Methods for creation of diffractive intraocular lenses

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Abstract

Hybrid intraocular lenses (IOLs) are diffractive-refractive lenses with pseudoaccomodation. They can imitate the optical system of health eye more precisely, than other types. These lenses have 2-3 or more stable focuses. I proposed a comparison of hybrid IOLs: their shape, their processing, their aberrations and diffractive efficiency. I showed a review of new methods for correction of chromatism and I proposed a method of using volume holograms. I discussed features of possible materials.

Keywords: computer optics; diffractive optics; focusator; intraocular lens; holography; digital holography

1. Introduction

Some of aged peoples have cataracta. Affected crystalline in this case must be removed. As an eye loose an ability of focusing an image on retina, it is necessary to use artificial IOLs (intraocular lenses). Some basic types of IOL exist: monofocal, accommodative and hybrid diffractive-refractive IOLs. Monofocal lenses [1] are the simplest in processing, but after implantation patients can't live without glasses. This problem was solved by making accommodative lenses [2]. But these lenses have small opportunities in correction of aberrations. Patients can receive the most natural sight after implantation of hybrid IOLs. Investigation of multifocal lenses, and, particularly, IOLs is object of interest in many countries from the 80th to our days [3-11]. A review of the most interesting hybrid IOLs, their processing is a subject of this paper. Also there is proposed a method of processing IOLs by using volume holograms.

2. Review of Russian and foreign lenses

2.1. Foreign lenses

There are well known American lenses «AcrySof ReSTOR» of the «Alcon» corporation from the USA, lenses «AcriLisa» of the German company «AcriTec», lenses «Tecnis ZM900» of «AMO» [12-15].

These lenses correspond to the next **standard claims**:

- Lenses must be soft for the implantation through the small section;
- Material must be hydrophobic for minimization of the treats and of the appearance of biological concretions on lenses;
- Additive optical power, formed by diffractive structure, is near +4 diopters − for reducing the intensivity of the defocused image;
- Lens must adsorb UV radiation because it can treat retina.

Advantage of lenses AcrySof ReSTOR is an opportunity of the far sight in different illumination. In case of diameter of pupil equal 3.5 mm the refraction part of IOL begins working and the energy moves to the far focus. The effect of blinding by headlights in case of night driving was eliminated by reducing the size of the central zone. Despite of the small increasing of the number of zones, the profit in energy in not significant. Also the small size of the diffractive zone is a sourse of increasing a sensitivity of the pupil's center relatively to axis.

The redistribution of the light energy in lenses ReSTOR is made by the reduction of the depth of diffractive relief. The radius of the central zone is

$$r_0 = \sqrt{2\lambda_0 f} \tag{1}$$

where λ_0 is constructive wavelength, f is a focus of lens in the 1st order of diffraction. The radius of the central zone can be reduced by using a phase shift

$$r_k^2 = r_0^2 + 2k\lambda f \tag{2}$$

But the next condition have place

$$r_2^2 - r_1^2 = r_k^2 - r_{k-1}^2 \tag{3}$$

It means that the number of zones can't be increased more than on one zone and there is no any significant effect [12-20].

Hybrid multifocal IOL AcriLisa (Acri. Tec GmbH, Германия) is a monolithic aspherical bifocal IOL with the correction of aberrations, which is processed of hydrophobic acryl. 65% of intensivity comes to the far focus and 35% - to the near focus. Bifocal work is undependent from the size and function of pupil, because the diffractive structure is on full light diameter. The refractive component has aspherical form.

Diffractive IOL of silicon with three components Tecnis ZM900 (Advanced Medical Optics, Inc., США) has a diameter of optical part equal 6 mm. Diffractive structure on back surface has the additional optical power +4 diopters, the incident light is distributed homogeniously free of size and function of pupil. The first surface have aspherical form.

2.2. Russian lenses

A group of scientists in Institute of Automation and Electrometry, Siberian Branch of the Russian Academy of Sciences has developed the first Russian IOL [16-20]. A great quality of far and near sight, IOL's independence on pupil. The function of correction of eye's and IOL's aberrations has added. Reverse slopes for decreasing the risk of appearance of concretions has added. An optical part of lens has plano-convex shape with the triangle profile and ring microstructure on back surface (fig. 1). The IOLs «MIOL-Accord» are processed in Hizhniy Novgorod by the company «Reper-NN» (fig. 2). The developing has done by the Institute of Automation and Electrometry SB RAS, Novosiberian branch of the MNTK «Eye microsurgery» and private corporation «Intra OL».

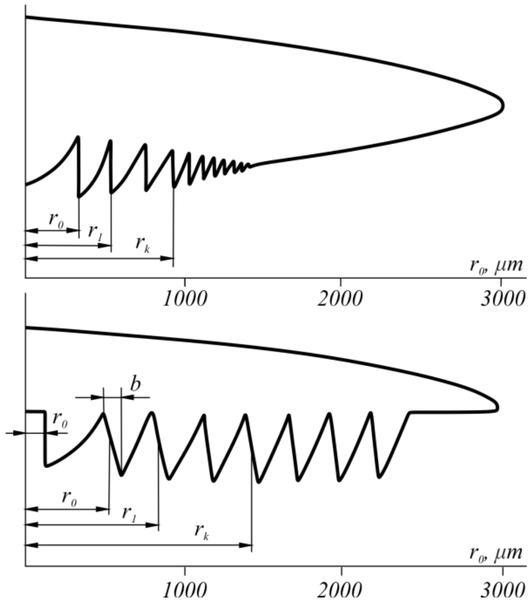

Fig. 1. (a) ReSTOR; (b) MIOL-Accord. *r* is radial coordinate, r_0, r_1, r_k are radiuses of central diffractional zones.

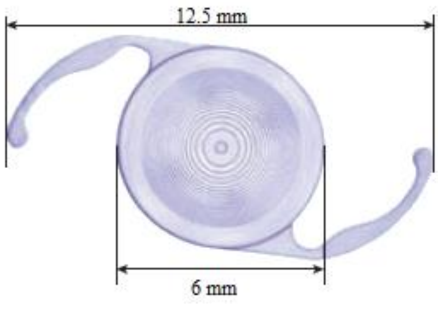

Fig. 2. Diffractive-refractive lens MIOL-Accord.

Forming of IOL can be made by photo-solidification of liquid oligomeres, which can be polymerized. Polymerizing lasts as crystal growth. Structure of polymer and absence of mechanical processing decrease the risk of appearance of concretions. The material has good bio-compatibility. The mold is a matrix of quartz with the diffractive micro-structure, processed by the method of direct laser recording, where the shape of the beam can be changed (fig. 3, 4).

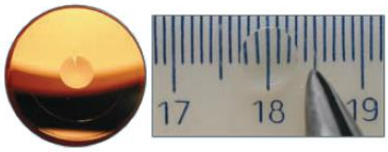

Fig. 3. Diffractive matrix and a final lens.

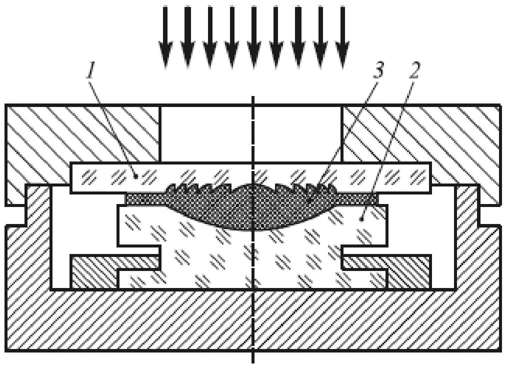

Fig. 4. Pressing of IOL by diffractive mold. where 1 is a diffractive matrix, 2 is another part of mold, 3 is a lens.

For compensating of decreasing of the diffraction efficiency the height of peaks was increased. The diffractive structure is situated on the entire light diameter. This construction effectively spread light equally between the focuses independent of pupil. If the IOL is decentered, the cutting of diffraction zones can't take place. For minimizing the blinding when the pupil diminishing the mini-zone has added. The curvature is the same as the curvature of the main base with diffractive structure. IOL has the ability of correction of refractive components of retina, IOL and vitreous body.

In comparison with lenses ReSTOR lenses MIOL-Accord have increasing square of every diffractive zone

$$M = c\lambda / f \qquad (4)$$

where c is a non-dimensional aberration coefficient. Increasing of zones is a result of the correction of aberrations. The model of eye is Lotmar's.

Later, in company «Reper-NN» hybrid lenses with rectangle profile of peaks were developed. It can give the possibility of using three orders of diffraction. A maximum of -1st order can be used for forming images of far objects, a 0th maximum – for average distances (500 mm) and a 1st order – for near objects (250 mm). For comparison: triangle profile, which is more widespread, can give only focusing in two orders of diffraction, also the diffraction efficiency is higher. Thus increasing the number of focuses improves vision on any distances [21-22].

IPSI RAS has many investigations in counting [23-36] and processing [37-55] of diffractive optics. IPSI RAS and Laser Center of Hannover have investigated the two photon polymerization technology for processing microdevices such as IOLs [56-58]. The element is three-focal, their diameter equals 2.7 mm, focal lengths is between 27 and 34 mm. The size of the element's section is less than the wavelength. In comparison with the method of diamond turning it is more economic. It gives the possibility to focus complicated 3D structures. A binary structure has processed and their features were analyzed. A height of stair of microrelief can be counted as

$$h = \frac{\mathrm{mod}_{2\pi}(\varphi)}{k(n-1)} \qquad (5)$$

where k is a wavenumber, n is a refraction coefficient, $\mathrm{mod}_{2\pi}(\varphi)$ is an excess of division eikonal to 2π.

Complex amplitudes of given and modified waves

$$W_0(\rho) = \sqrt{I_0(\rho)}\exp[i\varphi_0(\rho)] \qquad (6)$$

$$W(\rho) = \sqrt{I_0(\rho)}\exp\left(-\frac{ik\rho^2}{2f_1} + i\Phi[\mathrm{mod}_{2\pi}(\frac{k\rho^2}{2f_2})]\right)$$

where ρ is a current radius of an element, f_1 and f_2 are focal lengths.
Focuses of the element are

$$F_{-1} = \frac{f_1 f_2}{f_1 - f_2} \tag{7}$$

$$F_0 = f_1$$

$$F_1 = \frac{f_1 f_2}{f_1 + f_2}$$

The distribution of intensity is

$$I(r,z) = \left| \frac{k}{z} \int_0^R W(\rho) \exp\left\{ i \left[\varphi_{mf}(\rho) + \frac{k\rho^2}{2z} \right] \right\} J_0\left(\frac{kr\rho}{z} \right) \rho d\rho \right|^2 \tag{8}$$

where z is a longitudinal coordinate, $\varphi_{mf}(\rho)$ is eikonal, r is a radial coordinate. The graph is on the fig. 5.

Later these organizations considered an ability of constructing of diffraction relief with sub-micron height and sine profile. The possibility of processing of three-focal hybrid IOLs with the help of nanoprint technique was considered. The distribution of intensity between focuses can be counted before. Focal powers are -3, 0 and 3 diopters. In comparison with the method of two-photon polymerization this method is more precise and fast. The theoretical results are agreed with the experimental [59].

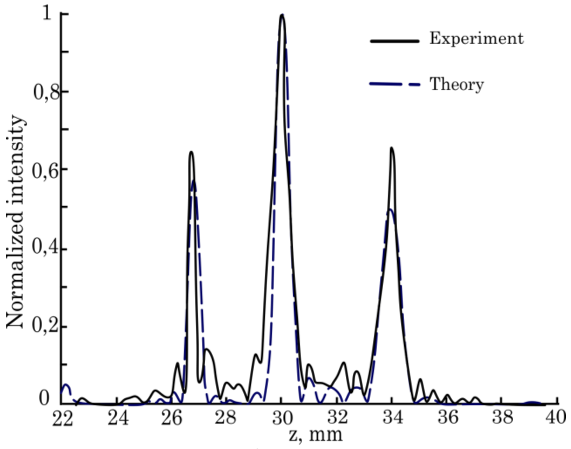

Fig. 5. The distribution of intensity along the optical axis.

3. Methods of eliminating chromatism

3.1 Multi-order diffractive lens

In Kyiv in 2015 an IOL with decreased chromatism has investigated [60-61]. It is a multi-order lens. These lenses has a diminished chromatism. These lenses have an increased in p times thickness.

A matrix of focal lengths can be determined as

$$f_N = \frac{p f_0 \lambda_0}{N\lambda} \tag{9}$$

where f_0 is a focal length for the main wavelength λ_0; N is a main order of diffraction; $\lambda \neq \lambda_0$; p is a parameter. The meaning of the equation is that if $p\lambda_0/N\lambda = 1$, some of the wavelengths can be focused in 1 point with the big diffraction efficiency. It can be determined as

$$\eta_N = sinc^2(\alpha\mu p - N) \tag{10}$$

where $\alpha = \frac{\lambda_0[n(\lambda)-1]}{\lambda[n(\lambda_0)-1]}$ is a relative phase retard when $\lambda \neq \lambda_0$, $\mu = t'/t$ is a thickness coefficient, where t' and t are real and counted thicknesses of profile, respectively. A μ coefficient can't influence on the location of focuses, but it can change the distribution of energy between them. In article [] it equals 1. When the p increase, the number of wavelengths, which can satisfy the condition of appearance of maximum, increase. For the main maximum $p = N$ and the wavelength is λ_0. The good meaning of for visible light is *p=6*. On the fig. 6 the relation between the diffraction efficiency and the wavelength is shown. When *p=20,* chromatism is as bigger as in spherical lenses. The dispersion for three wavelengths can be determined as

$$\nu_\lambda = \frac{N_3\lambda_3}{N_c\lambda_c - N_k\lambda_k} \tag{11}$$

On the fig. 7 the relation between the diffraction efficiency and focal length is shown. The numbers of orders of diffraction cannot be agreed. Two groups of wavelengths are considered: λ_b = 485 nm, λ_g = 573 nm, λ_r = 700 nm and λ_b = 420 nm, λ_g = 485 nm, λ_r = 573 nm. For the near and far focuses the dispersions are -32, 74 and 38.8 respectively. But the dispersion of the usual lens equals -3.5. Thus, chromatism of multi-ordered lens is significantly less than chromatism of refractive lens. These lenses have infinite accommodation.

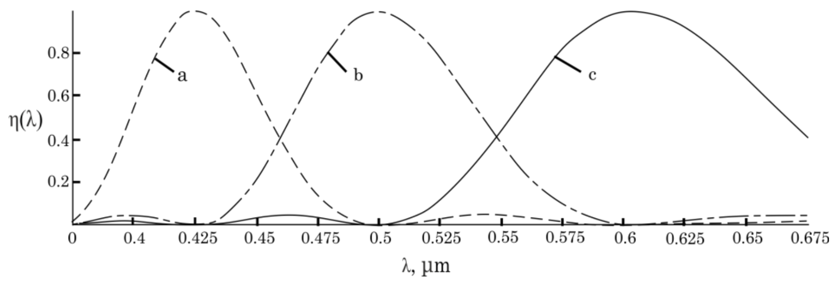

Fig. 6. Relation between the diffraction efficiency and the wavelength. a) N = 7; b) N = 6; c) N = 5.

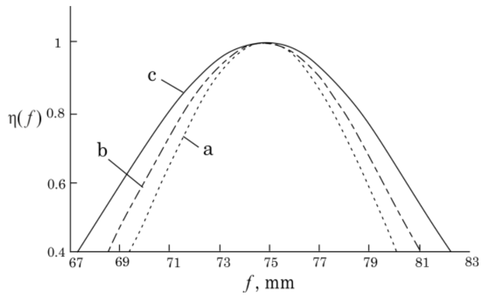

Fig. 7. Distribution of light along the optical axis: a) N = 7 (синий); b) N = 6 (зелёный); c) N = 5 (красный).

For proposed IOL the parameters are: f = 100 mm, *p=6*, the material is PMMA, λ_0 = 525 nm. In light diameter D = 7 mm 19 diffractive zones are situated, maximum depth of the groove is 6 μm. The anterior surface of lens is spherical, the model of eye is taken from Gullstrand [24].

3.2 Holographic approach for the creating of intraocular lenses

It is possible to use volume holograms for clearance of chromatism. The direction of rays is significant and the recording can be made by composing object and referent waves in the photosensitive layer [62-64]. The recording is comparatively fast. The required meanings of aberrations can be created by the methods of computer optics.

Holograms receive the features of volume holograms with the height of the layer near ~7 μm. In this case holograms have only the virtual image. Changing the scheme of recording give us a real image instead of virtual. The holograms are also phase, but their surface is smooth. These holograms can't have significant chromatism because the Bragg's condition haves place:

$$2d \cdot \sin\theta = n\lambda \tag{12}$$

where d is a period of grating, θ is an angle between the ray and the normal to surface, n is the order of diffraction, λ is a wavelength.

The good materials are bichromated gelatina, silver holograms like «PFG-01», «PFG-03», «Ultimate-08» [65], «Ultimate U-04». Photo-thermo-refractive glasses from the university IFMO are interesting medium (or matrix) for photosensitive matter, but glass is solid material [66]. Instead of glass nanoporous acryl can be used.

Bichromated gelatina can be used for any surface, the holograms have great resolution and good spectral selectivity [67]. The material needs a protective coating. But the hologram can change features at the temperature 34 ºC so this material can't be used.

Silver holograms are more convenient. The methods of increasing their diffractive efficiency are investigated by IFMO [68-69]. The material with the great color transfer Ultimate-08 is developed by Alkiss Lembessis.

The scheme of recording and reconstructing of a point source is on fig. 8. For receiving a real image the source must be imaginary. It means that the recording wave is divergent. Using optical elements or phase holograms for forming desired aberrations in IOL gives an optical system, which aberrations are compensated.

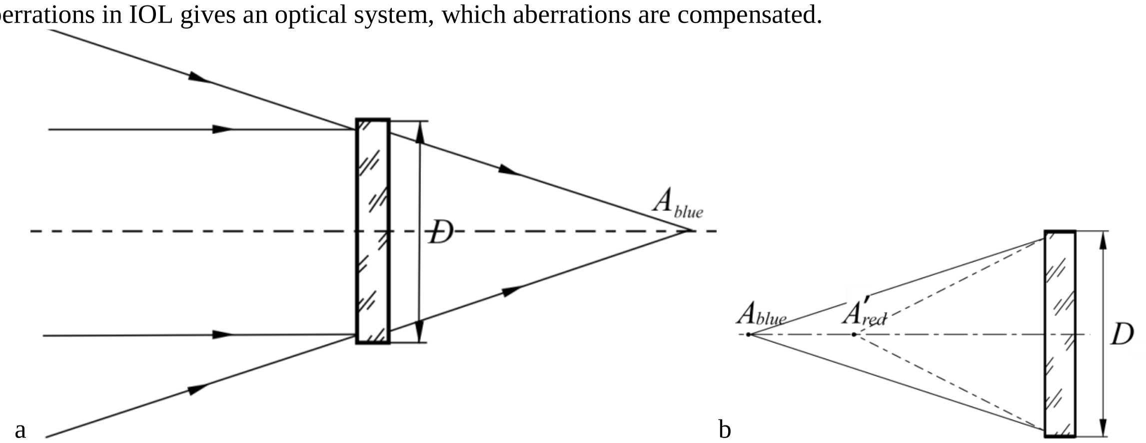

Fig. 8. (a) Recording with blue light (for example). (b) Change of the focus while the wavelength changes (blue – record, red - reconstruction).

Phase holograms (not volume) are another way for making of intraocular lenses. Image, which is made by using the hologram, can be stretched and the position can be changed. The photosensitive medium haves the possibility to record three or more holograms and for switching between them. The medium is polydimethyloxane with gold nanorods [70]. Using of these surfaces can make the possibility of decreasing errors of an eye's aberrations.

4. Conclusion

A review of existing intraocular lenses (IOLs) has shown that lenses can imitate crystalline with good quality, they can't be perfect in all directions like monochromatic aberrations, chromatic aberrations, diffractive efficiency, quantity of focuses simultaneously. Perhaps, the best criteria of the IOL's quality is optical performance, what means that IOL must give an image on retina, which must be as close to real image as possible. Some problems like chromatism or diffractive efficiency are actual now, also the decisions are exist. A proposed method of processing volume holograms as a diffractive part of hybrid intraocular lenses in comparison with others methods is faster and it can be done without complicate devices. The proposed method is interesting because intraocular lens has no significant chromatism. The diffraction efficiency is good for intraocular optics. Other aberrations can be reproduced by methods of computer optics. Traditional optics like lenses and plates can be used for forming aberrations, too. Thus, the analysis shows that the method of using volume holograms is perspective for further investigations.

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