

Geometric Modeling of Human Eyes Based on OCT Image of Anterior Segment and Its Application

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Abstract: The aqueous humor flowing in the human eye plays a very important role in maintaining the normal physiological function of the human eye. Once the outflow of aqueous humor is blocked, it will lead to the increase of intraocular pressure, which will lead to glaucoma and other ophthalmic diseases. Therefore, it is of great significance to study the aqueous humor dynamics mechanism of human eyes to explore the physiological structure of human eyes, the pathogenesis and treatment of ophthalmic diseases. In previous studies, most of the geometric models of anterior segment of human eye hydrodynamics are ideal simplified models based on the anatomical data of human eyes, so the simulated results may deviate from the actual situation. In this paper, the OCT image of anterior segment is denoised and segmented by using image processing technology. At the same time, combined with the conventional data of human anatomy, the geometric model of anterior segment is reconstructed, which is closer to the real human eye and has personalized characteristics. On this basis, the flow of aqueous humor in normal eyes was simulated and studied, and the vortex in iris recess was found. The results show that this method can reflect the aqueous humor flow in real eyes more accurately.

Keywords: Image processing, OCT images, Geometric modeling.

1. Introduction

The human eye is the most important sensory organ of the human body, and its organizational structure is very complex. The eyes are filled with aqueous humor, which plays a key role in the process of transporting nutrients for eye tissues and maintaining intraocular pressure [1, 2]. However, the pathogenesis and development of many eye diseases are closely related to the flow of aqueous humor. Take glaucoma and cataract, two common blinding eye diseases, for example. According to literature reports, there are about 70 million people suffering from glaucoma in the world today. It is estimated that by 2040, the number of people affected by glaucoma worldwide will increase to 110 million [3]. Most glaucoma is related to the increase of intraocular pressure, and the main reason for the increase of intraocular pressure is that the outflow of aqueous humor is blocked. The normal secretion and outflow of aqueous humor is an important physiological process to maintain the balance of intraocular pressure. As the world's leading blinding eye disease, the best way to treat cataract is to eradicate it through surgery. However, because many pathological mechanisms have not been fully understood at present, many postoperative complications cannot be solved. Clinically, the common complications of cataract surgery include corneal decompensation and secondary glaucoma, which are closely related to the aqueous humor flow in the eye. It can be seen that the hydrodynamic mechanism of aqueous humor plays an important role in the emergence, development and treatment of ophthalmopathy.

In recent years, many scholars have done a lot of research on aqueous humor dynamics in human eyes through various methods. Canning et al. [4] used the standard hydrodynamic model to study the flow process of aqueous humor in the anterior chamber. The experimental results showed that the temperature difference in the anterior chamber was the key factor driving the flow of aqueous humor. At the same time, they proposed a simplified formula of the relationship

between the flow velocity of aqueous humor in the anterior chamber and the temperature difference in the anterior chamber, and predicted the maximum velocity of aqueous humor due to natural convection. Heys and Barocas [5] regarded aqueous humor as Boussinesq fluid, established Boussinesq model of natural convection of aqueous humor in human eyes, and studied the influence of temperature difference between cornea and iris on aqueous humor flow. Ooi and Ng [6] established a two-dimensional human eye model, taking into account the process of aqueous humor flow and heat transfer in the anterior chamber, and studied the interaction between the velocity field and the temperature field. Karampatzakis and Samaras [7] established a three-dimensional model of human eye, compared the distribution of intraocular temperature with or without aqueous humor flow, and found that the temperature distribution in anterior chamber is closely related to the flow of aqueous humor.

These studies are very helpful for us to understand the hydrodynamics of human eyes. However, in many numerical simulation studies, almost all the geometric models of human eyes are ideal simplified models based on the anatomical data of human eyes, which lack certain authenticity. In fact, there are differences in the structures of different eyes, such as asymmetric anterior chamber, corneal deformation affected by external forces, etc., which will cause the changes of aqueous humor flow in human eyes. Therefore, the influence of these factors on the numerical simulation results must be considered during the simulation. In the study of Xu et al. [8], shallow anterior chamber and thick cornea are interrelated, and the thickness of cornea will take away some space from anterior chamber. Therefore, in the relevant numerical simulation, simply increasing the parameter of corneal thickness and ignoring its relationship with the depth of anterior chamber will inevitably lead to errors with the real results. In the case of angle-closure glaucoma, the morphological changes caused by iris bulge are more obvious, which is quite different from the structure of normal eyes. At this time, the ideal model based on parameters is no longer

applicable. Therefore, it is expected to improve the accuracy of numerical simulation by choosing geometric model based on real human eye structure instead of ideal model based on parameters.

2. Modeling

In the study of aqueous humor dynamics, the first task is to establish a geometric model that can accurately describe the shape and position of each structure in the anterior segment. OCT image of anterior segment is one of the applications of OCT in medical imaging. Compared with other imaging methods such as gonioscopy, the image of anterior segment can accurately show the tissue structure of anterior segment, which is very suitable for geometric modeling of anterior segment. However, due to the imaging mechanism of OCT, in the process of acquiring images, it will inevitably be polluted by noise, which is not conducive to the subsequent image

processing.

Fig. 1(a) shows a noisy OCT image of the anterior segment of the eye, and the result of edge detection directly using Canny edge detection operator is shown in fig. 1(b). As can be seen from the figure, the noise in the original image greatly interferes with the result of edge detection, and many noise points are mistaken for image edges. Fig. 1(c) is an image after denoising the original OCT image of the anterior segment of the eye by using Gaussian filtering, and a new edge image 1(d) is obtained by using Canny edge detection operator again. In the new edge image, most of the noise points in the background are eliminated. Through the comparison of 1(b) and 1(d), it can be found that the edge detection results of OCT images before and after denoising are quite different, so whether or not to denoise OCT images of the anterior segment has great influence on the subsequent image processing steps.

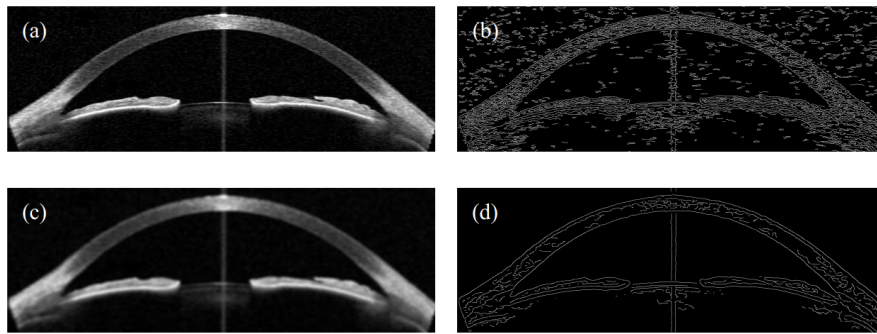


Figure 1. (a) the original image of normal human eye anterior segment with noise, (b) the image after edge detection using Canny edge detector, (c) the image after Gaussian filtering, and (d) the image after edge detection using Canny edge detector.

The method adopted in this paper is an image denoising algorithm based on Lattice Boltzmann anisotropic diffusion model (LBADM) [9]. Compared with other denoising models, this model can retain the key information of the image to the maximum extent. The equation is as follows:

$$f_i(x + e_i \Delta t, t + \Delta t) = g_i(x) \left\{ f_i(x, t) - \frac{1}{\tau} [f_i(x, t) - f_i^{eq}(x, t)] \right\} + (1 - g_i(x)) \left\{ f_i(x + e_i \Delta t, t) - \frac{1}{\tau} [f_i(x + e_i \Delta t, t) - f_i^{eq}(x + e_i \Delta t, t)] \right\}, \quad (1)$$

$g_i(x)$ is the particle passing rate here:

$$g_i(x) = \frac{1}{\left(1 + \frac{|G(x) * [\rho(x, 0) - \rho(x + e_i \Delta t, 0)]|}{k} \right)^n}. \quad (2)$$

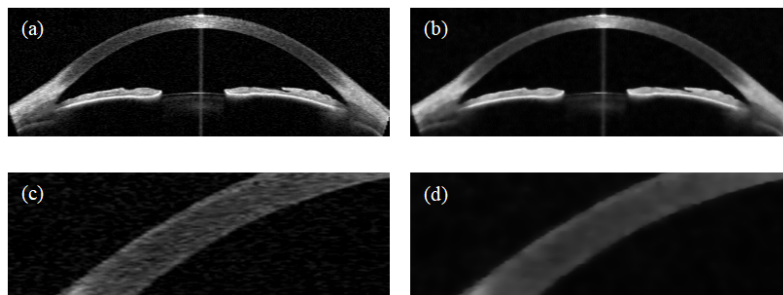


Figure 2. (a) the original OCT image of the anterior segment of the eye, (b) the result of denoising the original image using the LB image denoising algorithm based on CUDA, (c) an area of the enlarged original image, and (d) an area of the enlarged denoised image

Where the image gradient is large, $g_i(x)$ is small, and the particle diffusion speed is slow, while where the image gradient is small, $g_i(x)$ is large, and the particle diffusion speed is fast, so that the edge of the image can be kept while denoising.

Fig. 2 shows the result of denoising the OCT image of anterior segment by LB denoising algorithm. It can be found that the denoised OCT image still retains the basic information of the original image. From the enlarged part of the image, most of the noise in the OCT image of anterior segment is removed.

Because only the edge information of the OCT image of the anterior segment is needed in geometric modeling, and no other additional data is needed, this paper plans to adopt the image segmentation method based on edge detection in image processing. The method adopted in this paper is an edge detection algorithm based on lattice Boltzmann isotropic diffusion model (LBIDM) [10]. Compared with other edge detection algorithms, this algorithm has the characteristics of accurate edge detection and good anti-noise performance. The model equation is as follows:

$$\frac{\partial \rho(x,t)}{\partial t} = \frac{M \Delta h^2}{3 \Delta t} \left(\tau - \frac{1}{2} \right) \nabla^2 (\rho(x,0) * G(x)). \quad (3)$$

After obtaining the edge information of the image, we can extract the edge of the tissue from the edge map according to the needs of geometric modeling. For example, in Figure 3, the contour of the inner corneal surface is extracted by specifying the endpoint. According to the characteristics of the OCT image of the anterior segment, three points A, B and C are selected, and the edge points in the area above the line segment AC and BC are traversed from bottom to top, and the first edge point found in each column is recorded, which is the inner corneal edge point.

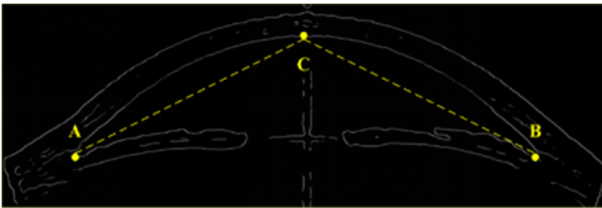


Figure 3. Extracting edge information

Limited by the imaging mechanism of OCT image of anterior segment, the image can't display the data of posterior chamber and other structures. Therefore, we need to

reconstruct the information of posterior chamber according to the standard anatomical data of human eyes. Starting from the lower left point of the left iris of the anterior segment, we draw down the aqueous humor inlet with a size of 0.5mm (that is, the height of the posterior chamber), then do the same for the right iris, and draw a suspensory ligament with a length of 12.8 mm. Secondly, based on the pupil axis, the lens structure with a curvature radius of 10mm is drawn. This completes the reconstruction of information such as the posterior chamber, as shown in Figure 4.

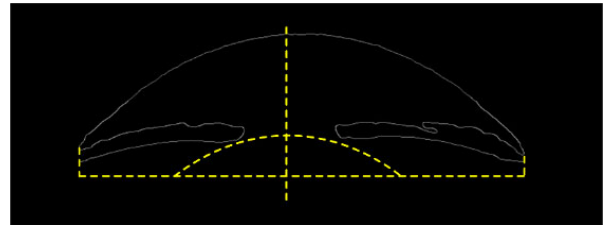


Figure 4. Establishing the structure of the posterior chamber

Figure 5 shows the final geometric model.

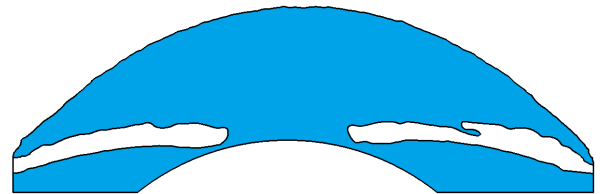


Figure 5. Geometric model of anterior segment

3. Simulation

Taking the geometric model established by the OCT image of the anterior segment of normal eyes in Section 2 as an example, we used the lattice Boltzmann method to simulate the aqueous humor flow in normal eyes.

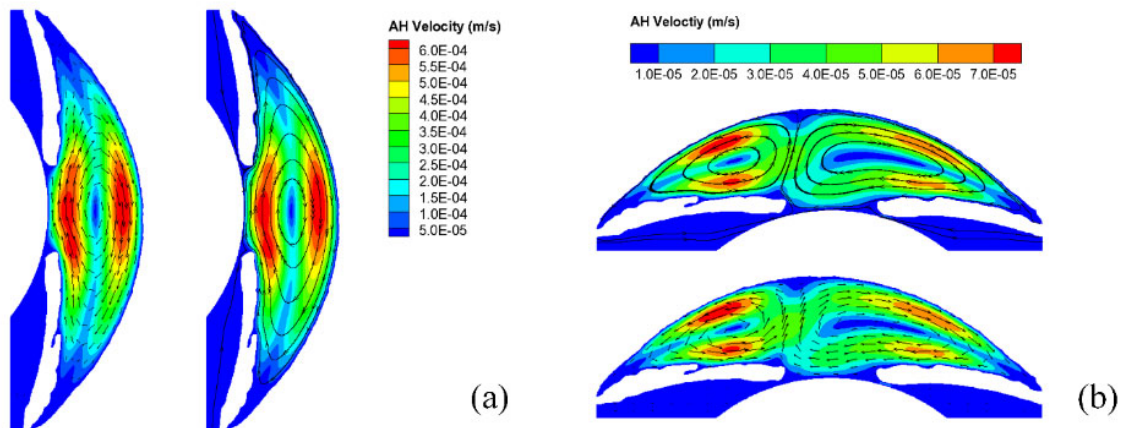


Figure 6. Velocity vector diagram and streamline diagram of aqueous humor in normal eyes

The aqueous humor velocity distribution in normal eyes is shown in Figure 6. In the standing situation, aqueous humor is produced from the ciliary body, then flows from the posterior chamber to the space between the lens and iris, and enters the anterior chamber through the pupil. The aqueous humor in the anterior chamber circulates driven by the temperature difference between cornea and intraocular tissues,

forming a clockwise vortex. The maximum velocity of aqueous humor appears in two areas near the lens and cornea on the pupil axis, and the maximum velocity is $6.53 \times 10^{-4} \text{m/s}$. Finally, aqueous humor is discharged from the small beam net and enters the blood circulation system. Under the condition of lying down, the aqueous humor flowing from the posterior chamber forms two vortices in opposite directions in the

anterior chamber. The aqueous humor flows from the pupil to the inner surface of the cornea along the contact line of the two vortices, and then flows to the two corners of the chamber respectively, with the maximum velocity of $7.88 \times 10^{-5} \text{ m/s}$.

In our numerical simulation, we also found some small eddy currents in the iris recess, as shown in Figure 7. In an ideal model, the iris surface is often assumed to be a smooth wall, and these phenomena cannot be observed during simulation. However, in the eyes of real people, the iris surface itself is not smooth, and there are many recesses. It is these special structures that cause the flow pattern of aqueous humor on the iris surface to change, resulting in small vortices. This further shows that compared with the ideal model, the geometric modeling method based on real human eyes can obtain more accurate and reliable results.

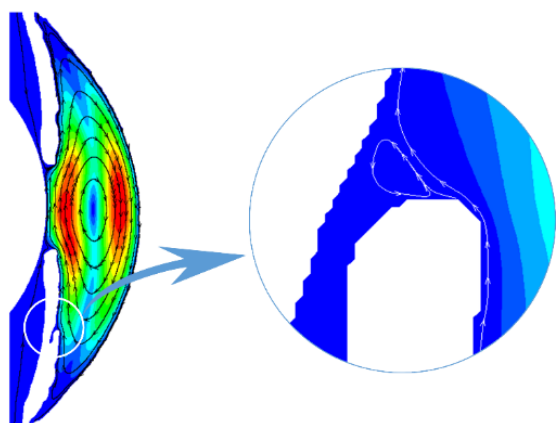


Figure 7. Vortex at iris recess

4. Conclusion

In this paper, firstly, the OCT image of the anterior segment is processed by image processing technology, and the image denoising method based on Lattice Boltzmann anisotropic diffusion model is used to denoise the image. The geometric contour of the anterior segment is extracted from the denoised image by using Lattice Boltzmann isotropic diffusion model, and the structure of the posterior chamber is reconstructed according to the anatomical parameters of the human eye, and a geometric model that can be used for LB numerical simulation is established. Then, based on the geometric model established by the OCT image of the anterior segment of normal eyes, the aqueous humor flow in human eyes is simulated by the model, the velocity distribution information

of aqueous humor is obtained, and the phenomenon of vortex in iris recess is observed. The results show that this method can reflect the aqueous humor flow in real eyes more accurately, and at the same time, some physiological and pathological parameters that are difficult to measure directly can be obtained, which can provide a numerical theoretical reference for ophthalmology.

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