	2.04

33	37	1.07	1.90
34	38	0.99	1.78
35	39	0.92	1.64
36	40	0.86	1.52



(a) (b)

Figure 6: Assigning constrain for analysis (a) cornea (b) eyelid

3 Results

Simulation results were obtained for known values of IOP in terms of shear stresses for contact interface between tip of the plunger and human eye. Here the results were obtained for case (1) cornea without eyelid (2) cornea with eyelid. From previous studies it has been found that the normal range of IOP is between 16-21 mm of Hg. For discussing simulation results elevated range of IOP 27 mm of Hg was considered.

3.1 Without eyelid

In this case the simulation results were obtained by applying a force on cornea. The model of human eye and the device constructed were used for analysis purpose. The value of IOP 27 mm of Hg was taken for sample calculation. First the simulation result was obtained for indentation depth of 2.39 mm and for indentation depth of 1.82 mm i.e. corresponding to 27 mm of Hg. The shear force on the contact surface was found out to be 3599.73 Pa. and 3483.3 Pa. respectively. Similarly, shear stress value was calculated for the range of IOP 5-40 mm of Hg with constant indentation depth and variable depth for IOP. The results are shown in Tab. 3.

Table 3: IOP and corresponding shear stress value got from simulation (variable and const. depth)

Sr. No.	IOP (mm of Hg)	Indentation depth (mm)	Shear Stress (Pa)	Indentation depth (mm)	Shear Stress (pa)
1	05	3.54	644.62	2.39	667.72
2	06	3.46	773.54	2.39	794.46

3	07	3.38	902.46	2.39	930.20
4	08	3.30	1031.39	2.39	1061.95
5	09	3.23	1160.31	2.39	1203.69
6	10	3.15	1289.34	2.39	1332.44
7	11	3.08	1418.16	2.39	1471.18
8	12	3.00	1547.08	2.39	1596.92
9	13	2.93	1676.01	2.39	1730.67
10	14	2.85	1804.93	2.39	1863.41
11	15	2.78	1933.86	2.39	2006.16
12	16	2.70	2062.78	2.39	2130.90
13	17	2.60	2191.70	2.39	2273.64
14	18	2.53	2320.63	2.39	2400.69
15	19	2.45	2449.55	2.39	2541.13
16	20	2.36	2578.48	2.39	2664.88
17	21	2.28	2704.40	2.39	2800.62
18	22	2.21	2844.24	2.39	2942.36
19	23	2.13	2965.25	2.39	3070.11
20	24	2.06	3094.17	2.39	3209.85
21	25	1.98	3223.1	2.39	3343.60
22	26	1.90	3351.9	2.39	3501.10
23	27	1.82	3483.3	2.39	3641.60
24	28	1.75	3609.8	2.39	3770.30
25	29	1.67	3738	2.39	3905.10
26	30	1.59	3867.72	2.39	4012.32
27	31	1.52	3996.64	2.39	4138.06
28	32	1.44	4125.56	2.39	4270.80
29	33	1.37	4254.49	2.39	4413.55
30	34	1.30	4383.41	2.39	4540.29
31	35	1.22	4521.34	2.39	4681.04
32	36	1.15	4641.26	2.39	4804.78
33	37	1.07	4770.18	2.39	4948.52
34	38	0.99	4899.11	2.39	5082.27
35	39	0.92	5028.03	2.39	5206.01
36	40	0.86	5156.96	2.39	5339.76

3.2 With eyelid

In this case the simulation results were obtained by applying a force on eyelid instead of cornea. This method differs than the various tonometry principles and techniques. The model of human eye built with an eyelid was used for analysis purpose. Here also the same value of IOP i.e. 27 mm of Hg was taken for sample calculation. Simulation was first done for indentation depth of 4.2 mm and for the indentation depth of 3.18 mm corresponding to 27 mm of Hg. Simulation was done and the shear force on the contact surface was found out to be 3055.8 Pa and 2717.6 Pa respectively. Similarly, the values of shear stress found are shown in Tab. 4.

Table 4: IOP and corresponding shear stress value got from simulation (variable and const. depth)

Sr. No.	IOP (mm of Hg)	Indentation depth (mm)	Shear Stress (Pa)	Indentation depth (mm)	Shear Stress (pa)
1	05	5.76	535.94	4.2	584.62
2	06	5.62	615.92	4.2	701.54
3	07	5.50	725.91	4.2	818.44
4	08	5.39	830.90	4.2	945.39
5	09	5.27	912.89	4.2	1052.32
6	10	5.18	1028.88	4.2	1189.24
7	11	5.10	1142.86	4.2	1286.16
8	12	4.98	1199.85	4.2	1403.08
9	13	4.84	1340.84	4.2	1560.01
10	14	4.72	1449.83	4.2	1666.93
11	15	4.60	1537.82	4.2	1753.86
12	16	4.52	1643.80	4.2	1913.78
13	17	4.46	1743.79	4.2	2015.70
14	18	4.32	1799.78	4.2	2104.63
15	19	4.20	1899.77	4.2	2221.55
16	20	4.08	2039.76	4.2	2338.48
17	21	3.94	2136.74	4.2	2555.40
18	22	3.82	2236.73	4.2	2672.32
19	23	3.68	2299.72	4.2	2797.25
20	24	3.56	2399.71	4.2	2966.17
21	25	3.44	2499.7	4.2	3096.10
22	26	3.30	2540.7	4.2	3246.64
23	27	3.18	2717.6	4.2	3353.80

24	28	3.06	2781.1	4.2	3486.80
25	29	2.92	2880.4	4.2	3527.70
26	30	2.80	2999.64	4.2	3757.72
27	31	2.66	3127.62	4.2	3896.64
28	32	2.56	3243.61	4.2	4029.56
29	33	2.42	3329.60	4.2	4168.49
30	34	2.30	3439.59	4.2	4297.41
31	35	2.16	3547.58	4.2	4452.34
32	36	2.04	3599.56	4.2	4559.26
33	37	1.90	3699.55	4.2	4696.18
34	38	1.78	3799.54	4.2	4836.11
35	39	1.64	3899.53	4.2	4962.03
36	40	1.52	4127.52	4.2	5096.96

4 Discussion

The work represented shows the simulation and analysis of constructed mechanical device over the human eye model. Initially a virtual model of the IOP measuring device was constructed. During simulation the shear force on the contact surface of the device was recorded in both the cases. Then the results were compared with the given IOP values which are represented in Fig. 7 and Fig. 8. In Tab. 1, the equivalent shear stress values are presented to applanate the cornea, since, closed eyelid itself exerts some pressure on cornea. Therefore, the pressure required to applanate the cornea through eyelid is less than that required to flatten the cornea directly (2.3).

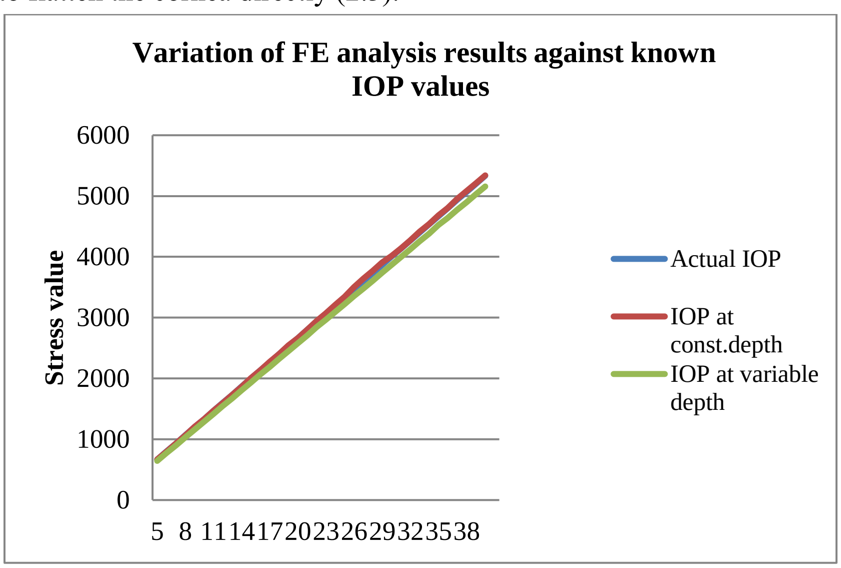


Figure 7: Variation of FE analysis results against known IOP values

The Fig. 7 and Fig. 8 show the comparison of the shear stress value obtained after simulation for various indentation depths with mathematically calculated stress values. It has been observed that the results were more accurate when the simulation was done only on the cornea. The graphs were much closer to the input IOP curve with the average percentage error of 1.15%. But for the other case (with eyelid) the results were not much accurate to the known IOP values. Hence the graph for the same is not much closer to the input IOP curve, the average percentage error was found to be 4.41%. Stress values obtained by simulation with eyelid are slightly higher than theoretical values for constant indentation depth due to intervention of eyelid over cornea.

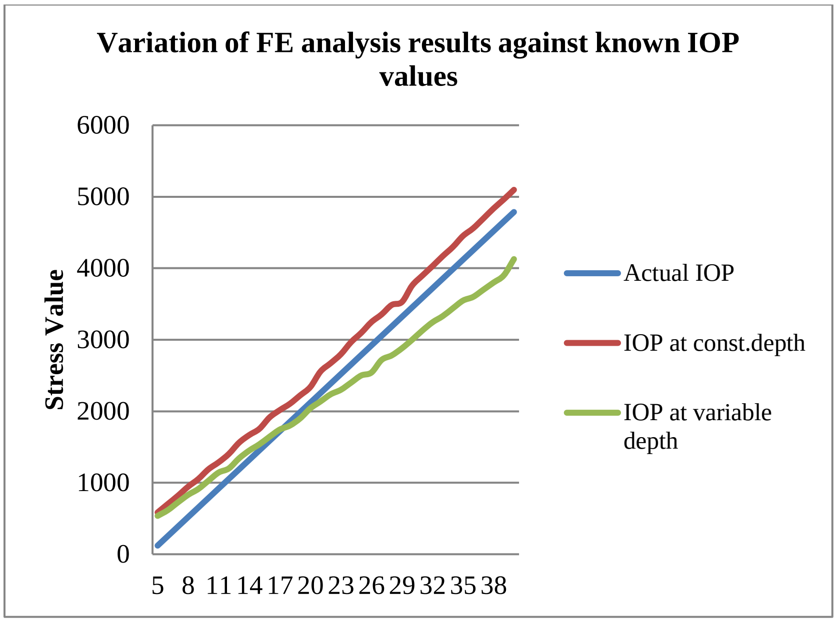


Figure 8: Variation of FE analysis results against known IOP values (with eyelid)

It has been observed that, the inaccuracy of the result may be due to some deficiency in the simulation environment because of neglecting the flows in anterior chamber and humor properties. The IOP measurement over the corneal surface is more accurate than the IOP measurement over eyelid surface. This may be due to the cornea and eyelid is modeled as soft tissues but in fact the eyelid pressure and properties differ. The compression spring used in the device for the measurement of force value may not be capable to measure very small changes in the pressure.

5 Conclusion

The FE results are found to be more precise and accurate for constant indentation depth. Also the error found in FEM results while measuring IOP through eyelid is small which represents the feasibility of further study with some advancement. For the further development of the device used to measure the IOP through eyelid, the indentation depth can be maintained constant throughout so that accurate measurement of IOP can be obtained. The proper calibration of the model can predict IOP more accurately.

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