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Human eye cataract microstructure modeling and its effect on simulated retinal imaging

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ABSTRACT

We designed a crystalline microstructure during cataract lesions and calculated the aberration value of the eye by using ray trace modeling to identify the corresponding spherical aberration, coma aberration, and trefoil aberration value under different pathological-change degrees. The mutual relationship between microstructure and aberration was then discussed using these values. Calculation results showed that with increased layer number of microstructure, the influence of aberration value on spherical aberration was the greatest. In addition, the influence of a relatively compact microstructure on spherical aberration and coma aberration was small, but that on trefoil aberration was great.

1. Introduction

Nuclear cataract and aging present a close correlation. Refractive error occurs in the elderly population because of their reduced visual function, and lens nuclear sclerosis can cause the change in refractive index. The deterioration of visual function of these patients cannot be completely explained by spherical aberration or refractive error; in addition, nuclear cataract may cause a decrease in contrast sensitivity and influence visual function [1]. In recent years, cataract patients show a gradually younger trend and also cause visual aberration effects. Previously, the Hartmann Shack (HS) aberrometer was developed to measure aberration changes in the eye, and an optical aberrometer was developed for measuring high-order aberration increase in cataract patients. Applegate and Donnelly et al. demonstrated that Shack Hartmann images and Scheimpfluq images can be acquired; they also used multiple regression to show that higher-order aberrations increased with increased nuclear cataract, whereas low-order aberrations were less affected. These data tended to align with the effect a microstructure mask could induce. Pure nuclear cataract resembling Mie scatter causes an attenuation of retinal imaging, but not necessarily changes in aberrations. The microstructure component of this current text provides a missing piece to the cataract-aberration simulation puzzle [2–5]. In the study of Teruhito Kuroda, the HS aberrometer was used for measuring the wavefront aberration of eye and cornea for a large number of patients; afterwards, the coma aberration of older patients was found to exhibit a linear increase with the increase in angle, and the spherical aberration was unrelated to visual angle. For mild cataracts (regardless of cortical or nuclear cataract), the higher order aberrations of eyes are the same as those of the normal subjects; in contrast, for moderate cataract, higher-order aberrations are evidently higher than those of normal subjects. These observation results show that local refraction rate changes in lenses lead to an increase in higher-order aberrations in cataract lesion eyes. As seen from an HS aberrometer, the polarity of spherical aberration is found to be different between nuclear and cortical cataract. As for moderate nuclear or cortical cataract, not only light scattering but also optical aberration of lens can cause contrast sensitivity reduction [6]. Spherical aberration of nuclear cataract in high-order aberrations shows a negative value range of −2.1 to −0.426 [6]. In the study of Joo-eun Lee and other scholars also say that spherical aberration in most of 33 groups shows a negative value range of −1.84 to −0.76 [7], whereas coma aberration range and trefoil aberration are invariably positive. These findings are consistent with our calculated results.

Lee et al. mentioned that nuclear cataract would affecting contrast acuity and cause visual function decline in the study [7], and the decrease in contrast acuity could be explained using the change in light

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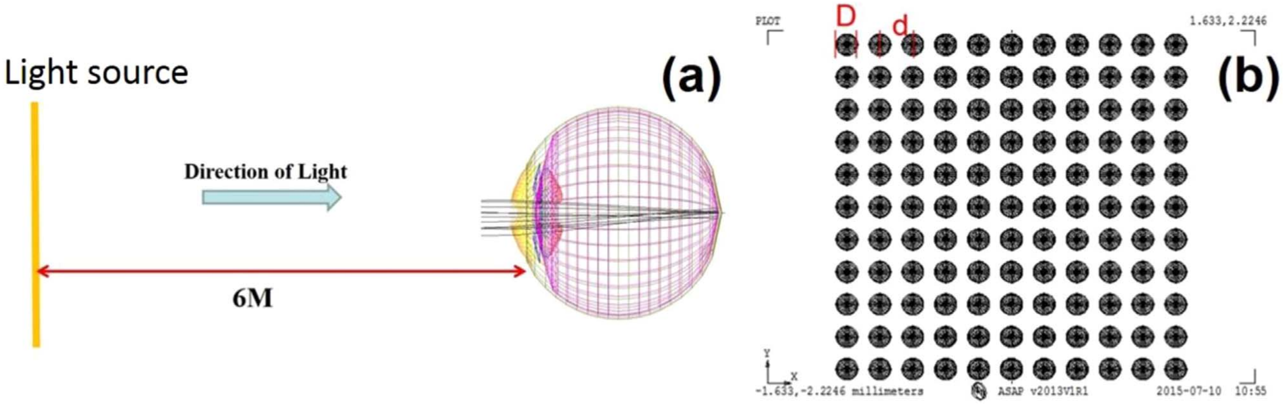

Fig. 1. (a) Research framework chart, (b) schematic of the microstructure placed on the anterior surface of lens.

Table 1
Parameters used in optical calculation. *Number* represents calculation of different parameters, *Array* represents the used periodic hole array, *Layer* is the hole periodic layer number on the anterior lens surface, *D* is the hole diameter, and *Area* is the distribution area of the periodic hole array.

Number	Array	Layer	D (mm)	Area (mm^2)
D1	100*100	1	0.02	4.0
D2	100*100	1	0.03	9.0
D3	100*100	1	0.04	16.0
D4	100*100	1	0.05	25.0
D5	50*50	2	0.07	24.5
D6	50*50	2	0.06	18.0
D7	50*50	2	0.05	12.5
D8	50*50	2	0.04	8.0
D9	50*50	2	0.03	4.5
D10	50*50	2	0.02	2.0
D11	100*100	2	0.04	32.0
D12	50*50	3	0.04	12.0

scattering and higher-order aberrations. The effect of light scattering on the eye is more serious in the peripheral cortex than that in central lens. Therefore, light scattering particularly influences the visual function of cortical cataract patients while exerting minimal influence on eye contrast acuity of nuclear cataract patients; therefore, higher-order aberrations possibly exerts the greatest influence on nuclear cataract and similar cases [8]. Fujikado et al. found that nuclear cataract would produce monocular diplopia; however, they were unable to determine the cause of triplopia. Thus, the group used high-order aberrations to assess triplopia and determine an evident trefoil aberration value increase in patients with triplopia, whereas trefoil aberration value may be related to aging and lens injury [8].

In the past, we used ray trace modeling and combined the method with the establishment of human module to develop retinal imaging technology [9–12]. The technology produces different degrees of periodic pore on the anterior lens surface to simulate visual impairment caused by cataract. In the study, we successfully predicted the corresponding cataract incidence degree from 300° to 900° of myopia. Moreover, we found that the most severe visual impairment is caused when the periodic hole is concentrated in the visual center, and when the lens distribution in the front surface of periodic holes became wide, its effect on vision was not too severe [13]. The motivation for this study is to produce varying degrees of periodic pore on the anterior lens surface to simulate the degree of cataract incidence, compute three kinds of aberration(s) under different degrees through optical calculation, and discuss the relationship between microstructure distribution and aberration value. The results can enable doctors to predict the degree of cataract incidence by measuring the aberration value in patient eye in the future.

2. Method

Fig. 1(a) is the experimental architecture diagram. A light source is placed in the position 6 m away from the eye. The direction of the incident light is from the light source to the eye, and the imaging light source is on the retina. We can reproduce a retinal image by optical calculation; however, in this study, we mainly added a certain microstructure in the lens to simulate a situation similar to cataract and then used ray trace modeling to calculate the aberration to determine the corresponding eye aberration value in different microstructures of the lens. A commercially available eye-modeling system is the advanced human eye model (AHEM). ASAP is the time-proven industry standard in optical software, offering optical-system designers unmatched capability, flexibility, speed, and accuracy [14]. In the present study, the pupil size and optical wavelength were defined as 5 mm and 550 nm, respectively. Fig. 1(b) is the periodic microstructure diagram, where *D* is the diameter of each microstructure, and *d* is the spacing between the microstructure center to another microstructure center, the particle size of design array, and distribution density. The material is air, and the external material is the lens with refraction rate of 1.49 [15]. We changed the distribution of layers I, II, and III and designed a total of 12 kinds of structure, denoted by D1–D12 as shown in Table 1. Given that cataract lesions occur in the lens, we placed the microstructure on the location of the eye lens. The simulated lens becomes muddy owing to cataract. The lens is positioned between the iris and the vitreous humor. Under normal circumstances, the lens is transparent; then, when the light penetrates through the cornea, after refraction of the lens, the image is clearly presented in the retina, as if the camera lens enables the light to focus on the negative. Fig. 2 is a flow chart of this study. First, we established an eye module, designed different microstructure diameters, spacings, and number of layers, and then imported the microstructure to eye lens to conduct three kinds of aberration value calculation in different microstructures; moreover, we established slit lamp modules outside the eye module and simulated slit lamp images under different microstructures; finally, we compared D1–D12 aberration data and discussed the relationship between cataract lesion degrees and aberration. Slit lamp examination system architecture is as shown in Fig. 3. In Fig. 3, the light irradiates on cornea through slit light generated from the objective slit and transmits to the eye module. Given that the cornea and lens are not completely transparent media, part of the light will be reflected, scattered, and finally received by the detector finally. The slit lamp itself is a microscope, which can be used to observe the degree and location of cataract to determine the type of cataract [16].

The simple introduction of spherical aberration, coma aberration, and trefoil aberration is shown below:

(1) Spherical aberration [17]

Spherical aberration is due to light irradiation on the spherical