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Influence of glistening and calcium deposits in artificial intraocular lenses on retinal image quality – numerical model

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In modern ophthalmology the natural eye lens is sometimes replaced with an artificial implant – intraocular lens which remains in the eye for a long time. This can lead to the formation of numerous microdefects occurring on the intraocular lens surface or inside its volume. The most common include calcium deposits or microvacuoles referred to as glistenings. The presence of those defects causes deterioration of retinal image thus lowering the quality of vision. The purpose of this research is to develop a numerical model of human eye with intraocular lens burden with defects useful to predict the impact of calcium deposits and glistenings on the retinal image quality. The calculations made in accordance with this model suggest that the quality of retinal image deteriorates when the density of defects increases, but the degree of image deterioration does not depend on the location of the defects and transmittance of individual particles. The main deterioration effect is observed for low spatial frequencies (< 12 cycles/deg) both in case of calcium deposits and glistenings while for the spatial frequency of 30 cycles/deg the changes in modulation transfer function are insignificant. The presence of microvacuoles in the intraocular lens influences the worsening of modulation transfer function parameters only for the diameter of microvacuoles greater than 10 μm.

Keywords: intraocular lens (IOL), glistenings, modulation transfer function (MTF), calcium deposits.

1. Introduction

Today, cataract is one of the most frequent reasons of blindness all around the world. The disease causes opacification of the crystalline lens which seriously deteriorates vision quality. The only available method to restore the clarity of optical structures of the eye is surgery. Surgical procedure includes removal of the opaque crystalline lens and implantation of an artificial intraocular lens (IOL) in its place. IOLs are implanted permanently, which means in practice the stay of the IOL inside the eye for many years. Being inside an eye for a long time artificial lenses are continuously in contact with aqueous humor containing various chemical compounds such as bicarbonates, lactic acid, ascorbic acid, chlorides, glucose [1]. The environment in which the lens implant resides may be therefore considered aggressive and inducing various aging processes. Several authors investigated the time-related changes taking place in the IOLs. The most common changes include formation of various types of deposits and sediments occurring on the lens surface and in its volume. Numerous researchers indicate that distribution and density of calcium deposits are not the same for different types of lens materials and designs but in most cases the layers of deposits are similar. Usually they have form of fine, granular calcium deposits (oftentimes the presence of calcium is described as dark brown color in von Kossa stain) distributed paralelly to the anterior and posterior optical surfaces of the IOL, with a clear area below the optical zone [2–6]. The location of calcium deposits varies: in many cases the deposits are observed right below the lens surface [2–4, 6] but they may also be located much deeper in the IOL's volume [6]. The formation of calcium deposits is dependent, among other factors, on the type of lens material, manufacturing methods, packaging conditions, osmolarity of the medium, patient's general health (comorbidities) and intake of medication [7–9].

Structures of similar appearance which are visible on the optical and haptic parts of IOLs are referred to as glistenings. In case of such formations, staining with alizarin red or using the von Kossa method will give negative results. Glistenings are caused by microvacuoles filled with fluid which form in IOLs made of various materials (hydrophobic acryl, hydrogel, silicone and PMMA) [10–13] as a result of contact with aqueous humor [9]. Usually the microvacuoles are distributed in the whole volume of the IOL optical part. The size of vacuoles varies from 1 to 20 μm, while those observed during *in vivo* studies are usually not larger than 10 μm. Larger vacuoles are found in *in vitro* studies when the lenses are immersed in salt solutions and subjected to temperature changes [9]. The severity of changes may vary between cases and may depend on the time elapsed since IOL implantation. Some authors use a scale based on glistenings observation in the slit lamp. The available publications include references to a five-degree Christiansen scale [14] and an alternative Miyata scale [10]. The Miyata scale includes grades from 0 to 3, based on slit lamp observation, where 0 means no signs of microvacuole presence, 1 – up to 50/mm^2; 2 – up to 100/mm^2 and 3 – the highest density (200/mm^2) [10].

An interesting issue is the impact of particular lens defect on the quality of vision. Certain researchers attempted to show the impact of age-related changes in the IOL on visual acuity and contrast sensitivity [9, 15, 16]. It was found that the degree of glistenings is not correlated with patient's visual acuity but it has significant impact on the decrease of contrast sensitivity to high spatial frequencies (> 12 cycles/deg) [15].

The direct investigation of the effects of IOL's damage resulting from the aging on the quality of retinal image using *in vivo* method is not possible. The only possibility is either *in vitro* experimental studies or numerical modeling. The purpose of this research was to develop a numerical model of the IOL with age-related changes useful to predict the impact of calcium deposits and glistening on IOL imaging quality.

2. Method

The main goal of this paper was to develop a numerical model of an eye in which the natural lens was replaced with artificial IOL having such defects caused by aging as calcium deposits and glistenings. The preliminary concept of such model taking into account the glistening phenomenon only was presented by GENIUSZ *et al*. [17]. To build our model, the non-sequential mode in Zemax software (OpticStudio Professional, Zemax Professional from Radiant Zemax, LLC) was used. Retinal imaging quality in the eye with IOL burdened with the defects described above was estimated on the basis of the modulation transfer function (MTF) obtained using standard procedures of the Zemax program enhanced with a module which calculated the scattering of light on the elements simulating defects according to the Mie theory. According to this model, the amount of scattered light depends on the density and size of scattering particles, their transmittance and the difference between the refractive index of the medium and the scattering particles themselves [7].

Parameters referring to refractive surfaces of the eyeball used in this model were based on Atchison's eye model from 2005 [18] in which the natural lens was replaced with an artificial IOL. As an example, the IOL with optical power equal to 21 D made of PMMA was taken (the P359UV Bausch&Lomb IOL). The parameters of the eye model with artificial IOL used in the present paper are specified in Table 1 and illustrated in Fig. 1.

T a b l e 1. Design parameters of the Atchison eye model [18] with the IOL used in the present paper.

Medium	Radius of curvature r [mm]	Asphericity k	Index of refraction n	Thickness d [mm]
Air			1.000	Infinity
	7.77	−0.150		
Cornea			1.376	0.55
	6.40	−0.275		
Aqueous			1.3374	3.16
	15.00	–		
IOL			1.49	1.000
	−15.00	–		
Vitreous			1.336	18.38
	−12.91			
Retina				

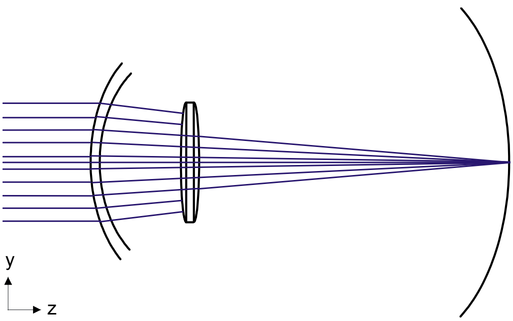

Fig. 1. Schematic eye model with IOL.

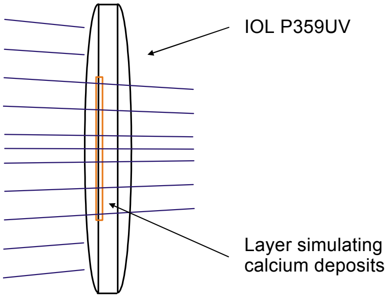

Fig. 2. Model of IOL with calcium deposits.

Different pupil sizes can be taken for calculations. The data presented and discussed in this paper were referred to the pupil diameter equal to 3 mm. This is the average pupil diameter in elderly patients (aged 60 and above) who are most prone to cataracts.

2.1. Calcium deposits

Calcium deposits were simulated as a set of individual spheres of 1 μm diameter randomly distributed along a 50 μm thick flat disc located in anterior part of the IOL at a certain depth below the surface (Fig. 2). The influence of those spheres on the light passage was modeled with Mie type volume scattering. Three parameters were subjected to change, namely: the transmittance t of single scattering particle, the distance x of the deposit layer from posterior lens surface and the density d of particles in the layer volume. The refraction index of the spheres n was set as 1.63 according to GARTAGANIS *et al.* [19].

2.2. Glistenings

To simulate the glistenings, it was assumed that spherical microvacuoles are uniformly distributed in the entire volume of the lens. Different densities d and different diameters D of a single spherical particle were allowed. Refraction index was constant and equal to the refraction index of the aqueous humor in Atchison eye model ($n = 1.3374$). The densities d of spheres in the IOL volume were chosen according to Miyata scale but the 0 degree (no glistenings) was not included into the analysis. The diameter D of a single sphere was varying from 1 up to 50 μm. The impact of glistenings on image quality was modeled as Mie scattering as well.

3. Results

Typically image quality is described with such measure as MTF. However it is difficult to compare two or more such functions as a whole if the changes are subtle. It is more convenient to operate with simple numerical parameters developed on the basis of the MTF. In this paper four such image deterioration parameters are used. They are:

1) MTF_{50} – spatial frequency (in cycles/deg) for which the value of MTF drops to 0.5;

2) MTF(30) – value of MTF at spatial frequency equal to 30 cycles/deg. This value of spatial frequency corresponds to the visual acuity equal to 1 (VA = 20/20) and thus is strongly related to the quality of vision;

3) MTF(8) – value of MTF at spatial frequency equal to 8 cycles/deg. This value of spatial frequency corresponds to maximum of typical contrast sensitivity function;

4) SQRI (square root integral) – area under the curve resulting from multiplication of MTF by scotopic CSF [20]:

$$\mathrm{SQRI} = \frac{1}{\ln(2)}\int_0^{f_{\max}}\sqrt{\mathrm{MTF}(f)\mathrm{CSF}(f)}\,\frac{\mathrm{d}f}{f}$$

The authors' intention was to develop a numerical model of an eye including the IOL with defects appearing due to aging for analysis of the retinal image quality. In order to test the model, the individual parameters describing particular defects were changed separately and the impact of these changes on the image quality was evaluated.

3.1. Calcium deposits

Since the values of transmittance of individual particles creating real calcium deposit layer are not clearly given in the available publications, several values of transmittance t ranging from 0 to 100%[1] were arbitrarily chosen for purposes of this test. Volume density and location of deposit layer were set constant (respectively $d = 50\%$ and $x = 0.25$ mm from anterior lens surface).

T a b l e 2. Numerical parameters characterizing deterioration of the retinal image quality for different transmittances of the scattering particles.

Transmittance t [%]	MTF_{50} [cycles/deg]	MTF(30) [%]	MTF(8) [%]	SQRI [a. u.]
1	18.046	27.11	75.24	4.31
10	18.046	27.11	75.24	4.31
20	18.046	27.11	75.25	4.31
30	18.047	27.11	75.25	4.31
50	18.047	27.11	75.26	4.31
70	18.048	27.11	75.27	4.31
99.9	18.048	27.11	75.28	4.31

Table 2 presents the values of the image deterioration parameters for different transmittances of individual particles composing a simulated calcium deposit. It can be seen that there are no noticeable changes in the image quality related to the transmittance of scattering particles.

The second test was to check whether, in our model, the retinal image quality depends on the depth under the IOL surface where the simulated calcium deposit layer is located. Seven different locations of this layer were taken into account, namely in the distance of $x = 0.015$, 0.03, 0.05, 0.15, 0.25, 0.35 and 0.45 mm from the IOL apex. All layers had 50% density and 30% transmittance (see Table 3). The obtained results suggest that the correlation between the location of the layer and the image deterioration parameters is very weak and in practice not statistically significant ($r = -0.57$ and

[1]For numerical reasons instead of 0% the value of 0.0001% was used, and similarly 99.9% instead of 100%.

Table 3. Numerical parameters characterizing the deterioration of retinal image quality for different locations of the scattering layer.

Depth of scattering layer *x* [mm]	MTF_{50} [cycles/deg]	MTF(30) [%]	MTF(8) [%]	SQRI [a. u.]
0.015	18.05	30.28	75.49	4.31
0.03	18.10	27.21	75.52	4.32
0.05	17.97	27.27	75.20	4.31
0.15	18.03	27.02	75.38	4.31
0.25	18.05	27.11	75.25	4.31
0.35	18.04	27.05	75.36	4.31
0.45	17.98	26.90	75.35	4.31

Table 4. Numerical parameters characterizing the deterioration of retinal image quality for different density of the scattering particles.

Density *d* [%]	MTF_{50} [cycles/deg]	MTF(30) [%]	MTF(8) [%]	SQRI [a. u.]
10	19.69	29.61	82.28	4.50
30	18.86	28.30	78.85	4.41
50	18,05	27.11	75.25	4.31
70	17.09	26.03	72.24	4.22
90	16.32	24.88	69.14	4.13

$p = 0.25$ for MTF_{50}, $r = -0.42$ and $p = 0.35$ for MTF(30), and $r = -0.40$ and $p = 0.36$ for MTF(8)).

Further numerical estimations showed that the most important parameter characterizing the modeled calcium layer is density *d* of scattering particles. The image deterioration parameters calculated for the deposit layer of 30% transmittance and located $x = 0.25$ mm from the IOL surface are shown in Table 4. The correlation between density of scattering particles and image deterioration parameters is high and statistically significant ($r > 0.96, p < 0.005$ for each case). This dependence can be also

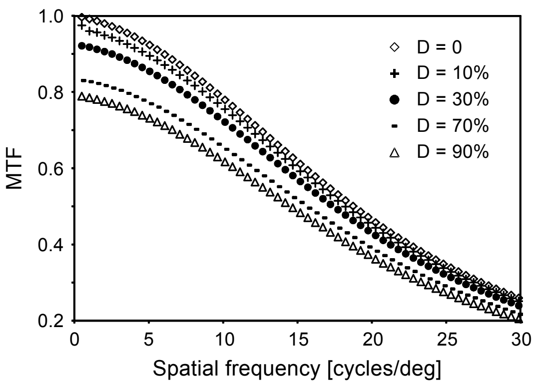

Fig. 3. Modulation transfer function for different density *d* of scattering particles.

deduced from the course of the MTF curves presented in Fig. 3. It is clearly seen that the higher the density of the simulated layer, the lower the image quality.

3.2. Glistenings

In the case of glistenings, the density of scattering particles was expected to be the most important parameter. Therefore the retinal image was evaluated for the densities of scat-

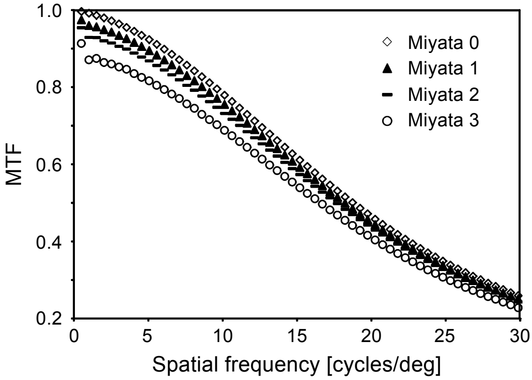

Fig. 4. Modulation transfer function for four degrees of glistening density according to Miyata scale.

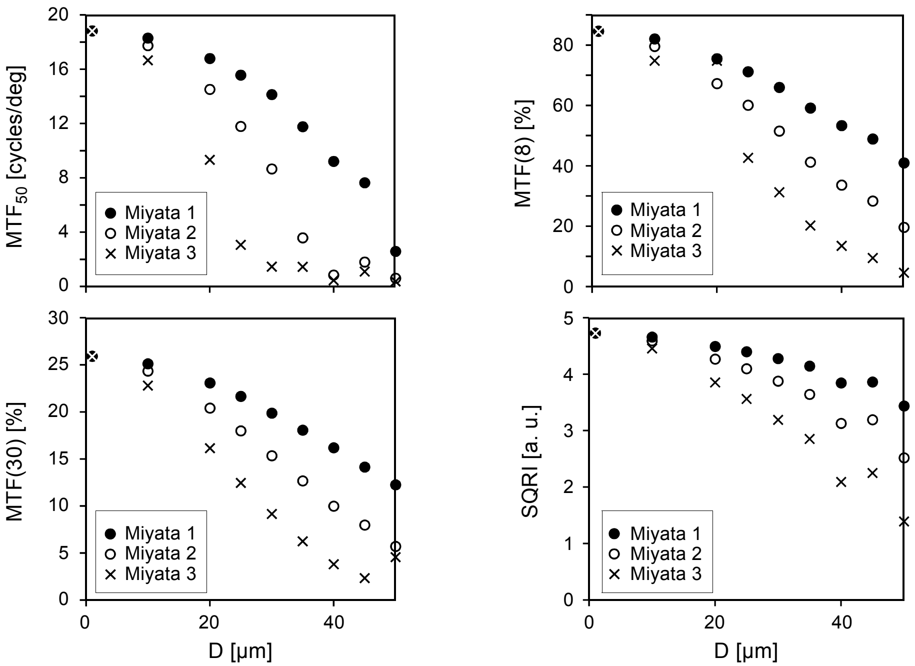

Fig. 5. Relation between retinal image deterioration parameters and diameter *D* of scattering particles for three degrees of density according to Miyata scale.

tering particles corresponding to four Miyata scale degrees. Figure 4 presents the respective MTF curves. It can be seen that the image quality falls down with the increase of simulated scattering particles density (*i.e.*, degree of glistenings according to Miyata scale).

In further tests, the changes in scattering particles diameter was added. Figure 5 presents the changes in image deterioration parameters depending on particles diameter *D* for three degrees of density according to Miyata scale.

It is seen that the higher the density of simulated glistenings, the lower image quality. This effect can be also observed in Fig. 6 where the value of abovementioned image quality parameters is presented in dependence on individual scattering particles diameter *D* for three degrees of density according to Miyata scale.

4. Discussion

The presented model of both phenomena: glistening and calcium deposits showed the dependence of the retinal image quality on the microvacuoles density. Unfortunately, this result cannot be verified experimentally because it is not possible to produce the IOL with vacuoles of precisely determined diameter. From the developed model, it fol-

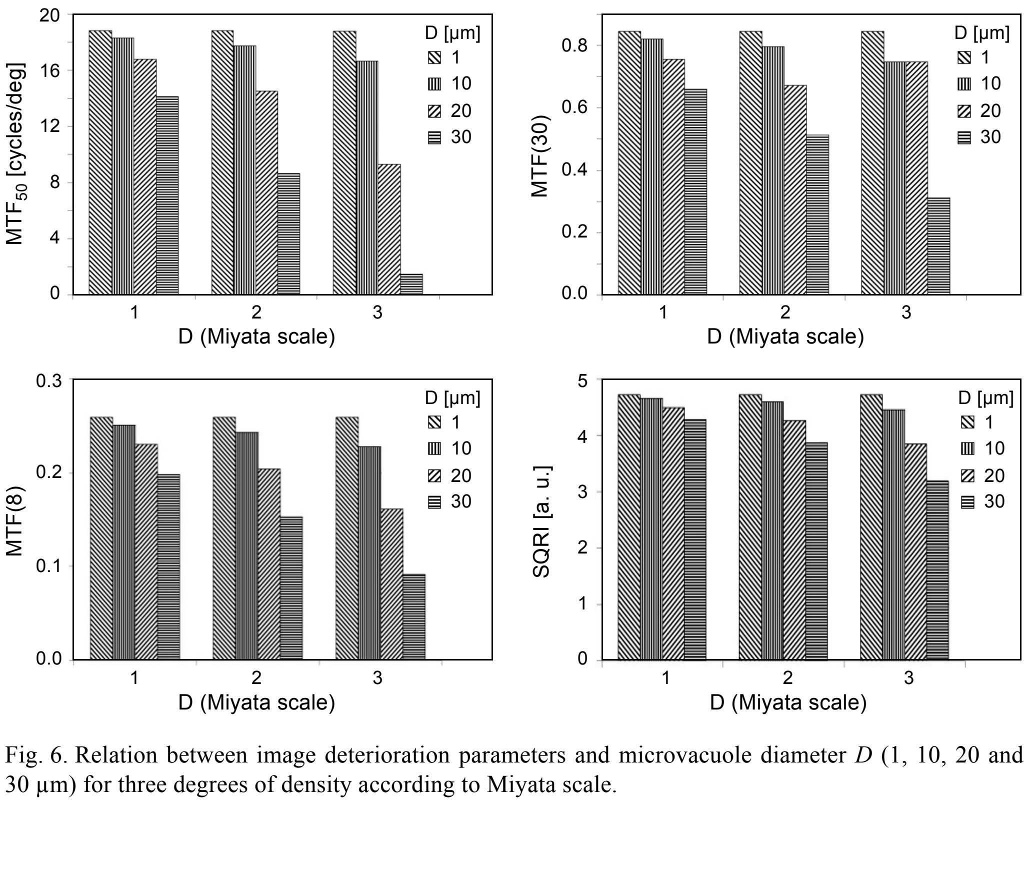

Fig. 6. Relation between image deterioration parameters and microvacuole diameter *D* (1, 10, 20 and 30 μm) for three degrees of density according to Miyata scale.

lows that the MTF should drop down at low spatial frequencies while at higher ones it does not change substantially. This result can be compared to the effect observed in the experiments in which the contrast sensitivity in low spatial frequencies is decreased in patients with IOLs implanted for many years [9, 15, 16, 21].

The reduction of vision quality in real patients (especially for low spatial frequencies) due to deterioration of the retinal image was reported by several researchers who identified the relation between the intensity of glistenings in the IOL and decreased contrast sensitivity without any changes in visual acuity [21, 22]. In the developed model there is no changes in MTF(30) which is equivalent to visual acuity VA = 1.0. The above findings are in line with the results of subjective measurement which confirmed that the occurrence of glistenings impacts only contrast sensitivity and not visual acuity [7, 9].

According to our model, the increase in the diameter of individual scattering particle causes a significant reduction in all parameters describing image quality. It may be expected therefore that in the case of large-diameter microvacuoles visual acuity should be deteriorated significantly.

The presented above analysis confirmed deHoog's observations that glistenings in IOLs will lead to reduction in the MTF of the IOL [7].

Several studies show that the layer of deposits may be located either directly under the lens surface [9] or deep inside the lens structure [2]. According to the model presented in this paper the location of the deposit layer is not directly related to the retinal image quality. On the other hand, the increased density of scattering particles should result in the decrease of all parameters describing image quality (see Table 4, Fig. 3).

5. Conclusion

The model of ageing defects in IOLs was developed. Two kinds of defects were simulated: calcium deposits and glistenings. The model presented in this paper clearly shows that there is a relationship between these phenomena and the quality of retinal image. The conclusion resulting from this model corresponds with the observations present in the literature. Also the analysis provides a significant new insight into both lens defects: glistenings and calcium deposits.

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