Physiology & Behavior 135 (2014) 112–118

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/phb

Physiology of aqueous humor dynamic in the anterior chamber due to rapid eye movement

SeyedAmirreza Modarreszadeh [a], Omid Abouali [a,*], Alireza Ghaffarieh [b], Goodarz Ahmadi [c]

[a] School of Mechanical Engineering, Shiraz University, Shiraz, Iran
[b] Department of Ophthalmology and Visual Sciences, University of Wisconsin, Madison, WI, USA
[c] Department of Aeronautical and Mechanical Engineering, Clarkson University, Potsdam, NY, USA

HIGHLIGHTS

- The CFD technique was performed for simulation of the Rapid Eye Movement (REM).
- REM generates complex 3D flow pattern and has major effect on the mixing of the AH.
- REM can induce higher mixing during sleep compared with most of other mechanisms.
- REM is responsible for mixing of AH and carrying the nutrients to the cornea.
- The shear stresses caused by REM on the cornea are not in the damaging range.

ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 28 April 2014
Accepted 16 May 2014
Available online 24 May 2014

Keywords:
Eye
Anterior chamber
Aqueous humor
REM
CFD

ABSTRACT

The nature of aqueous humor (AH) mixing in the anterior chamber (AC) of the human eye due to rapid eye movement (REM) has not been fully understood and has been somewhat a controversial issue. This study uses a computational modeling approach to shed light on this issue. For this purpose a numerical method was developed and used to solve the mathematical equations governing the flow and mixing of aqueous humor motion in the eye subjected to such movements. Based on the experimental measurements available in the literature for the average and maximum amplitudes of the eye movements, a harmonic model for the REM was developed. The corresponding instantaneous and time-averaged velocity fields were evaluated. The simulation results showed that, contrary to earlier reports, the REM led to complex flow structures and a 3-D mixing of AH in the anterior chamber. In addition, the mixing velocity increased in direct proportion to the REM amplitudes. Thus, the AC flow generated by REM could carry nutrients to the posterior surface of the cornea during the sleep. Furthermore, the shear stress acting on the corneal endothelial cells due to REM was computed and compared with that of buoyancy driven flow in the AC due to temperature gradient. It was found that the shear stress generated by REM is much higher than that introduced by the natural convection. A video file for providing a better understanding of the AH mixing process in the AC was also prepared. This video is available on the web.

1. Introduction

Rapid eye movement (REM) refers to the random movement of the eyes in a normal stage of sleep. REM sleep is characterized by rapid (and typically jerky) movements of the eyes behind closed lids. These movements appear to take place in all directions and may involve single disconnected movements or oscillatory motions. The REM sleep period typically occupies 20–25% of the total sleep in adult humans and decreases with aging. For newborn babies, 80% of total sleep time is in the REM phase [1]. During a normal night's sleep, humans typically experience four or five REM periods, which are short at the beginning and become gradually longer. It should be noted that the REM during sleep was discovered and first reported by Aserinsky and Kleitman [2].

REM has been of interest to many researchers in the fields of ophthalmology, psychology, neurology and psychiatry. Two different ideas regarding REM sleep are relatively popular among scientists and even the public. One idea is that the rapid eye movements are related to watching dream imagery; however, the idea more accepted in the scientific community is that the REM occurs when the brain sorts and reprocesses the information gathered during the day (similar to a computer hard disk defragmentation process). Crick and Mitchison [3] suggested that the function of REM sleep is to remove certain undesirable modes of interaction in cell networks of the cerebral cortex. Hobson [4] hypothesized that sleep is a complex neurobiological and

* Corresponding author. Tel.: +98 711 613 3034; fax: +98 711 628 7294.
E-mail address: abouali@shirazu.ac.ir (O. Abouali).

http://dx.doi.org/10.1016/j.physbeh.2014.05.017
0031-9384/

Table 1
The data for REM measured by Takahashi and Atsumi [9].

	Frequency (per minute)	Amplitude (deg)	Speed of rotation (deg/s)	REM power (deg^2/s)
Mean	15.9	6.27	58.73	525.85
SD	–	4.86	40.9	884
Max	–	61.51	491.98	19,014.97
Min	–	1.23	8.85	9.08

behavioral strategy for simultaneously promoting energy regulation and automatic information processing by the brain. He postulated that the reciprocal interaction with cholinergic neuronal functions, which favors energy conserving states for processing internal data, leads to REM sleep and dreaming.

Maurice [5] presented an important alternative on the importance of REM sleep. Earlier, Maurice [6,7] had shown that nutrients that are required to sustain the cornea cannot come from the limbus and must be carried to the posterior surface of the cornea by the aqueous humor motion in the anterior chamber. Among the studies of corneal vascularization in a patient without any ocular motility, Maurice [5] hypothesized that there should be a reason for the aqueous flow in the anterior chamber when the eyelids are open. The buoyancy mechanisms (as a result of the temperature difference between the cornea and iris and lens) are normally responsible for stirring the aqueous humor in the anterior chamber. However, this raises the question of how the nutrients reach the cornea when people are asleep, when the eyelids are closed and there is no buoyancy-driven motion of aqueous humor in the anterior chamber. Maurice [5] suggested that one important consequence of the REM may be to promote mixing in the otherwise stagnant aqueous humor so that the oxygen and nourishment supply to the cornea could be maintained. To provide a better understanding of this process, Holm [8] performed an experimental investigation for assessing the mixing of the aqueous humor in a rabbit eye due to the REM.

Takahashi and Atsumi [9] analyzed individual eye movements during REM sleep from 40 nights of polysomnography for 20 healthy young men. They reported that the mean frequency of eye movement (EM frequency) was 15.9 per minute. The mean amplitude of eye movement rotation was 6.27 ± 4.86 deg (maximum = 61.51 and a minimum = 1.23 deg); the mean speed of rotation was 58.73 ± 40.9 deg/s (maximum = 491.98, minimum = 8.85); and mean REM power (defined as $(\text{REM rotation})^2$ / (REM duration) as an estimation of expended energy) was 525.85 ± 884.0 deg^2/s (maximum 19,014.97, minimum 9.08). The data of Takahashi and Atsumi [9] which are used in the present study are summarized in Table 1. The average time of movement was around 0.1 s with a typical mean sagittal diameter of 24 mm for the eye globe.

Fitt and Gonzalez [10] presented a comprehensive review of the AH flow in the AC. They tried to assess whether such movements are sufficient to generate the required amount of mixing. They also discussed the physical mechanisms that are responsible for different kinds of flow that may take place in the AC of a human eye. They concluded that the buoyancy effect induced by temperature gradients in the AC is the dominant mechanism for causing anterior chamber flow. Because of the complexity of the flow mixing in the AC due to eye movement, however, they could not find an analytic solution. They noted that if the eye movement is purely translational, then the AH moves as a rigid body with no mixing. Despite their comprehensive study, Fitt and Gonzalez [10] concluded that rapid eye movement cannot produce aqueous mixing; this conclusion led Ooi and Ng [11] to ignore the AH flow due to AC rotation in their study. Nevertheless, a computer simulation by Abouali et al. [12] conclusively showed that saccade movements led to significant AH mixing in the AC.

The anterior chamber shown schematically in Fig. 1(a) is a space inside the eye between the iris and innermost surface of the cornea, which is filled with aqueous humor [1]. AH inflates the globe of the eye by maintaining the intraocular pressure and provides the nutrients needed for the ocular tissues, including the posterior cornea, trabecular meshwork, lens and anterior vitreous. The ciliary body secretes the AH into the posterior chamber, and then this fluid flows through the narrow cleft between the lens and the iris in order to escape through the pupil into the anterior chamber. The AH finally drains out of the eye via the trabecular meshwork.

AH flows inside the AC are generated by various mechanisms, namely: 1) natural convection due to temperature difference between the cornea and iris; 2) secretory flow from the ciliary body through the pupil aperture and ultimately into the trabecular meshwork; and 3) the mixing of

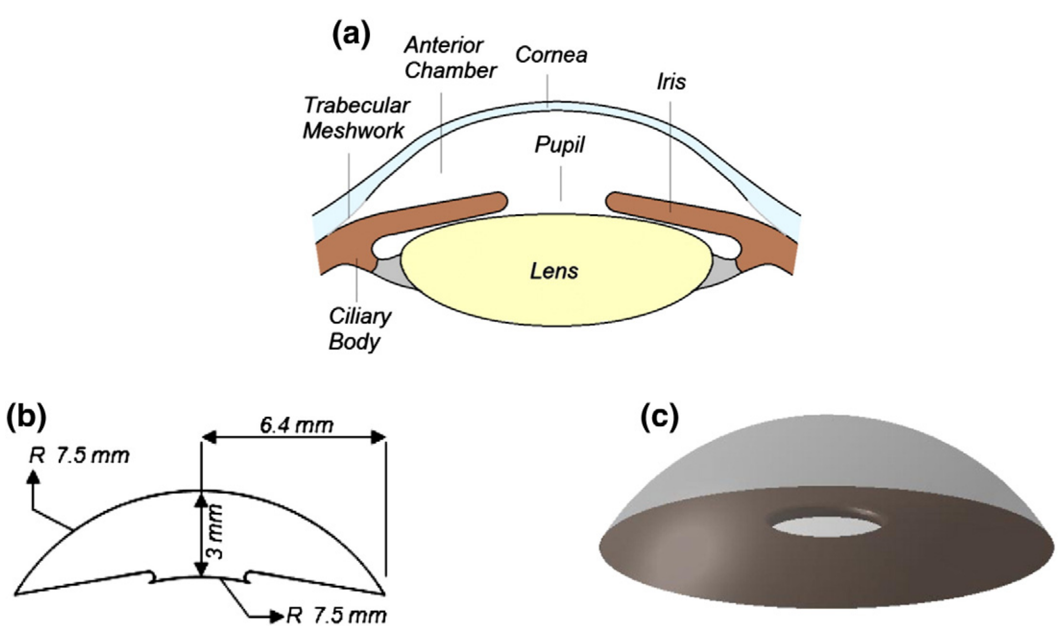

Fig. 1. (a) The anatomy of the anterior chamber (b) A cross section of the computational model for the anterior chamber (c) A 3-D perspective view of the anterior chamber.