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Integration of physics and physiology in the study of the eye as an optical system

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Abstract. The relevance of studying the eye as a complex optical system, combining principles of physics and physiology, lies in the need for a thorough understanding of image formation processes and the mechanisms of visual perception. This study aimed to identify the interrelations between the physical characteristics of the eye's optical components and their physiological functions, which together ensure clear and accurate visual perception. The research employed methods of geometric optics to model the path of light rays through the eye's optical media, physiological methods to assess accommodation and visual acuity, as well as a comparative analysis of data obtained from both healthy and pathological eye models. The optical properties of the cornea, crystalline lens and vitreous body were examined, with aberrations introduced by each component analysed, and the effect of accommodation on image formation on the retina established. It was also found that deviations in the optical parameters of the eye, such as changes in the curvature of the cornea or crystalline lens, lead to visual impairments (myopia, hypermetropia, astigmatism) that affect daily functioning. The findings may be of use to ophthalmologists and optometrists in the diagnosis and correction of visual disorders, as well as in the development of new optical devices

Keywords: vision; refraction; accommodation; crystalline lens; myopia; hypermetropia; physiology

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INTRODUCTION

In today's world, where technology is rapidly advancing and the understanding of biological processes is growing, the integration of disciplines within natural and medical sciences is becoming a necessity. Traditionally, natural and medical sciences developed relatively independently. However, it is clear that progress in understanding health and disease, as well as in developing effective treatment methods, requires a deep integration of knowledge from various disciplines. Interdisciplinary integration facilitates the creation of hybrid models that contribute to broadening the horizons of knowledge and deepening the understanding of health and illness. The importance of such an approach has become particularly evident in recent years, as scientific progress demands more flexible, interconnected formats for learning and research (Sadyrova & Sagymbaeva, 2022). In this context, knowledge gained from different disciplines contributes to a more complete understanding of complex biological and medical processes and also fosters the development of innovative approaches to treating and preventing diseases. According to numerous contemporary studies, a key factor in successful interdisciplinary integration is the development of skills in critical thinking, creative problem-solving, and a scientific approach (Kolesnyk *et al.*, 2023; Egamberdieva *et al.*, 2024). These skills are essential for adapting to changes in science and technology and for solving complex problems that demand a comprehensive approach. Interdisciplinary integration allows students to perceive the interrelationships between different subject areas and to understand their mutual influence and interaction. As J. Schmitt *et al.* (2023) note, this fosters the development of a deep and comprehensive understanding of societal and natural science processes and also cultivates the ability to apply acquired knowledge in various situations.

In modern dictionaries, the term "integration" is most often defined as follows: integration (from Latin) – restoration, replenishment, the combining of parts into a whole (*integer* – whole), notable not as a mechanical connection, but as mutual penetration and interaction (Nurmatova *et al.*, 2022). Biophysics is an interdisciplinary field combining elements of natural sciences, such as biology, chemistry, and physics, with those of medical sciences – biochemistry, physiology, surgery, radiography, orthopaedics, and pharmacology. The biophysics course covers a range of problems absolutely necessary for the professional training of doctors (Aitkenova *et al.*, 2022).

T. Kreps (2019) and A. Ader *et al.* (2020) note that the integration of knowledge is of great significance in contemporary education and is becoming a key element, as it addresses the challenges faced by students and professionals in their activities. Interdisciplinary integration also contributes to the development of universal skills among students, such as critical thinking, creative problem-solving, communication, and collaboration. These skills are essential for successful adaptation to a rapidly changing world and for tackling complex tasks that require a comprehensive approach (Tiwen, 2023). In modern education, increasing attention is being paid to interdisciplinary projects and assignments that allow students to apply knowledge from various fields in practice. Such projects foster the development of creative thinking, independence, and research skills among learners. As L. Shestakova (2013) points out, from the perspective of contemporary requirements for the content of higher professional education, a future specialist must possess interdisciplinary professional mobility.

Students of medical specialities study the fundamentals of human body structure and function. One of the most vital sense organs is the eye, whose function is based on complex interactions between physical laws and physiological processes. Vision is one of the most important human senses, enabling the perception of information about the surrounding world. Studying the eye as an optical system requires a complex approach, combining knowledge from various fields of science, including physics and physiology. Physics provides an understanding of the optical principles governing the eye's operation, while physiology explains the processes occurring within biological tissues that facilitate the conversion of light into nerve impulses. Integrating these two disciplines allows for the formation of a more complete understanding of how vision works and its disorders.

In recent years, there has been a significant increase in interest in various aspects of integration. The problem of interdisciplinary integration is of key importance for both the theoretical development of pedagogy and the practice of teaching. It is linked to the necessity of structuring educational content and establishing systemic connections between disciplines. Educational components that reflect the trends of integrating scientific knowledge play a crucial role. It is precisely integration that shapes an individual's style of scientific thinking and worldview (Nurmatova *et al.*, 2022). This article aimed to explore the possibilities and significance of integrating the disciplines of physics and physiology when teaching medical students, specifically in the context of studying the eye as an optical system. The article investigated how principles of optical physics, such as light refraction, diffraction, and focusing, are interconnected with physiological processes occurring in the eyes, including accommodation, the perception of light and images, and the mechanisms of vision. The article underscored the importance of a multidisciplinary approach for a deeper understanding of eye function, its role in visual perception, and the development of effective methods for diagnosing and correcting vision disorders. It also considered how a comprehensive approach, combining fundamental knowledge from physics (optics, light phenomena) and physiology (eye anatomy, processes of light perception and visual information processing), contributes to a deeper and more comprehensive understanding of the visual organ's function. This will enable future doctors, particularly ophthalmologists, to better understand the mechanisms of vision, diagnose disorders, and develop effective treatment methods. Prospects for improving the educational process in medical institutions through the implementation of interdisciplinary teaching approaches were also examined.

MATERIALS AND METHODS

In the research process, methods of theoretical analysis, empirical research, and comparative analysis were employed, allowing for a comprehensive approach to the issue of teaching optics and physiology of vision in medical universities. The method of theoretical analysis was used to study the physical principles of the visual apparatus, including the laws of optics (refraction, diffraction, focusing) and physiological processes (accommodation, nerve impulse transmission, image perception). It allowed for the justification of the necessity of integrating knowledge from physics and physiology for a deeper understanding of vision mechanisms and their disorders. Empirical research was used to collect data that helped to identify shortcomings in existing educational programmes and propose ways for their improvement.

A comparative analysis of the curricula of medical universities, including programmes in ophthalmology and anatomy, was conducted to evaluate existing educational approaches. Special attention was given to the integration of the disciplines of physics and physiology, as well as to the analysis of teaching materials used for student instruction. The comparative analysis allowed for the identification of the advantages and disadvantages of various teaching approaches and the proposal of recommendations for improving the educational process. Within the framework of theoretical analysis, existing models for teaching the physics and physiology of vision were examined, and scientific articles and monographs dedicated to the integration of these disciplines were studied. A systematisation and classification of the main physical and physiological concepts necessary for understanding the eye as an optical system were carried out. Particular attention was paid to analysing the interrelationship between the physical laws of optics and the physiological processes occurring in the eye. Textbooks and teaching aids on physics and physiology used in medical universities were analysed (Semenyuk, 2011; Leshchenko & Ilyich, 2012). Examples of lectures and practical classes dedicated to studying the eye as an optical system were also considered.

RESULTS AND DISCUSSION

Challenges in integrating the disciplines of physics and physiology in medical university curricula

Integrating the disciplines of physics and physiology in the education of medical university students is of key importance for a deeper understanding of the eye's function as a complex optical system. Physical laws, such as light refraction, focusing, and diffraction, combined with the physiological processes of the visual apparatus, form a unified picture of how the organ of vision functions. The eye can be viewed as an optical system where light rays pass through the cornea and the crystalline lens, and are then focused onto the retina. This process is closely linked to the physiological mechanisms of accommodation, whereby the eye changes the shape of the crystalline lens to focus on objects at different distances. Understanding these processes requires knowledge of both physical principles and physiological characteristics. For instance, it is important to understand how the angle of light refraction depends on the curvature of the cornea and crystalline lens, as well as how the muscles responsible for accommodation control the focusing of the image on the retina. These processes are connected to the accuracy of image perception and the analysis of light fluxes, which necessitates knowledge of both optics and neurophysiology.

Despite the clear advantages of integrating physics and physiology, the implementation of this approach in the educational process of medical universities faces several challenges. Firstly, there is a significant separation between disciplines within the curricula. Physics is often treated as a standalone subject, not always actively linked with medical subjects such as physiology or anatomy (Khabibulina, 2016). This separation leads to students having insufficient awareness of the interrelationship between physical and physiological processes in the eyes. Furthermore, in the teaching of physics, particularly at the level of medical universities, there is often insufficient attention paid to the biological aspects of eye function. Instruction is limited to basic laws of optics, without a deep explanation of how these laws directly influence physiological processes like accommodation, image perception, and the neurophysiology of vision. This creates gaps in students' understanding, which hinders the diagnosis and effective treatment of eye diseases. Teaching the physiology of vision also has its own peculiarities. While the physiological approach emphasises the biological side of the eye's function, the physical aspect, such as the principle of light focusing, often remains on the periphery of attention. Students studying physiology exclusively may underestimate the importance of physical processes in diagnosing diseases such as glaucoma, cataracts, or myopia, where intervention in the physics of light flow is crucial for developing effective treatment methods. Thus, for effective integration of disciplines, it is necessary not only to revise educational programmes but also to train educators to work in an interdisciplinary environment (Drake & Reid, 2018; Wang *et al.*, 2020). It is important to combine theoretical and practical approaches in teaching so that students can see the interrelationship between physical laws and the physiology of the eye, which will enable them not only to understand the visual system more deeply but also to improve the level of diagnosis and treatment of diseases.

Example of a lecture session taking into account the integration of physics and physiology

Currently, the generally accepted form of organising physics teaching in higher education is the lecture-practical format. The term "lecture-practical format" indicates that the main organisational forms of student learning are lectures and practical sessions. For effective teaching and discipline integration in the first year, conducting joint lectures by physics and physiology lecturers can be utilised, where common topics are considered from the perspective of both disciplines. For example, a lecture topic might be: Light Refraction and Eye Accommodation: PhysicoPhysiological Integration. The aim of the lecture is to form a holistic understanding among students of the mechanisms of vision, integrating knowledge from physics and physiology; to demonstrate how physical laws of optics are reflected in the biological structures of the eye; and to explain the process of accommodation as a result of the interaction between physiological processes and physical principles. This will contribute to the development of students' critical thinking and their ability to use knowledge from different fields for a deep understanding of the visual system's function. A proposed lecture structure is presented below.

Introduction (10 minutes). The physiology lecturer briefly introduces students to the importance of vision as the primary sensory channel for perceiving the external world and the role of the eye as an optical device. They explain how light serves as a stimulus for visual perception. The physics lecturer highlights the significance of understanding the principles of light propagation and refraction for studying optical systems, including the eye. It is also emphasised that only through the integration of knowledge from both disciplines can one understand how physical and physiological mechanisms interact to achieve effective visual perception.

Theoretical part (main body of the lecture). For a deeper understanding of the eye's function as an optical system, it is important to explain in detail both the physical and physiological processes occurring during the perception of visual information. These processes can be divided into two main parts: the physics and the physiology of vision.

Physical basis of light refraction (20 minutes). Refraction is the change in the direction of light when it passes from one medium into another with a different density. For instance, light entering the eye is refracted as it passes through the cornea, aqueous humour, crystalline lens, and vitreous body. The physics lecturer explains the concept of the refractive index of a medium, formulates Snell's Law, and explains its application at the boundary between two media (1):

$$n_1 \cdot \sin\alpha = \sin\beta \cdot n_2, \tag{1}$$

where n_1, n_2 are the refractive indices of the first and second media, respectively; sin α, sin β are the sines of the angles of incidence and refraction of light.

For the eye, the refractive indices of different media (air, cornea, crystalline lens) are important, as is how a change in the angle of incidence affects the focal point of the image on the retina. When light passes through the optical elements of the eye, it is focused onto the retina. The primary focusing surface is the cornea, which refracts about 70% of the light, and the crystalline lens, which is responsible for the remaining 30%. The crystalline lens has the ability to change its shape to focus on objects at various distances (the process of accommodation). The lecturer explains the concept of a lens, its focal length, and optical power. They demonstrate how lenses form images and show the following examples, such as using simple lenses to illustrate light refraction and diagrams of light refraction when passing through a plane-parallel plate and a prism. The physics lecturer can use the thin lens equation to explain focusing (2):

$$\frac{1}{f} = \frac{1}{a_1} + \frac{1}{a_2}, \tag{2}$$

where f is the focal length; a_1 is the distance from the object to the lens; a_2 is the distance from the lens to the image (retina).

If the eye has ideal optics, the image will always be clear on the retina. In the case of vision defects (myopia, hypermetropia), focusing occurs not on the retina, but in front of or behind it.

The optical system of the eye (20 minutes). The eye consists of several optical elements, each playing a role in focusing light: the cornea – the eye's first refractive surface, which focuses light; the crystalline lens – an adjustable lens that changes its shape to focus the image on the retina; the vitreous body – a transparent substance that transmits light to the retina. The physics lecturer describes the optical characteristics of the cornea and crystalline lens (refractive indices, radii of curvature). They explain that the eye represents a complex lens system that focuses the image on the retina. They demonstrate how lenses with different characteristics influence image formation. Here, the lecturers provide examples: diagrams of light passing through various structures of the eye and a comparison of the optical power of the cornea and crystalline lens. The physiology lecturer describes the structure of the eye, highlighting the main elements of the optical system: the cornea, crystalline lens, anterior and posterior chambers, and vitreous body. They emphasise the role of the cornea and crystalline lens in light refraction. They explain how light is focused on the retina. They mention that the shape of the crystalline lens can change.

Accommodation of the eye: physiology and physics (30 minutes). The physiology lecturer explains the physiological processes of accommodation and perception, that is, the mechanism of accommodation. Accommodation is the eye's ability to change the shape of the crystalline lens to focus on objects at various distances. This process is regulated by the ciliary muscle, which, upon contraction, loosens the tension on the crystalline lens ligaments, allowing the crystalline lens to become more convex for focusing on near objects. When an object moves further away, the ciliary muscle relaxes, the ligaments tighten, and the crystalline lens becomes flatter, focusing light on the distant object. The mechanism of accommodation itself consists of the following: 1) for near objects, the ciliary muscle contracts, allowing the crystalline lens to become more convex, which increases its refractive power; 2) for distant objects, the ciliary muscle relaxes, the crystalline lens becomes flatter, which decreases its refractive power and focuses the image on the retina. The physics lecturer explains that the change in the curvature of the crystalline lens leads to a change in its optical power and demonstrates using diagrams how the change in the crystalline lens's optical power allows the image to be focused on the retina at different object distances. They also explain how the focal length of a lens changes with its curvature.

When the distance to an object changes, the eye automatically adjusts to maintain focus. In the case of vision defects, images of distant objects, when the eye is relaxed, can be focused either in front of the retina – myopia (short-sightedness) – or behind the retina – hypermetropia (long-sightedness). The most common vision defects include myopia (short-sightedness) and hypermetropia (long-sightedness), which are associated with excessive or insufficient convexity of the crystalline lens.

If the crystalline lens is excessively convex, the optical power of the eye exceeds the norm. In this instance, the position of the posterior focal point, when the ciliary muscle is relaxed, falls in front of the retina (Fig. 1a). Such an eye cannot clearly see distant objects. Even with a small degree of myopia, the far point of accommodation decreases to a few tens of centimetres (for a normal eye, it is infinity). The near point of accommodation also decreases in this case. A person with myopia is better at performing tasks requiring close vision than someone with normal sight. If the convexity of the crystalline lens is insufficient, the optical power of the eye is less than normal. In this case, the position of the posterior focal point, when the ciliary muscle is relaxed, falls behind the retina (Fig. 1b). A hypermetropic eye can only clearly see distant objects by tensing the ciliary muscle (which quickly leads to fatigue). The near point of accommodation in hypermetropia significantly exceeds 25 cm. Consequently, the linear limit of resolution increases. The person loses the ability to perform tasks requiring fine vision, and difficulties arise when reading. To compensate for hyperopia, convex lenses are used in glasses.

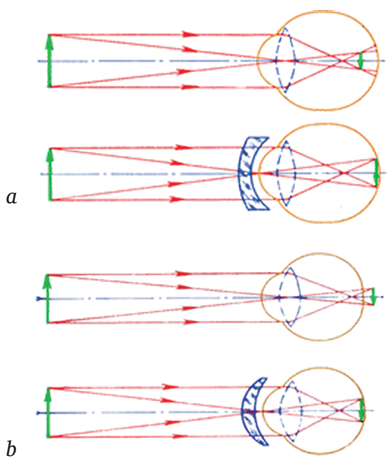

Figure 1. *Compensation of myopia (a) and hypermetropia (b)*
Source: *authors' development*

After the image is focused on the retina, it is converted into electrical signals that are transmitted to the brain. The physiology lecturer explains the function of the retinal photoreceptors (rods and cones), which are responsible for the perception of light and colour. Rods are sensitive to dim light and are responsible for vision in low illumination. Cones perceive light in bright conditions and are responsible for colour perception. When light acts upon the photoreceptors, a chemical reaction occurs, resulting in the generation of nerve impulses. These impulses are transmitted through a network of retinal neurons, then along the optic nerve to the brain. Retinal neural pathways (e.g., ganglion cells) transmit electrical impulses to the visual cortex of the brain, where image interpretation takes place. The brain integrates and processes visual information, extracting shapes, colours, motion, and depth, which enables humans to perceive the surrounding world in high resolution and detail.

Conclusion (10 minutes). Both lecturers jointly summarise the lecture, emphasising the integration of physical principles and physiological mechanisms and highlighting the importance of understanding the mechanisms of refraction and accommodation for comprehending the visual system's function. Questions for independent study are proposed.

Advantages of integrating knowledge from two disciplines

To enhance students' academic and cognitive engagement, interest, and motivation to study the eye's optical system, interactive elements are incorporated into the educational process (Tsvetikova, 2013). Simple experiments involving a laser pointer and lenses are used to demonstrate light refraction, alongside animations illustrating the change in crystalline lens shape during accommodation, diagrams showing images focusing on the retina at different crystalline lens positions, and calculations of the change in the crystalline lens's optical power during accommodation. Discussion, by posing questions to students to prompt debate, is also utilised.

A joint lecture combining physics and physiology represents an effective teaching method that contributes to a more complete and holistic understanding of the visual system's function (Leshchenko & Ilyich, 2012). Integrating knowledge from the two disciplines allows students to more deeply grasp the connection between the physical principles of optics and the physiological processes that occur in the eye:

1. Knowledge integration. Students see how the physical laws of optics interact with physiological processes in the eyes. This helps them realise that the mechanisms of vision do not exist in isolation but constitute a complex, interconnected system.

2. Increased interest. Joint lectures delivered by two lecturers make the material more engaging and dynamic. This allows for a more lively and vivid presentation of the topic, which in turn increases student motivation and interest in the subject matter.

3. Deep understanding. Students gain not only knowledge but also an understanding of how the mechanisms of vision function. This approach facilitates the assimilation of material at a deeper level, as students begin to understand not only "what" but also "why" certain physiological processes occur in the eyes.

4. Development of critical thinking. Students learn to apply knowledge from different disciplines when analysing complex biological systems such as the visual system. This contributes to the development of critical thinking and the ability to integrate information from various fields, which is an important skill for a medical professional.

Joint lectures help to form a holistic understanding of vision, emphasising the importance of an interdisciplinary approach in medicine (Sadyrova *et al.*, 2024). Students see how knowledge from physics and physiology is combined to solve complex medical problems. This approach not only improves the understanding of physiological processes but also prepares students for solving medical problems in real-world practice, where integration of knowledge from different areas is often required.

Based on the analysis of the data obtained during the research, it can be concluded that medical university students need to be taught the interrelationship between the optical properties of the visual apparatus and its physiological functions. This will enable them to understand more fully how the visual organ adapts to different conditions, how image perception occurs, and how various pathologies can affect the system's functionality. Including this knowledge in the educational programmes of medical universities provides an opportunity for students to perceive the eye as a complex biophysical instrument, rather than simply as an organ responsible for light perception.

CONCLUSIONS

Integrating interdisciplinary approaches into the process of teaching physics not only improves educational outcomes but also enhances students' motivation to learn, which is important for their comprehensive development and preparation for future education. An integrated approach to teaching, including joint lectures, creates an effective educational environment that promotes deep mastery of the material and the development of important skills for students' future professional activities. This approach underscores the importance of interdisciplinary analysis in medicine, where knowledge of physical laws and physiological processes is necessary for accurate diagnosis and effective treatment.

The prospects for improving the integration of physics and physiology into medical curricula are quite extensive. Firstly, changes are needed in teaching approaches, whereby the physics and physiology of the eye will be viewed as complementary disciplines. For this purpose, more integrated courses can be used, covering both the physics of optics and the physiological aspects of the visual organ's function. This approach will allow students not only to understand the fundamental physical principles but also to see their practical application in medicine. Secondly, it is important to implement new technologies and teaching methods into the educational process, such as visual apparatus simulators and virtual laboratories. This will enable students to study practically how various physical and physiological parameters influence visual perception. Virtual simulations can be used for modelling processes like accommodation, light refraction, and the diagnosis of visual disorders, providing students with a unique opportunity for hands-on study of complex biophysical processes. Furthermore, an important aspect is enhancing the qualifications of lecturers working in the interdisciplinary field. Professional development programmes aimed at preparing lecturers for interdisciplinary teaching will help to make education more effective and relevant. Close collaboration between physics and physiology lecturers is also necessary so that they can jointly develop educational materials that will cover both aspects of the eye's function.

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Физика жана физиология дисциплиналарынын көздү оптикалык система катары изилдөөдөгү интеграциясы

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Аннотация. Көздү жөнөкөй оптикалык система катары изилдөө, физика жана физиологиянын принциптерин бириктирип, сүрөт түзүлүшү процессин жана көздү кабыл алуу механизмдерин терең түшүнүүнүн зарылдыгы менен белгиленет. Бул иштин максаты – көздүн оптикалык элементтеринин физикалык мүнөздөмөлөрү менен алардын физиологиялык иштешинин ортосундагы байланыштарды аныктоо, бул болсо так жана туура көрүү процесстерин камсыз кылат. Иште геометриялык оптика методдору колдонулду, көздүн оптикалык чөйрөлөрү аркылуу нурлардын өтүшүн моделдөө үчүн, физиологиялык ыкмаларды колдонуу менен аккомодацияны жана көздүн ачуулугун баалоо жүргүзүлдү, ошондой эле ден-соолуктагы жана патологиялык көздүн моделдеринен алынган маалыматтардын салыштырмалуусу жүргүзүлдү. Роговица, линза жана айнек кумурскасынын оптикалык касиеттери изилденди, ар бир элементтин киргизген аберрациялары талданды жана аккомодациянын сетчатканы сүрөттөгөнгө таасирин ачып көрсөтүлдү. Ошондой эле, көздүн оптикалык параметрлериндеги кемчиликтер, мисалы, роговицанын же линзанын ийилгендигинин өзгөрүшү, көздүн көз карашына (миопия, гиперметропия, астигматизм) таасир берип, адамдын күнүмдүк иш-аркетин өзгөртөт деп аныкталды. Иштин натыйжалары офтальмологдорго жана оптометристтерге көздүн көрүнүшүн диагностикалоо, оңдоо жана жаңы оптикалык аспаптарды иштеп чыгууда колдонулушу мүмкүн

Негизги сөздөр: көрүү; сынуу; аккомодация; хрусталик; миопия; гиперметропия; физиология

Интеграция дисциплин физики и физиологии при изучении глаза как оптической системы

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Аннотация. Актуальность изучения глаза как сложной оптической системы, сочетающей принципы физики и физиологии, обусловлена необходимостью глубокого понимания процессов формирования изображения и механизмов зрительного восприятия. Целью данной работы было выявление взаимосвязей между физическими характеристиками оптических элементов глаза и их физиологическим функционированием, обеспечивающим четкое и адекватное зрительное восприятие. В работе использованы методы геометрической оптики для моделирования хода лучей через оптические среды глаза, физиологические методы для оценки аккомодации и остроты зрения, а также сравнительный анализ данных, полученных на здоровых и патологических моделях глаза. Были исследованы оптические свойства роговицы, хрусталика и стекловидного тела, проанализированы аберрации, вносимые каждым элементом, и установлено влияние аккомодации на формирование изображения на сетчатке. Также было выявлено, что отклонения в оптических параметрах глаза, такие как изменение кривизны роговицы или хрусталика, приводят к нарушениям зрения (миопия, гиперметропия, астигматизм), влияющим на повседневную деятельность человека. Результаты работы могут быть использованы офтальмологами и оптометристами для диагностики, коррекции нарушений зрения и разработки новых оптических приборов

Ключевые слова: зрение; преломление; аккомодация; хрусталик; миопия; гиперметропия; физиология