Original Research Article

Controversial Issues of the Mechanism of Crystalline Lens Accommodation and the Rationale the Hydraulic Component in Its Implementation

ABSTRACT

Purpose: To consider controversial issues of the mechanism of crystalline lens accommodation and to justify the hydraulic component in its implementation.
Materials and Methods: Theories of the mechanism of accommodation and its assessment according to ultrasound biomicroscopy, magnetic resonance imaging and optical coherence tomography were analyzed. For the first time, the features of accommodative activation of intraocular fluid exchange in the closed hydrostatic system of the lens with the participation of mechanosensitive aquaporins were considered. When substantiating the hydraulic component in the mechanism of the crystalline lens accommodation, special emphasis was placed on the rapid decrease in pressure in the anterior and posterior chambers of the eye during contraction of the meridional portion of the ciliary muscle.
Results: Analysis of various theories of accommodation has shown that mechanism of the crystalline lens its implementation continues to be discussed to this day. For the first time, the lens was considered as a unique closed hydrostatic system in which the pressure level is established through ultrafiltration and diffusion of intraocular fluid with the participation of aquaporins. Aquaporins form ion channels in the capsule, cuboidal epithelial cells, lens fibers and are mechanosensitive receptor proteins. The opening and closing of ion channels regulates the potassium-sodium pump, directed transport and exchange of intraocular fluid in the lens. The hydrostatic balance between the pressure in the crystalline lens and the anterior and posterior chambers of the eye is ensured by the crystalline lens capsule. The capsular bag of the crystalline lens can be considered as a curved diaphragm that separates two hydrostatic systems with different levels of pressure. Due to the hydrostatic buffering effect, the IOP level does not affect the crystalline lens, but it responds to a rapid decrease. This decrease in pressure in the anterior and posterior chambers is realized through the tension of the scleral spur by the meridional portion of the ciliary muscle and the activation of the valve mechanism of the scleral sinus. The greater the decrease in pressure, the more convex the crystalline lens takes on and increases its refraction.
Conclusion: The presence of a hydraulic component in the mechanism of crystalline lens accommodation allows us to understand how the contraction of the small ciliary muscle can change the shape and refractive power of the large crystalline lens.

Key words: crystalline lens, vision, eyeball, ciliary muscle, hydraulic component, lens accommodation, aquaporins, scleral sinus.

1. INTRODUCTION

Accumulated new data on the accommodation of the human eye indicate the participation in its implementation of the entire iridocyclolenticular complex, the vitreous body, extraocular muscles and hydrohemodynamic fluctuations in the eye [1-6]. In this case, the leading role is given to crystalline lens accommodation, the mechanism of which continues to be debated among ophthalmologists to this day. First of all, this concerns the question of how strong the small ciliary muscle must be in order to, through the tension and relaxation of the ligaments of Zinn, cause changes in the shape and refractive power of such a voluminous crystalline lens. No less controversial is the question why, at rest of accommodation, the ciliary muscle is relaxed, and the Zinn ligaments are stretched. Contradictory is the position according to which the Zinn ligaments relax during contraction of the ciliary muscle, despite the fact that the diameter of the crystalline lens decreases. Finally, the predominant change in the curvature of the anterior surface of the crystalline lens and the sufficiency of the elastic properties of its capsule to change the shape of crystalline lens during accommodation require explanation.

All of the above questions need to be discussed, and the mechanism of crystalline lens accommodation needs to be clarified.

1.1 Purpose

Consider controversial issues of the mechanism of crystalline lens accommodation and to justify the hydraulic component in its implementation.

2. MATERIALS AND METHODS

Theories of the mechanism of accommodation and its assessment according to ultrasound biomicroscopy, magnetic resonance imaging and optical coherence tomography were analyzed. For the first time, the features of accommodative activation of intraocular fluid exchange in the closed hydrostatic system of the crystalline lens with the participation of mechanosensitive aquaporins were considered. When substantiating the hydraulic component in the crystalline lens accommodation mechanism, special emphasis was placed on the rapid decrease in pressure in the anterior and posterior chambers of the eye during contraction of the meridional portion of the ciliary muscle. In addition, a new concept of the energy-saving work of accommodation was considered, taking into account modern ideas about the role of the iridocyclolenticular complex, scleral sinus, extraocular muscles and vitreous body in hydro- and hemodynamic shifts in response to an accommodative stimulus.

3. RESULTS and DISCUSSOINS

Studies by various authors assessing changes in the shape of the crystalline lens during accommodation have revealed an increase in its thickness and a decrease in the equatorial diameter. Such changes were confirmed by ultrasound biomicroscopy, magnetic resonance imaging (Fig. 1) and optical coherence tomography. During accommodation, the profile of the anterior surface of crystalline lens became steeper and the depth of the anterior chamber decreased. In this case, only minor changes in the profile of the posterior surface of crystalline lens, the depth of the vitreous chamber and the axial length of the eye were noted [7-12].

An analysis of various theories of accommodation has shown that the mechanism of crystalline lens and its implementation continues to be discussed by ophthalmologists around the world to this day [2-6]. The main position of Helmholtz's theory, that at rest of accommodation the ciliary muscle is relaxed and the ligaments of Zinn are tense, conflicts with physiology, when contraction of the muscle causes tension in the ligament [2]. According to modern data, the lens ligaments do not have direct attachment to any portion of the ciliary muscle, and the end point of their fixation is the anterior cortical layers of the vitreous. It is enough to note that the most powerful and longest meridional portion of the ciliary muscle is attached at one end in the area of the scleral spur and corneoscleral trabecula, and its second end is woven into the choroid [1-3]. That is why the question of how the small ciliary muscle changes the shape and refractive power of the large crystalline lens remains debatable. It is difficult to agree with the change in the shape of crystalline lens due to relaxation of the ligaments of Zinn, since during accommodation the equatorial diameter of crystalline lens decreases [2]. Taking into account the above, it is legitimate to say that the ligaments of Zinn act as a supporting apparatus. This ensures a stable position of the lens during accommodation and avoids phacodonesis.

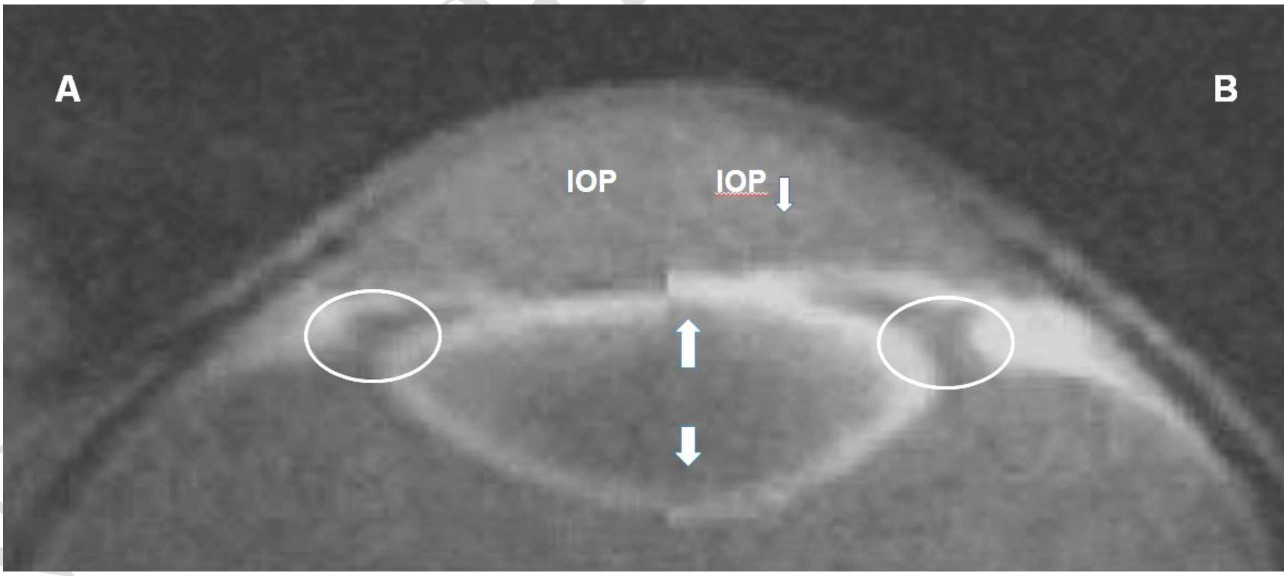

Fig.1. Changes in the depth of the anterior chamber, volumetric ratios between the value Volumetric relationships between the depth of the anterior chamber, the size ciliary muscle and crystalline lens at rest (A), under tension accommodation (B) and rapid decrease in IOP (B) in the anterior region eyes (according to magnetic resonance imaging).

It is not possible to explain the change in the shape of crystalline lens during accommodation only by the elastic properties of the capsule and the varying degrees of its tension by the ligaments of Zinn. An overestimation of the importance of the capsular bag in changing the shape of crystalline lens is indicated by the fact that upon completion of refractogenesis, the elasticity of the capsule decreases. This is indicated by the lack of expansion of the circular capsulorhexis when removing the transparent crystalline lens for refractive purposes in young patients. In addition, with accommodation stress, due to a decrease in the diameter of crystalline lens, there is no decrease in the distance between the equatorial profile of crystalline lens and the profile of the edge of the ciliary body (Fig. 1). This was confirmed by magnetic resonance imaging, ultrasound scanning and optical coherence topography data [7-12].

All of the above controversial issues of crystalline lens accommodation indicate the need to study other mechanisms in its implementation.

The new concept of the presence of a hydraulic component in the implementation of crystalline lens accommodation mechanism is based on the features of the closed hydrostatic system of the lens, the transport of intraocular fluid in crystalline lens with the participation of mechanosensitive aquaporins, the presence of a hydrostatic buffer effect, the activation of the valve mechanism of the scleral sinus during contractions of the ciliary muscle and the rapid decrease in pressure in the anterior and posterior cameras of the eye,

We propose to consider crystalline lens as a unique closed hydrostatic system in the eye, limited by an elastic capsule. In this system, the required level of pressure is ensured by active directed transport of intraocular fluid. Such directed transport of intraocular fluid from the anterior to posterior cortical layers of crystalline lens and further into the vitreous body has been proven by experimental studies [13-16]. Mechanosensitive aquaporins are of particular importance in the transport and exchange of intraocular fluid in the eye [17-24]. Aquaporins (AQPs) are a class of transmembrane proteins that function as water channels. These water channels exist in 13 known isoforms (AQP0-AQP12) and act to move water across biological membranes through osmotically driven passive diffusion [21]. Aquaporins form ion channels in crystalline lens capsule, subcapsular cuboidal epithelium and lens fibers and selectively allow water molecules to pass through (Fig.2). They are very sensitive to fluctuations in intraocular pressure, regulate the transfer of intraocular fluid and the operation of the potassium-sodium pump. A special role in this is given to the cubic epithelium in the central and peripheral zones of the anterior capsule of crystalline lens. These cells do not have mitotic activity and perform the function of active directed transport of intraocular fluid from the anterior to posterior cortical layers of crystalline lens. Normally, the water content in the lens ranges from 60 to 65% and it can be considered as a complex hydrocolloid structure containing water-soluble proteins represented by α-, β- and γ-crystallins. It should be noted that soluble cytoplasmic proteins form an ordered gel, in which the value of the refractive index depends on the level of hydrostatic pressure [25]. In addition, the fibers of the cortical layers of the lens also contain ion channels of mechanosensitive aquaporins, which are involved in the transport of intraocular fluid. We believe, that mechanosensitive aquaporins act as microvalves that open, constrict, or close ion channels in the lens at certain magnitudes of IOP fluctuations. Depending on the nature of the accommodative load, this can maintain the required level of optical pressure inside crystalline lens, affect the hydrocolloid structure, the degree of compaction of the lens fibers, the refractive index and the refractive power of crystalline lens. Such changes in the lens may explain the development of various accommodative disorders. According to the literature, ion channels represented by aquaporins are capable of responding to mechanical stress in a wide range of external mechanical stimuli. Ion channels have the shape of a narrow slit in the center and widening at opposite ends (Fig.2). With this form of ion channel, water can only penetrate in the form of a thin chain of molecules connected by hydrogen bonds. It should be noted that aquaporins are a type of mechanosensitive receptor proteins present in membrane structures and cell membranes in all human organs and tissues. They were first identified in 2010 by a team of scientists led by Ardem Pataputyan, and he was awarded the Nobel Prize in Physiology or Medicine in 2021 for their discovery.

In our opinion, in the ion channels of the capsule, cuboidal epithelium and crystalline lens fibers, mechanodependent aquaporins provide activation of intralenticular fluid transport, the required level of intralenticular pressure and the accommodative ability of crystalline lens. Aquaporins (AQPs) carry out rapid transport of large amounts of liquid and are capable of transporting 3x109 water molecules per second per monomer [25]. It is possible that the pressure inside crystalline lens may even slightly exceed the level of IOP, which is due to the active function of transport of intraocular fluid by aquaporins of the cuboid epithelium and its passive diffusion through the posterior capsule, where the cuboid epithelium is absent. In the closed hydrostatic system of crystalline lens, there is a directed flow of fluid from the anterior to the posterior cortical layers, followed by its diffusion into the retrolental space through the thinnest posterior capsule of crystalline lens in the central optical zone (Fig. 2). The question of the participation of aquaporins in the directed transport of intraocular fluid through the posterior capsule and cortical layers of crystalline lens into the central nuclear zone (Fig. 2), and its outflow through the equatorial part of crystalline lens capsule is debatable [21]. It is difficult to agree with this route of outflow of intrauterine fluid. It is enough to note that the thickness of the capsule in the equatorial part is 4-5 times greater than the thickness in the central zone of the posterior capsule. Moreover, in the equatorial part there are larger cuboidal epithelial cells with mitotic activity (Fig. 2). As already noted, the directed flow of intraocular fluid from the anterior to the posterior cortical layers, then into the retrolental space and the vitreous body has been proven by experimental studies of a number of authors [12-16]. It should be noted that the lenticomacular canal begins from the retrolental space, limited by the Viger's capsular-vitreal ligament. In this channel, there is a

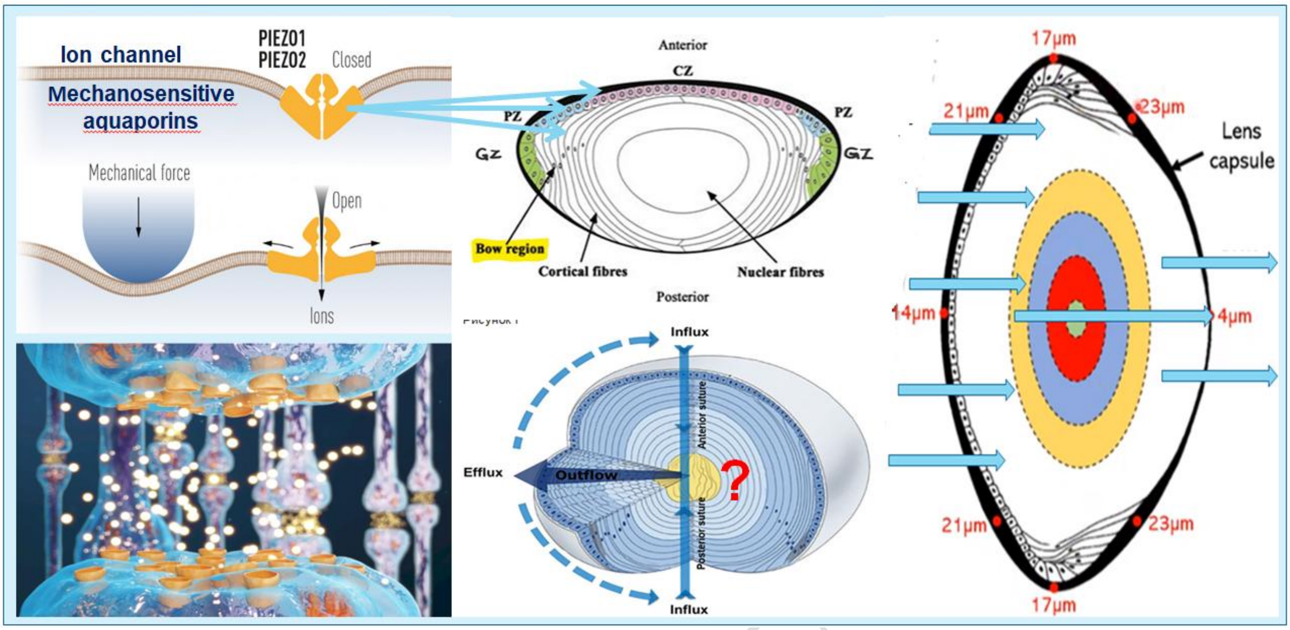

Fig.2. Directed transport of intraocular fluid in a closed hydrostatic system of the crystalline lens with the participation of mechanosensitive aquaporins.

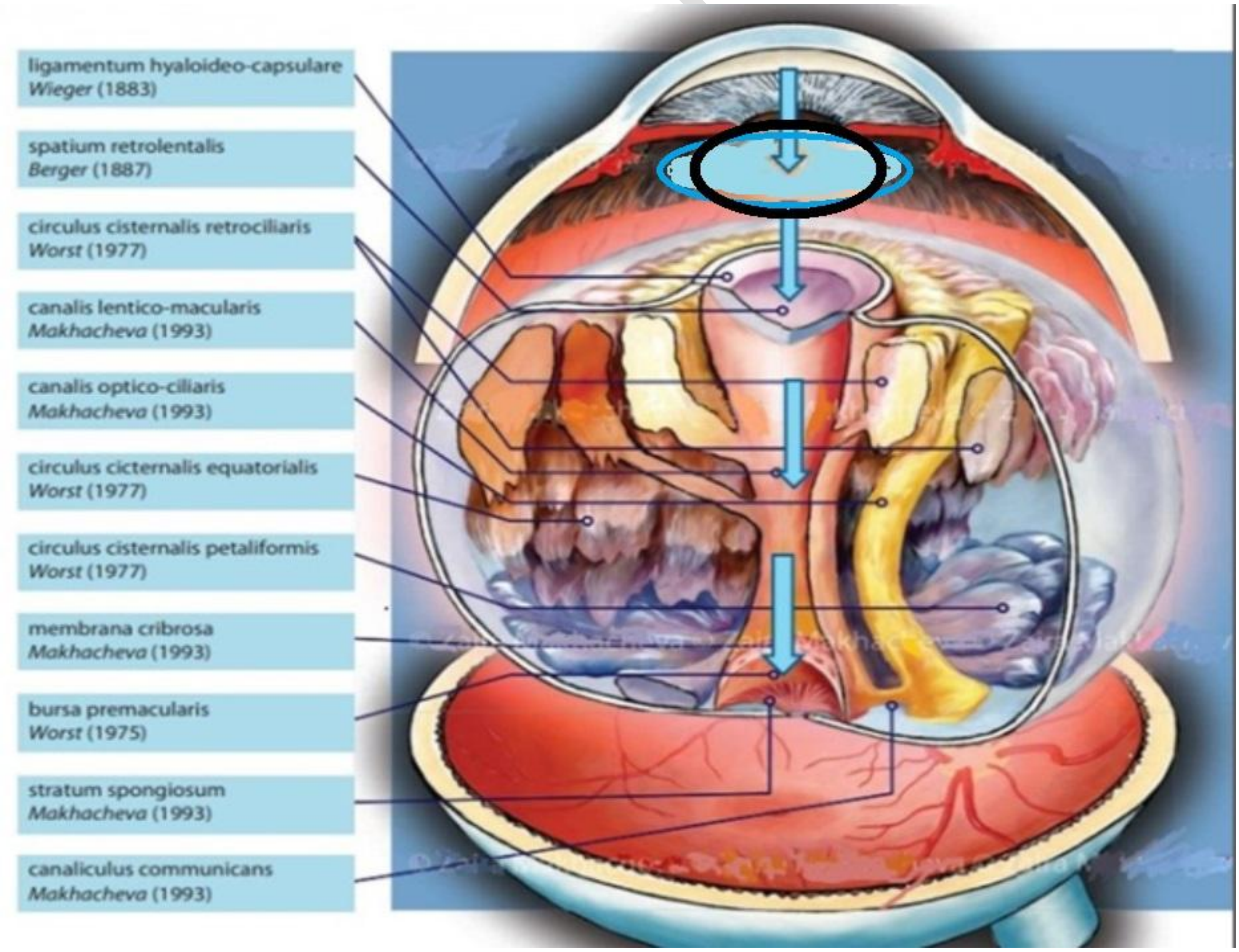

Fig.3. Accommodative activation of intraocular fluid circulation in the lentico-macular canal of the vitreous body.

directed flow of intraocular fluid and its transretinal dialysis in the macula. Accommodative activation of the circulation of intraocular fluid in the lenticomacular canal (Fig. 3) plays an important role in the functional preservation of the macular region of the retina. Due to the high concentration of ascorbic acid in the intraocular fluid, which exceeds that in the blood plasma by 25-50 times, the inactivation of peroxide radicals formed during the photochemical reaction is ensured. At the same time, directed transretinal dialysis of intraocular fluid in the macular region of the retina is also carried out with the participation of retinal aquaporin-4 [26] and along the gradient of oncotic pressure of blood proteins in the choroid. It is no coincidence that the thickness of the choroid in the macular region is greater than in its other parts.

The pressure in the closed hydrostatic system of crystalline lens plays an extremely important role in the implementation of the hydraulic component of the mechanism of lens crystalline accommodation. Just a rapid decrease in pressure in the anterior and posterior chambers of the eye is enough for crystalline lens to take the shape of a “convex” ellipsoid and increase its refractive power.. At the same time, the main regulator of rapid IOP fluctuations is the scleral sinus (Schlemm’s canal). The relationship of the ciliary muscle with the trabecular apparatus and scleral sinus is not accidental. There is evidence that trabeculae are connective tissue fibers of the ciliary muscle, cornea and sclera, stretched during goniogenesis, and the inner wall of the scleral sinus (Schlemm’s canal) contains the tendons of the ciliary muscle [27]. The varying degrees of opening and functional reversible blockade of the scleral sinus during contractions and relaxations of the ciliary muscle allows us to consider it as a unique valve mechanism that provides rapid fluctuations in pressure in the anterior part of the eye during accommodation. In this case, the decrease in pressure in the anterior and posterior chambers outpaces its increase in the posterior part of the eye during accommodation and convergence. It is these hydrodynamic shifts in the anterior part of the eye that change the shape of crystalline lens. Moreover, the profile of the anterior surface of crystalline lens becomes steeper. Such changes can be explained by Laplace’s hydraulic law, according to which the anterior capsule, which has a larger radius of curvature, experiences greater intralens pressure. In addition, it is necessary to take into account the fact that the thickness of the anterior capsule in the center of crystalline lens is 3.5 times greater than in the center of the posterior capsule and their average values are 14 µm and 4 µm, respectively (Fig. 2). In this regard, in the anterior capsule there is initially less internal tension and greater extensibility with a rapid decrease in pressure in the anterior chamber. In addition, during accommodation and convergence, stretching of the posterior capsule is counteracted by an increase in pressure in the retrolental space.

The entire iridocyclolenticular complex (ICLC) takes part in the implementation of the mechanism of crystalline lens accommodation. In this complex, crystalline lens can be considered as a kind of pump that pumps intraocular fluid from the anterior part of the eye into the vitreous body. In other words, there is an accommodative activation of the intraocular fluid circulation in the hydrostatic system of the vitreous body. All of the above allows us to consider ICLC as an activator of hydrodynamics and hemodynamics in the eye. With contractions and relaxations of the ciliary muscle, the outflow of intrascleral fluid from the scleral sinus into the collector canals and further into the interconnected intrascleral and episcleral venous plexus increases. In addition, with contractions and relaxations of the ciliary muscle, blood flow and secretion of intraocular fluid in the ciliary processes are activated (Fig. 4). From these positions, the ICLC can be called the heart of the eye, which beats in a certain rhythm during visual perception of the world around us and determines the safety of all intraocular structures [2]. Disruption of the ICLC in presbyopia can be considered as an important pathogenetic link in the development of age-related pathologies such as cataracts, glaucoma and macular degeneration of the retina.

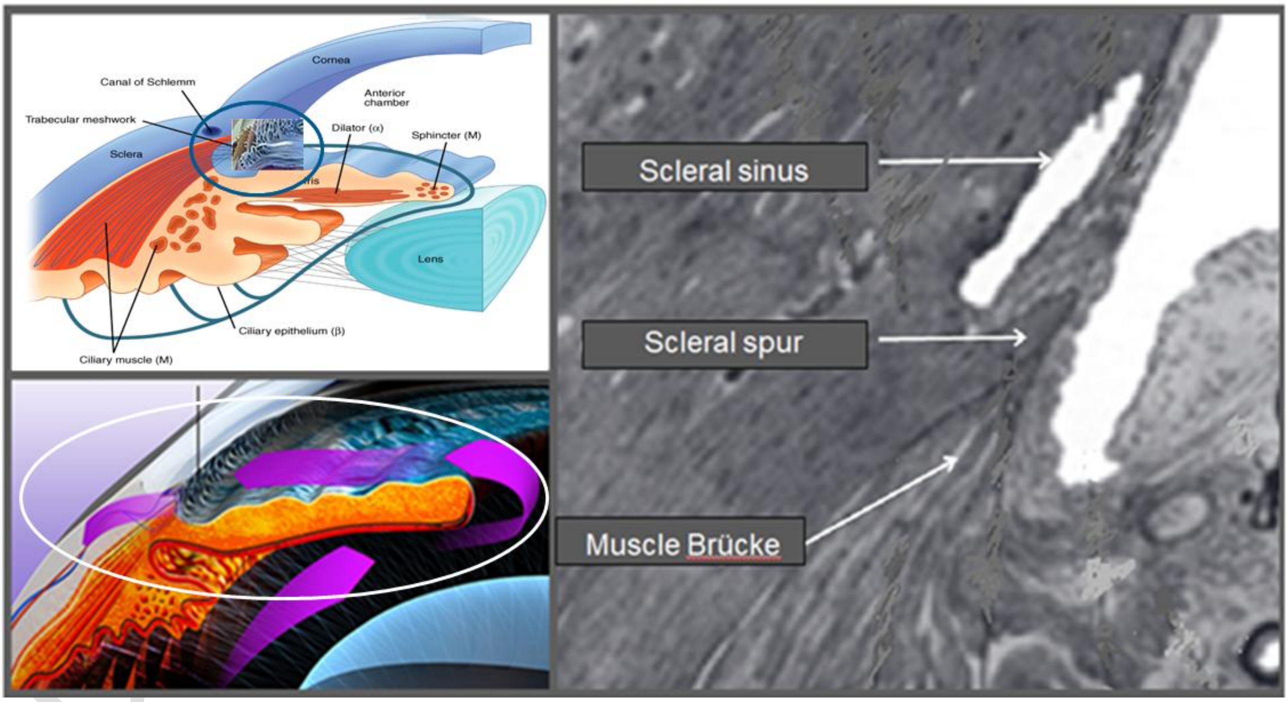

Fig.4. Activation of intraocular fluid circulation in the angle of the anterior chamber during accommodative contraction of the Brücke muscle, tension of the scleral spur, corneoscleral trabeculae, expansion of intertrabecular spaces and scleral sinus.

It should be noted that in the mechanism of accommodation, the ciliary muscle retains its leading position and plays an extremely important multifunctional role. This role is to ensure varying degrees of tension of the scleral spur, corneoscleral trabecula, expansion of intertrabecular gaps and activation of the valve mechanism for regulating the lumen of the scleral sinus, redistribution of blood flow in the secretory part of the ciliary body and activation of the secretion of intraocular fluid [2]. It is necessary to once again emphasize that it is due to the valve mechanism of the scleral sinus that the effect of a rapid decrease in IOP in the anterior and posterior chambers during accommodation is realized. Under the influence of greater pressure in crystalline lens, its shape and refractive power change. From the perspective of the new concept of the hydraulic component in the implementation of the mechanism of crystalline lens accommodation, it becomes clear how contraction of a small ciliary muscle can change the shape of such a voluminous lens.

The formation of accommodation in the human eye has gone through a long evolutionary path, and it has become more advanced from the standpoint of biomechanics and economical from an energy point of view. Research by various authors indicates that the ability of the eye to see objects at different distances is realized not only through a change in the refractive power of the lens. This involves a whole complex of interconnected structures of the eye, which ultimately determine the ability to see objects at different distances and provide work at close ranges of varying durations. Among all the structural elements of the eye, the iridocyclolenticular complex (ICLC) should rightfully be considered the leading one in the implementation of the energy-saving mechanism of accommodation. This complex plays an extremely important role in the act of visual perception, hydrodynamics and hemodynamics of the eye. It is enough to note the important role of the diaphragmatic function of the iris, when only constriction of the pupil can lead to a decrease in optical aberrations, increase visual acuity and increase the depth of clinical focus. With emmetropia, such an increase in the depth of focus is sufficient to view objects at a distance of more than a meter, without the participation of crystalline lens accommodation. In addition, when working at close range, convergent muscle tensions and hydraulic shifts in the vitreous lead to anterior displacement of the entire ICLC. If pupillary and muscular compensation of the response to an accommodative stimulus is insufficient, crystalline lens accommodation is activated. In this case, there is a contraction of various portions of the ciliary muscle, tension of the scleral spur, expansion of the intertrabecular gaps, scleral sinus and a rapid decrease in IOP in the anterior part of the eye. This is accompanied by a change in shape and an increase in the refractive power of crystalline lens. In all cases, the tension and relaxation of the scleral spur and corneoscleral trabeculae by the ciliary muscle triggers the valve mechanism of the scleral sinus. It is the presence of a hydraulic component in crystalline lens accommodation mechanism that allows, with minimal energy costs, to increase the refractive power of crystalline lens for working at close range. With tension and relaxation of various parts of the ciliary muscle, the uveoscleral outflow tract and the transition of the intravenous fluid from the scleral sinus to the collector tubules, which are connected to the superficial and deep venous plexuses, are activated (Fig. 4). An increase in pressure and an increase in the speed of movement of intraocular fluid in the collector tubules, in turn, activates blood flow in the venous system of the eye. It can be assumed that it is the appearance of the scleral sinus (Schlem's canal) in primates and humans that plays an important role in the formation of the effect of rapid IOP fluctuations in the anterior segment of the eye and is directly related not only to the close relationship between the hydrodynamic and hemodynamic systems of the eye, but also directly to the act accommodation. Due to the activation of the valve mechanism of the scleral sinus, the effect of a rapid decrease in IOP in the anterior segment of the eye is realized, which is ahead of the monocular accommodative and binocular accommodative-convergent increase in IOP with corresponding hydrodynamic shifts in its posterior segment. In our opinion, hydrodynamic shifts in the posterior part of the eye during accommodation and convergence have their own mechanism of implementation. In this mechanism, a special role is played by the direct connection of the retrolental space with the current and exchange of intraocular fluid in the vitreous body. During accommodation, a kind of hydraulic shock occurs, transmitting the pressure of the fluid of the retrolental space to the lens.

According to the new concept, significant tension and relaxation of the Zinn's ligaments is not required to implement lens accommodation. In fact, in this case, all the work of the ciliary muscle comes down only to better tension the scleral spur, expanding the intertrabecular gaps, the scleral sinus, and activating the outflow of the intraocular fluid. In this case, it is necessary to take into account the stimulating effect of ciliary muscle contractions in activating blood flow and secretion of intraocular fluid in the ciliary processes. The hydraulic component in the implementation of lens accommodation, in our opinion, is quite legitimate from an energy point of view and provides a number of other important functions. These functions consist of activating the directional flow of intraocular fluid and its exchange in the lens, stimulating hydrodynamics in the vitreous channels and activating hemodynamics with the redistribution of blood flow in the tissues of the anterior and posterior parts of the eye.

In 2010, we were the first to propose an energy-saving hydrohemodynamic theory of accommodation [2]. According to this theory, in the mechanism of crystalline lens accommodation, an important place was given to the hydraulic component and the valve mechanism of the scleral sinus. However, the interpretation of such a mechanism of crystalline lens accommodation turned out to be not entirely correct. The weak point in this theory of accommodation turned out to be the position according to which, under the influence of IOP, the normal crystalline lens is flattened and has the shape of a "compressed" ellipsoid. This is precisely what caused fair criticism of the hydraulic component in the accommodation mechanism, since the features of the hydrostatic buffer effect were not taken into account. Research by A.P. Nesterov [28] showed that all intraocular tissues can be considered as diaphragms that separate chambers, cavities and slit-like spaces. Thus, each intraocular structure is surrounded by fluid under approximately the same pressure, and therefore does not experience the mechanical action of the entire ophthalmotonus. No matter how high it rises, a force not exceeding 2-3 mm Hg acts on the eye tissue. It is due to the presence of this effect that IOP cannot give crystalline lens the shape of a “compressed” ellipsoid. The exception in this regard is the outer shell of the eye, which experiences the effect of the entire ophthalmotonus, and the optic nerve head, due to the pressure difference on both sides of the lamina cribrosa [28].

The crystalline lens taking on the shape of a “convex” ellipsoid and increasing its refractive power during accommodation is possible with a rapid decrease in IOP in the anterior and posterior chambers of the eye. This effect is explained by the fact that crystalline lens is a closed hydrostatic system in which the pressure level is established through ultrafiltration and diffusion of intraocular fluid with the participation of mechanosensitive aquaporins in the capsule, cuboidal epithelium and lens fibers. The hydrostatic balance between the pressure in the lens and the anterior and posterior chambers of the eye is ensured by crystalline lens capsule. In this case, crystalline lens capsule can be considered as a curved diaphragm that separates two hydrostatic systems with different levels of pressure. Even if the pressure inside crystalline lens corresponds to IOP, then with a rapid decrease in pressure in the anterior and posterior chambers, crystalline lens takes on a more rounded shape. The greater this pressure difference, the more the capsule stretches and the more convex crystalline lens takes on. A rapid decrease in pressure in the anterior and posterior chambers is realized through the activation of the valve mechanism of the scleral sinus when the scleral spur is pulled by the meridional portion of the ciliary muscle. The described mechanism is fully consistent with all the provisions of hydrostatics and the effect of reversible functional blockade of Schlemm’s canal in the eye, which were substantiated by the fundamental research of A.P. Nesterov [28]. It is necessary to note the research of Oliveira R.H. et al., which revealed a rapid response of the ciliary muscle to accommodative impulses. The dynamic response of the ciliary muscle to input impulses showed a distinct peak amplitude [29].

All of the above indicates the important role of accommodation, cuboidal epithelium and mechanosensitive aquaporins in the active transport and exchange of intraocular fluid in crystalline lens. Presented new concept of the presence of a hydraulic component in the implementation of lens accommodation expands our clinical understanding of the energy-saving mechanism of accommodation in the perception of the world around us and the possibility of long-term visual performance at close range. The iridocyclolens complex and the valve mechanism of the scleral sinus play an important role in this. It is precisely this mechanism of accommodation, developed in the process of evolution, that is the most adequate from an energetic point of view. The energy-saving concept of the operation of the accommodative apparatus of the eye indicates an important role in its implementation of the diaphragmatic function of the pupil. In addition, the pupillary regulation of the light flux and its accommodative focusing provide the least light load on the retina, allow for the highest image contrast and the formation of a strong accommodative stimulus. This is confirmed by different accommodation under photopic, mesopic and scotopic lighting.

4. CONCLUSIONS

1. The crystalline lens is a closed hydrostatic system in which the required level of pressure is ensured by the active directed transport of intraocular fluid by the cubic epithelium from the anterior to the posterior layers of the cortex with its passive diffusion through the posterior capsule. Mechanosensitive aquaporins take part in this, forming ion channels in the capsule, cuboidal epithelium and lens fibers.

2. With accommodative contraction of the ciliary muscle, the scleral spur and corneoscleral trabecula are tensiled the intertrabecular spaces and scleral sinus are expanded, the outflow of the intraocular fluid increases and the pressure in the anterior and posterior chambers quickly decreases, which outstrips the accommodative-convergent increase in pressure in the posterior part of the eye.

3. Due to the presence of a hydrostatic buffer effect, the crystalline lens does not experience external pressure, however, with a rapid decrease in pressure in the anterior and posterior chambers of the eye, the crystalline lens takes the shape of a convex ellipsoid and increases its refractive power.

4. Different degrees of opening and blockade of the scleral sinus during contractions and relaxations of the ciliary muscle allows us to consider it as a unique valve mechanism that provides rapid fluctuations in IOP in the anterior part of the eye.

5. The hydraulic component in the implementation of the mechanism of crystalline lens accommodation allows us to take a fresh look at the role of the ciliary muscle, Zinn ligaments and scleral sinus in the energy-saving work of accommodation and to understand how the small ciliary muscle can change the shape of such a voluminous lens.

REFERENCES

1. Iomdina E.N., Poloz M.V. Biomechanical model of the human eye as a basis for studying its accommodative ability. Russian Journal of Biomechanics. 2010; 14(3):7-18.
2. Kornilovsky I.M. New energy-saving hydrohemodynamic theory accommodation. Refractive surgery and ophthalmology. 2010;10, (3):16-22.
3. Strakhov V.V., Iomdina E.N. Accommodation: anatomy, physiology, biomechanisms. Accommodation. A guide for doctors, edited by L.A. Katargina. Publishing house “April”, Moscow, 2012:12-34.
4. Ovenseri-Ogbomo GO, Oduntan OA. Mechanism of accommodation: A review of theoretical propositions. Afr Vision Eye Health. 2015; 74(1), Art. 28, 6 pages. http://dx.doi.org/10.4102/aveh.v74i1.28

5. Koshits IN, Svetlova OV, Egemberdiev MB, Guseva MG, Makarov FN, et al. Theory: Morphological and functional features of the structure of the Zonula Lens Fibers as a key executive link in the mechanism of the human eye accommodation. J. Clin. Res. Ophthalmol., 2020; 7(2): 061-074. DOI: https://dx.doi.org/10.17352/2455-1414.000075.
6. López-Gil, N. Gullstrand Intracapsular Accommodation Mechanism Revised. Photonics, 2022; 9:152. https://doi.org/10.3390/photonics9030152
7. Strenk SA, Strenk LM, Semmlow JL, DeMarco JK. Magnetic resonance imaging study of the effects of age and accommodation on the human lens cross-sectional area. Invest Ophthalmol Vis Sci.,2004 Feb;45(2):539-45. doi:10.1167/iovs.03-0092. PMID: 14744896.
8. Tadahiro Mitsukawa, Yumi Suzuki, Yosuke Momota, Shun Suzuki, Masakazu Yamada Anterior Segment Biometry During Accommodation and Effects of Cycloplegics by Swept-Source Optical Coherence Tomography. Clinical Ophthalmology, 2020; 14:1237-1243 DOI:10.2147/opth.s252474.
9. Li Z, Meng Z, Qu W, Li X, Chang P, Wang D and Zhao Y. The Relationship Between Age and the Morphology of the Crystalline Lens, Ciliary Muscle, Trabecular Meshwork, and Schlemm's Canal: An in vivo Swept-Source Optical Coherence Tomography Study. Front. Physiol., 2021;12:763736. doi: 10.3389/fphys.2021.763736.
10. Wang L, Jin G, Ruan X, Gu X, Chen X, Wang W, Dai Y, Liu Z, Luo L. Changes in crystalline lens parameters during accommodation evaluated using swept source anterior segment optical coherence tomography. Ann Eye Sci 2022;7:33. doi: 10.21037/aes-21-70.
11. Rozanova, O.I. Scheimpflug Imaging of the Anterior Eye Segment during Standardized Accommodation Stimulation in Patients with Emmetropia, Myopia and Hypermetropia. Open Journal of Ophthalmology 2023;13:73-82. https://doi.org/10.4236/ojoph.2023.131008.
12. Liu, G.; Li, A.; Liu, J.; Zhao, Y.; Zhu, K.; Li, Z.; Lin, Y.; Yan, S.; Lv H.; Wang, S.; et al. Establishment of Personalized Finite Element Model of Crystalline Lens Based on Sweep-Source Optical Coherence Tomography. Photonics, 2022; 9:803. https://doi.org/10.3390/photonics9110803.
13. Sychev G.M., Lazarenko V.V., Stepanova L.V., Sychev A.G. Direction of transport streams of the bovine lens epithelium. Siberian medical review. 2003;1:.29-31.
14. Sychev G.M., Lazarenko V.V., Sychev A.G., Stepanova L.V., Marchenko I.Yu. Water exchange lens in the surrounding media of the eye. Siberian Medical Review. 2003; 4:55-57.
15. Stepanova L.V. Marchenko I.Yu., Sychev G.M. Direction of fluid transport in lens Bulletin of Experimental Biology and Medicine, 2005; 39 (1): 57-58.
16. Stepanova L.V. Transport functions of the lens epithelium (biophysical aspects) Abstract of the dissertation for the scientific degree of Candidate of Biological Sciences Krasnoyarsk 2005. 19C.
17. Hamann S. Molecular mechanisms of water transport in the eye. Int Rev Cytol. 2002;215:395-431. doi: 10.1016/s0074-7696(02)15016-9. PMID: 11952236.
18. Verkman AS, Ruiz-Ederra J, Levin MH. Functions of aquaporins in the eye. Prog Retin Eye Res. 2008 Jul;27(4):420-33. doi: 10.1016/j.preteyeres.2008.04.001. Epub 2008 May 22. PMID: 18501660; PMCID: PMC3319433.
19. Tran TL, Bek T, Holm L, la Cour M, Nielsen S, Prause JU, Rojek A, Hamann S, Heegaard S. Aquaporins 6-12 in the human eye. Acta Ophthalmol. 2013 Sep;91(6):557-63. doi: 10.1111/j.1755-3768.2012.02547.x. Epub 2012 Sep 13. PMID: 22974000.
20. Tran TL, Hamann S, Heegaard S. Aquaporins in the Eye. Adv Exp Med Biol. 2023;1398:203-209, doi: 10.1007/978-981-19-7415-1_14. PMID: 36717496.
21. Schey KL, Gletten RB, O'Neale CVT, Wang Z, Petrova RS, Donaldson PJ. Lens Aquaporins in Health and Disease: Location is Everything!. Front. Physiol., 2022;13:882550. doi: 10.3389/fphys.2022.882550.

22. Gao, J., Sun, X., Moore, L. C., Brink, P. R., White, T. W., and Mathias, R. T. (2013). The Effect of Size and Species on Lens Intracellular Hydrostatic Pressure. Invest. Ophthalmol. Vis. Sci., 2013; 54:83–192. doi:10.1167/iovs.12-10217.
23. Gao, J., Sun, X., White, T. W., Delamere, N. A., and Mathias, R. T. (2015). Feedback Regulation of Intracellular Hydrostatic Pressure in Surface Cells of the Lens. Biophysics J., 2015;1091:830–1839. doi:10.1016/j.bpj.2015.09.018.
24. Goodman MB, Haswell ES, Vásquez V. Mechanosensitive membrane proteins: Usual and unusual suspects in mediating mechanotransduction. J Gen Physiol. 2023 Mar 6;155(3): e202213248. doi: 10.1085/jgp.202213248.
25. Koroleva I.A., Egorov A.E. Metabolism of the lens: features and ways of correction. Russian medical journal. Clinical ophthalmology. 2015; 4:191-195.
26. Ueki S, Suzuki Y, Igarashi H. Retinal aquaporin-4 and regulation of water inflow into the vitreous body Invest Ophthalmol Vis. sci. 2021; 62(2):24. https://doi.org/10.1167/iovs.62.2.24
27. Zolotarev A.V. Microsurgical anatomy of the drainage system of the eye. Samara, 2009: 22-23.
28. Nesterov A. P. Glaucoma. – M.: Medical Information Agency LLC, 2008:360p.
29. Oliveira RH, Silva MD, Nunes GA, Faria RM, Santos KS, Rosa LL, Rosa MF, Rosa SD. Control engineering investigation of the effects of proliferative diabetic retinopathy on the crystalline lens and ciliary muscle dynamic behavior. Research on Biomedical Engineering. 2023 Aug 28:1-4.