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RESEARCH PAPER

Research of the human eye model with variable-focus liquid lens

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Abstract The human eye optical model with variable-focus liquid lens based on Chinese human eye model is presented for the first time. The Varioptic Arctic 316 liquid lens is used as a substitute for the crystalline lens in the model. The dioptric power and the MTF of the human eye model with variable-focus liquid lens are analyzed theoretically. The result shows that the human eye model with the liquid lens under applied voltage of about 53 V can be used as an emmetropia model. This research work can provide a novel idea for suitable model for clinical regulation and control with Chinese eye.

Keywords Vision modeling · Ophthalmic optics and devices · Geometric optical design

1 Introduction

A schematic eye model is helpful in teaching aids in optics, optometry, ophthalmology, psychology (vision and visual perception) and visual ergonomics (Smith 1995). Moreover, this can be used to understand and research the optical performances of eye in refractive surgical procedures, such as photorefractive keratectomy (PRK), laser-assisted in situ keratomileusis (LASIK) (Gobbi et al. 1999; Curatu et al. 2002; Guo et al. 2005) and intraocular lens implants (Norrby et al. 2007; International Organization for Standardization 1999; Rosales and Marcos 2007). In current research of the human eye optical system, the information about the human crystalline lens is sparse because of the difficulties of measurement and the complexity itself. In order to build a practical eye model that is more suitable for clinical regulation and control, the human eye model with the replacement of human crystalline lens based on variable-focus liquid lens is proposed in the paper.

Variable-focus liquid lens is a novel optical element, whose focal length is varied by changing the surface curvature or internal refractive index of the lens without mechanically moving the lens (Kong et al. 2016). The variable-focus liquid lens presents the simplest and the highest-quality performances, so the lens has been studied extensively for eye glasses, cameras, camcorders, projectors, as well as other machine vision (Ren and Shin-Tson 2005).

The liquid lens based on the electrowetting effect is highly regarded because of its outstanding performance (Peng et al. 2013), which can provide considerable power savings and eliminate wear associated with moving parts. So it is widely used in a large variety of application areas, such as mobile phones (Wippermann et al. 2007), surgical instruments (Kuiper and Hendriks 2004) and miniature cameras (Tsai et al. 2008). Currently, the French Varioptic Company and the Netherlands Institute of Philips have the mature technology of liquid lens, they have produced focusable liquid lens for mobile phone camera (Xin 2010). So the Varioptic Arctic 316 liquid lens which is a commercial variable-focus liquid lens (Varioptic, France) with good stability and controllability is used here.

Based on our previous work result on Chinese human eye model (Kong et al. 2009; Kong and Li 2014), a double-liquid variable-focus lens (the Varioptic Arctic 316 liquid lens) is placed in the human eye model in this work.

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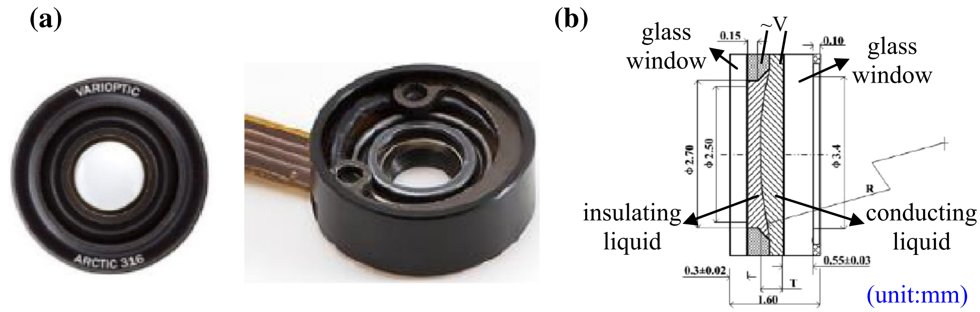

Fig. 1 Photograph of Arctic 316 liquid lens (**a**), the structure schematic diagram of Arctic 316 liquid lens with the external voltage of 30 V (**b**): The refractive index of insulating liquid and conducting liquid are 1.495 and 1.386, respectively

2 Chinese generic eye model with Arctic 316 liquid lens

The Arctic 316 liquid lens consists of two kinds of liquid (insulating liquid and conducting liquid) and two glass windows (Berge 2005). Based on the electrowetting effect (Berge 2005), the focal length of the double-liquid lens is varied by means of an external voltage, which can change the curvature radius of the liquid interface. The photograph and structure schematic diagram of Arctic 316 liquid lens with the external voltage of 30 V are shown in Fig. 1 (Model Arctic 2010). Figure 1b shows this liquid lens structure: Between two glass windows, two nonmiscible liquids are trapped in a closed cell. One of the liquid (conducting liquid) is based on a water solution and thus it is conducting electricity. The other liquid (insulating liquid) is apolar and should be non-conducting (the oil phase). The natural interface between the liquids thus forms a natural diopter, due to the refractive-index difference of the two liquids (Berge 2005). The interfacial shape between the two liquids is controlled by the applied external voltage.

Based on the corresponding data of the optical characteristic parameters of Arctic 316 liquid lens surface and the applied voltage value (Model Arctic 2010), the human eye models with Arctic 316 liquid lens under different applied voltages are built by Zemax optical design software.

As shown in Fig. 2, in Chinese generic eye model (Kong et al. 2009; Kong and Li 2014), the variable-focus performance of the crystalline lens is simulated by the replacement of Arctic 316 liquid lens. In Fig. 2a, the optical element in the dashed box is Arctic 316, incident to the human eye model under applied voltage of 53 V, the light rays converge good at the last surface which is represented as the retina. From Fig. 2b–g, the applied voltages are 25, 30, 35, 40, 45 and 55 V, respectively. As the voltage increases, the curvature radius of the liquid interface (red solid line) changes from negative to positive gradually, the convergence of light rays increased gradually, so the human eye model changes from the form of hyperopia to the form of myopia gradually. The data of curvature radius of the liquid interface at different voltages are shown in Table 1.

Figure 3 shows how the dioptric powers of human eye models vary with the applied voltages. The dioptric power of human eye models increases gradually with the increase in the applied voltage. The dioptric power of the normal aging human eye is about 60D (Smith et al. 1992). So from Fig. 3, it is found that the human eye model under applied voltage of about 53 V can be used as an emmetropia model. Moreover, according to the different diopters of myopia and hyperopia, the corresponding human eye models can be chosen to represent different myopia and hyperopia models.

Figure 4 displays the monochromatic MTF of Chinese generic eye model with Arctic 316 liquid lens under applied voltage of 53 V (a) compared with Chinese generic eye model (Kong et al. 2009) for the pupil diameter of 3 mm. In Fig. 4a, the agreement of the MTF curves is good. From Fig. 4b–g, the applied voltages are 25, 30, 35, 40, 45 and 55 V, respectively; Chinese generic eye model is an emmetropia model (Kong et al. 2009), so there is no MTF curve comparison under these voltages. From Fig. 4, it is found that the MTF of eye model with liquid lens under applied voltage of 53 V is clearly better than the ones under other voltages. This result indicates that the imaging quality of the human eye model under applied voltage of about 53 V, which can be used as an emmetropia model, is better than the ones under other voltages, which can be used as myopia and hyperopia models. This result of the MTF analysis is consistent with the result of the previous dioptric power analysis of the human eye models.

3 Discussion and conclusion

Therefore, it is feasible that the liquid lens is used as a substitute for the crystalline lens in the human eye model. And this method to build the human eye model with variable-focus liquid lens can provide a novel idea for the practical human eye model for clinical regulation and control in the future.

Limited by the aperture size of the liquid lens (shown in Fig. 1), only the MTF analysis of the human eye model for 3-mm pupil diameter is presented here; in the future work,

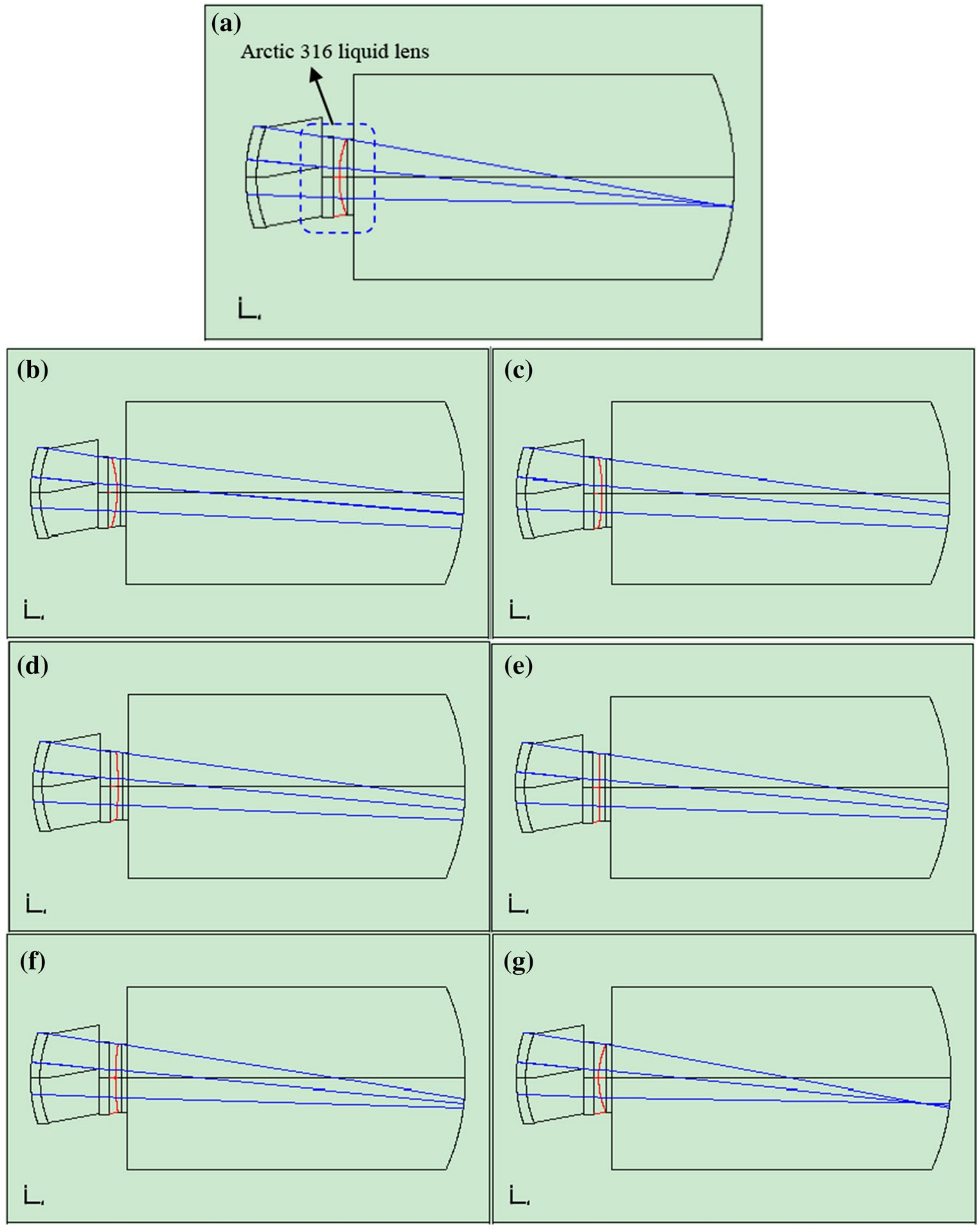

Fig. 2 Schematic plots of Chinese generic eye model with liquid lens at the pupil diameter of 3 mm under applied voltage of 53 V (**a**), 25 V (**b**), 30 V (**c**), 35 V (**d**), 40 V (**e**), 45 V (**f**) and 55 V (**g**)

Table 1 Data of curvature radius of the liquid interface at different voltages

The applied voltage values (V)	The curvature radius of the liquid interface (mm)
25	−6.289308
30	−9.090909
35	−19.569472
40	76.335878
45	12.150668
53	4.950495
55	4.273504

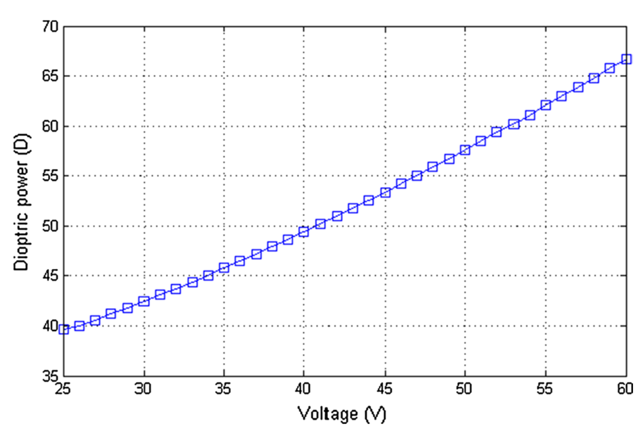

Fig. 3 Dioptric power of the human eye model versus the applied voltage

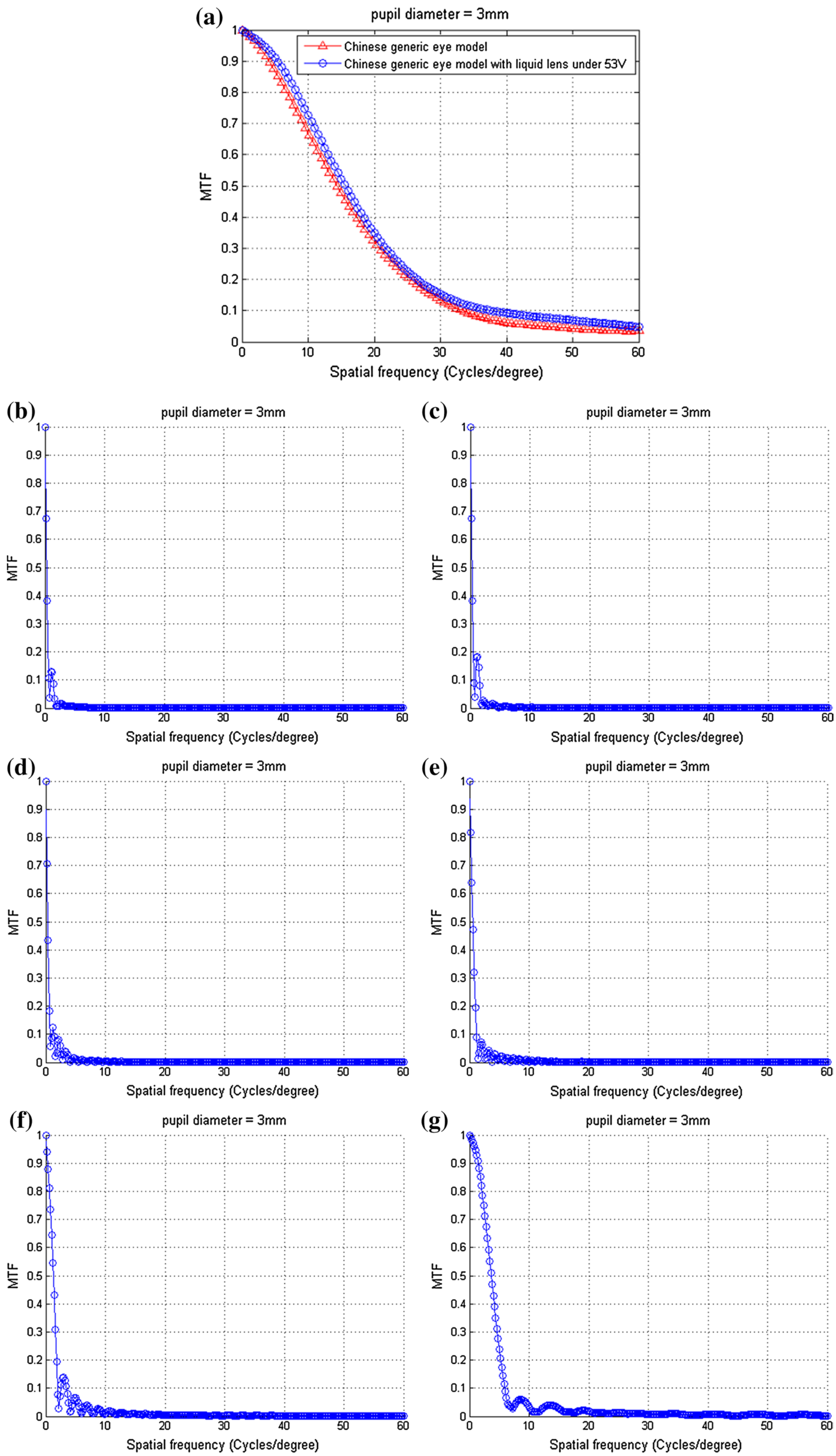

Fig. 4 MTF of Chinese generic eye model with liquid lens under applied voltage of 53 V (**a**) compared with Chinese generic eye model; the MTF of Chinese generic eye model with liquid lens under applied voltage of 25 V (**b**), 30 V (**c**), 35 V (**d**), 40 V (**e**), 45 V (**f**) and 55 V (**g**)

the liquid lens with large aperture size, which can be used for the human eye model with large pupil diameter such as 6 mm, will be studied.

On the other hand, in addition to the voltage-driven liquid lens in this paper, there are some other liquid lenses based on different working mechanisms, such as magnetic-driven liquid lens (Malouin et al. 2010), acoustics-driven liquid lens (López and Hirsa 2008) and pressure-driven liquid lens (Zhang et al. 2004). Therefore, the comparative study of liquid lenses with different driving methods as a substitute for the crystalline lens in the human eye model would be a very good research direction, and we will do more work in this direction in the future.

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