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The role of artificial intelligence in ophthalmology — brief review

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ABSTRACT

Artificial intelligence (AI) is rapidly developing and supporting all areas of medical science and clinical practice. This review discusses the development and potential practical use of AI in the field of ophthalmology. The aim of the study was to assess to what extent the opportunities offered by the introduction of artificial intelligence into ophthalmology have been exploited and what their developmental potential is, with a particular focus on clinical practice. The identified scientific gap lies in the very early stage of research into the application of AI in ophthalmology. A comprehensive review of existing applications of AI in ophthalmology shows how AI is already or can be used to support ophthalmologists in preventing, diagnosing, predicting disease, planning and monitoring treatment, and then evaluating changes cyclically. Wider implementation of AI technology in ophthalmology could improve early lesion detection, reduce misdiagnosis and contribute to better overall patient care.

KEY WORDS: artificial intelligence; machine learning; deep learning; ophthalmology; clinical applications.

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INTRODUCTION

Nowadays one can observe the development of technologies related to artificial intelligence (AI). AI refers to systems or machines that mimic human intelligence in action [1]. Performing tasks and improving their performance based on collected information is the main role of AI. In addition, sets of unstructured data are used to analyze patterns of information with the help of AI algorithms and merge the information to obtain results [2]. Programs whose operations are based on artificial neural networks are characterized by their ability to learn on their own and improve their results. As a result of the above capabilities, new applications of it are being developed all over the world [3, 4]. AI algorithms are created based on huge amounts of data that cannot be analyzed and interpreted by humans. It is worth noting the significant impact of AI on medical advances (Tab. 1) [5, 6].

Identified scientific gap lies in the very early stage of research concerning AI application in ophthalmology [4, 7]. The aim of the study was to assess to what extent the opportunities offered by the introduction of Ai into ophthalmology have been exploited and what their development potential is, with particular reference to clinical practice.

The novelty of this article lies in a comprehensive study of the state of the art from the perspective of

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Table 1. Potential areas of the artificial intelligence (AI) impact in ophthalmology	
Area	**Proposed tasks and support of AI**
Screening	Automated AI-based systems in screening programmes will help identify people at risk of vision loss due to medical conditions (e.g. diabetic retinopathy). This will improve access to early detection and treatment for patients.
Diagnostic assistance	AI algorithms can automatically or semi-automatically analyze retinal images, optical coherence tomography (OCT) scans and other imaging modalities to identify abnormalities more quickly and accurately, thereby detecting and diagnosing eye diseases (diabetic retinopathy, age-related macular degeneration, glaucoma and retinopathy of prematurity).
Surgical Assistance	AI technologies can give surgeons real-time guidance and assistance (e.g. by analyzing intraoperative images, identifying critical structures, measuring tissue parameters), increasing the precision, efficiency and safety of surgery.
Personalized and remote treatment	AI, through faster analysis of large datasets of different modalities (images, numerical and descriptive data), can help ophthalmologists develop personalized treatment plans for patients based on their unique characteristics and disease progression, including by comparing the predictive efficacy of different treatment options and helping to optimize treatment strategies. Additionally, AI-based telemedicine systems enable remote monitoring of patients with chronic eye diseases.
Drug and therapies development	AI supports and accelerates the discovery and development of new drugs and treatments for eye diseases, including analyzing complex biological data and identifying patterns in disease mechanisms, drug targets, and the efficacy of new therapies.

the interdisciplinary team gathering specialists both in medical sciences and AI. Thus, the contribution may be at least threefold:

- wider acceptance among specialists,
- further cooperation within the interdisciplinary team,
- relevant development of the clinical practice thanks to the novel scientific approach.

MATERIAL AND METHOD

For this paper's purpose, the authors searched 6 major bibliometric databases using specific and related keywords in English: "artificial intelligence/AI" and "ophthalmology". After reconciling the duplicate records — 1958 publications from 1990–2024 were listed. It is important to mention the rapid increase in the number of publications starting in 2018, which continues today (see: Fig. 1).

STATE OF THE ART

Machine learning (ML)-based methods are increasingly used in medicine [2, 8–10]. They work in a way that they process data to find repetitive patterns, based on which they also learn. With the learned patterns, the system creates complex analytical models. The ML algorithm consists of three components. The first is the decision-making process, which involves analyzing input data to predict or estimate a data pattern. The second element is the error function based on evaluating the prediction from existing examples. The third is the model optimization based on weight reduction and optimization until a preset accuracy threshold is reached [11].

Additionally, supervised ML methods were distinguished, which involves creating a set of input learning data and supervisor-specified expected values. Based on these, the algorithm looks for patterns

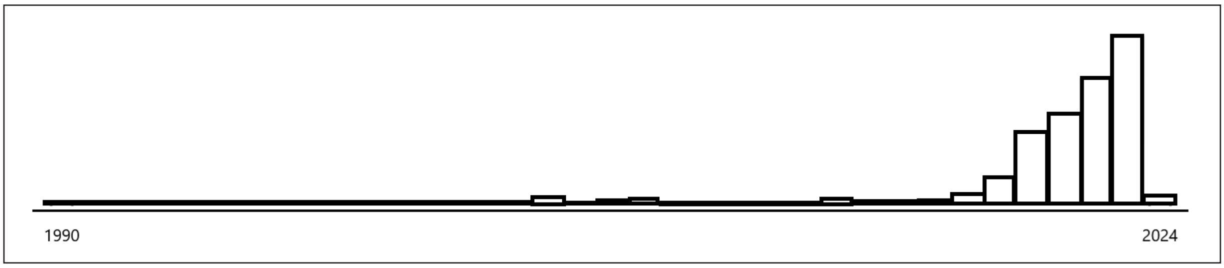

FIGURE 1. Number of analyzed publications

and generalizations. Supervised learning models are used in two types of problems: classification and regression [12]. In unsupervised learning, algorithms use unlabeled data, grouping and analyzing it. The goal is to discover patterns and, similarities, and differences. Unsupervised learning does not assume the appearance of specific outputs, distinguishing it from supervised learning. Unsupervised learning is used for three tasks: clustering, association, and dimensionality reduction. There are two more methods of ML. One is semi-supervised learning, which uses a minimum number of labeled data. The last is reinforcement learning, in which the algorithm uses trial and error to achieve the desired goal [13].

Ophthalmology uses diagnostic tests based on information technology. ML is widely used in this field of medicine [10, 14]. With the help of AI, we can increase efficiency in treating patients. This is related to the ability to diagnose severe, difficult cases. In addition, it is possible to reduce costs and errors in medical procedures. The purpose of this article is to show how AI has a significant impact on the development of ophthalmology [6, 14].

AI algorithms are being used to screen for diabetic retinopathy. It is worth noting that AI algorithms can help diagnose retinal diseases using fundus photos and optical coherence tomography (OCT) scans [15, 16]. OCT scanning is the gold standard for diagnosis in patients, for example, with age-related macular degeneration. ML can be used to analyze fundus images. Images are captured as high-resolution retinography using a fundus camera [17]. The advantage of the device is full automation. The equipment independently detects the patient's head on the chin and automatically locates the eye. It then sets the focus and flash intensity and takes the picture. Depending on the needs, images can be captured in different areas of the retina [18].

Age-related macular degeneration (AMD) is an eye disease directly affecting the retina's central part [19–21]. The central part is called the macula. It plays a very important role in vision, as it is responsible for visual acuity and related functions [22]. The disease occurs in both eyes [21]. It can occur in two forms: exudative and dry [23]. The exudative form is less common, and its course is more rapid. The dry form is more common but has a milder course. Early symptoms of macular degeneration include blurred vision of objects and distorted vision of straight lines. Variability of vision is quite typical — on some days, patients see better. Late macular degeneration changes include distorted vision and haziness of the image at the central point of gaze, often making short-distance vision and reading impossible. Patients in the advanced stage see only the periphery of the image [24].

In contrast, the symptom of micropsia or macropsia, or seeing unnaturally reduced or magnified objects, is rare [25]. As the disease progresses, significant deterioration of vision can make it difficult to perform daily activities, prevent reading and writing, and even facial recognition [24]. If you experience visual impairment, you should immediately seek an ophthalmological examination. The Amsler test can be performed at home. The causes of the disease are not entirely known. Genetic factors and environmental influences are likely important.

According to studies, cigarette smokers have the disease 6 times more often than non-smokers. Other factors affecting the incidence of AMD include advanced age, hypertension, diabetes, and obesity. Caucasians are more likely to have AMD. Women are also more likely to develop the disease than men. In addition, people with blue irises are more likely to have the disease [26]. A protective factor against AMD is a diet based on general dietary recommendations, including sources of carotenoids and antioxidants [27]. AMD is one of the most common causes of blindness among the elderly. As a result of the lengthening of human life, advances in civilization, and improvements in quality of life, the proportion of older adults is steadily increasing, leading to a more significant number of AMD patients. It has been estimated that the number of patients with age-related macular degeneration will increase by more than 25% in the next 10 years, from 196 million to 243 million [28]. With the increased number of potentially affected people, screening a larger percentage of the population is essential. Therefore, AMD diagnosis needs to be faster and more effective. In recent years, researchers have developed an automated AMD detection classification compatible with manual evaluation. It involves evaluating fundus images using technologies based on AI and ML. The test can assess retinal abnormalities and the size of the optic nerve disc drusen [29]. ML can be useful for assessing the benefits of anti-VEGF therapy, which will affect the quality of treatment [30]. The therapy involves injections administered under local anesthesia without the need to stay in the hospital. The preparations are supposed to inhibit the development of subretinal neovascularization and the progression of the disease. Treatment with injections often maintains a baseline or achieves better visual acuity [31]. According to the study, ML used to assess the severity of the disease is comparably more efficient than the assessment made by ophthalmologists. The above study was conducted using 67401 fundus images [32]. It is also possible to highlight a study in which the severity of the disease was assessed using DeepSeeNet.

The superiority of the above method over ophthalmologists' fundus assessments in detecting druses and pigmented lesions was demonstrated, which proves the high sensitivity of DeepSeeNet. Based on studies, the lower sensitivity of DeepSeeNet has been proven for advanced stages of AMD [33]. ML could also be used in ophthalmology for the quantitative evaluation of prints in OCT examinations, so the program would indicate whether there is a risk of AMD. The examination performed by a specialist takes much more time and is fraught with errors. In addition, ML proved to be helpful in the quantitative assessment of exudative fluid in AMD based on OCT examination. The sensitivity of the test was 94%. This shows that the automatic fluid evaluation corresponds to that performed by a specialist [34]. In the above works, how many benefits can be achieved by implementing ML in the diagnosis of eye diseases should be emphasized. One of them is faster diagnosis, which will affect the early inclusion of treatment.

Diabetic retinopathy is retinal damage and the most common microangiopathic complication of diabetes [35]. The first symptoms are often noticeable in patients as early as 5 years after the diagnosis of hyperglycemia [35, 36]. Diabetic eye disease in the early stages is asymptomatic, or the changes occur so slowly that the patient becomes accustomed to them. Therefore, it is essential to educate oneself about the complications, to have regular examinations, and to react quickly if alarming symptoms occur. Symptoms of diabetic retinopathy include deterioration of vision and impaired visual acuity. At the onset of retinopathy, there may also be complaints typical of dry eye symptoms. The patient experiences burning and pinching of the eyes. In addition, there may be pain, redness of the eyeball, and night vision impairment. As a result of the disease, the patient gradually loses vision [37, 38]. Patients diagnosed with diabetic retinopathy should go for ophthalmological check-ups systematically once a year, even if they do not notice any of the above symptoms. The dangerous changes caused by diabetes do not hurt and progress very slowly at first, and regular visits to a specialist allow the eyes to be fully healed if the disease is diagnosed. Retinopathy usually develops 15 years after the diagnosis of diabetes [37]. Its development is accelerated by pregnancy, anemia, and hypertension. Risk factors also include long duration of diabetes, smoking, and obesity [38]. There are several types of diabetic retinopathy. One is non-proliferative retinopathy, in which vision remains normal, but intraretinal strokes form, so it must be monitored. There is also a distinction between preproliferative retinopathy. The last type is proliferative retinopathy, in which retinal ischemia leads to retinal detachment, and extensive strokes are difficult to treat. ML has also found application in the diagnostic process of diabetic retinopathy, which is the most common microangiopathic complication of diabetes [39]. Diabetic retinopathy currently affects 146 million diabetics. According to the International Diabetes Association, the number of patients will reach 578 million by 2030 [28]. Due to the increasing proportion of patients and the shortage of specialists, performing screening on such a large scale will be difficult. Regular fundus examination of diabetic patients is recommended. Retinography, fluorescein angiography, and OCT are used for the examination. Studies on automating the diagnosis of diabetic retinopathy have shown it to be sensitive and specific enough to be a cheaper alternative to manual diagnosis [40].

Glaucoma is an eye disorder that, if left untreated, leads to damage and atrophy of the optic nerve. If left untreated, irreversible blindness can result [41]. More than 70 million people worldwide suffer from glaucoma. More than 6 million people are blind because of it [42]. The most common symptoms of glaucoma include frequent tearing of the eyes, photophobia, decreased visual acuity, seeing dark circles when looking at a light source, impaired adaptation of the eyes to darkness, and reduced field of vision. The causes of all forms of this disease are not fully understood. One can distinguish between congenital glaucoma, childhood glaucoma, juvenile glaucoma, adult glaucoma, and secondary glaucoma in the course of other eye diseases. The above forms of glaucoma are usually accompanied by an increase in eye pressure. At the beginning of the disease, there are losses in the visual field, and then we observe complete atrophy of the optic nerve and blindness. Depending on the structure of the anterior segment of the eye, we can divide the disease into: open-angle glaucoma and closing-angle glaucoma. Risk factors for open-angle glaucoma include stress, elevated eye pressure, myopia, and low blood pressure. Causes affecting the onset of glaucoma with a closing angle are hyperopia and diabetes.

People with glaucoma may be genetically burdened with the disease. Lipid disorders are also a factor in the development of the disease. If the disease is detected early enough, it is possible to stop its progression or slow its progression with medical and surgical measures [43]. Another disease where attention is being paid to the possibility of using ML is glaucoma. The experiment involved researchers segmenting an image of the optic nerve disc into a layer of retinal nerve fibers and pigment cells. The automatic segmentation of the optic nerve disc that was used in the above method has yielded promising results in OCT studies of glaucoma patients. Therefore, it can be an effective method to help the doctor in the diagnosis of glaucoma [44].

The use of a smartphone ophthalmoscope system, which is an overlay on a smartphone camera, can also improve diagnosis, especially for inexperienced medical professionals. It is a replacement for the traditional ophthalmoscope speculum. An interesting concept is the use of a portable phone attachment and an application installed on the device. Thanks to the applied measures, we are able to take a photograph of the fundus of the eye without the need for pharmacological pupil dilation. A smartphone-based ophthalmoscopic system would significantly improve the diagnosis of the symptom of a congestive disc. In addition, it would speed up the performance of lumbar puncture procedures in patients for whom rapid decision-making and treatment are important [45].

The analysis of complex medical data allows the detection of new pathological mechanisms/links and provides full support for inference, classification, and prediction. To date, some AI algorithms have been approved by the US Food and Drug Administration for diagnostic testing and can be used specifically in diabetic retinopathy, age-related macular degeneration, and retinopathy of prematurity. When used en masse as screening tests, these AI applications could effectively identify patients with preventable vision loss and refer them to specialists. However, there are questions about ethical issues - the exact characteristics of medical AI systems have not yet been established [46–52].

Technologically, AI encompasses various components (advanced algorithms, ML, and deep learning - DL) and their hybrids, which can improve automated devices for early diagnosis and timely treatment of eye diseases. So far, they have mainly been used for image reading, verification of disease diagnosis, corneal topographic mapping, and intraocular lens calculations [50–52]. So far, efficient performance of AI-based classification has been achieved in detecting diabetic retinopathy and retinopathy of prematurity, glaucoma-like disc, macular oedema, and age-related macular degeneration [53, 54]. There are hopes for combined AI-supported imaging in telemedicine for remote screening, diagnosis and monitoring of eye disease in patients in primary care and community settings [14]. What also matters in screening tests is the consistency and scalability of the test, which can be ensured by AI-based system automation.

DISCUSSION

The lifestyle of today's society has changed significantly. We are using more imaging devices (laptops, tablets, smartphones, display screens in cars and other vehicles, e-book readers, etc.), so the degree of exposure has also changed. This is also overlaid by changes in demographics, increasing life expectancy, and the changing pattern of chronic diseases (obesity, diabetes, glaucoma) [50–52].

AI will affect the quality of doctors' work, as it will speed up and improve disease diagnosis. Rapid diagnosis will affect the early implementation of treatment [53]. Another advantage is the reduction of the queue to ophthalmologists, thanks to faster description of examinations. In addition, it is worth noting that automating the method of analyzing examinations will not involve specialists, thus reducing the cost of examinations. It is worth noting that the interaction of artificial and human intelligence will undeniably improve doctors' performance.

Further development of the technology will validate the systems and lead to their popularization. An important aspect is the effectiveness of the above systems, which will become indispensable for performing daily work. The above advances are dependent on the acceptance of the public. Due to possible diagnostic mistakes, stand-alone computer programs should be supervised by a human in order to minimize error [6].

In addition to the positive aspects, it is worth mentioning the flaws that need to be resolved before implementing an AI-based medical device into medical practices. Moreover, AI may someday be used to abuse privacy based on the data collected. Retinal images should be protected because they identify a person. Furthermore, AI systems may be vulnerable to potential cyber-attacks.

An important factor in applying AI-based methods in ophthalmology is the quality and quantity of data, as AI models rely heavily on large and diverse datasets for training. In ophthalmology, obtaining high-quality, well-described data for various eye conditions can be challenging, and limited or biased datasets can lead to suboptimal model performance. Models trained on specific patient populations may not generalize well to different patient demographics. Differences such as ethnicity, age, type of work may affect the accuracy and reliability (and consequently: clinical usefulness) of the model in different patient populations.

These arise challenges and limitations of implementing AI in ophthalmology:

- data privacy issues,
- bias;
- interpretability of AI models;
- potential barriers to widespread adoption;
- a complete understanding of the AI methods and techniques used, and the results achieved;
- cybersecurity.

The main challenge is to comprehensively understand AI's current status and future prospects in preventive medicine (vision prevention, including workplace) and ophthalmology. Then, this research can make a valuable contribution to the ongoing development and application of AI technologies in ophthalmology in a more systematic way. We should also invest in developing educational programmes and training initiatives for medical professionals to effectively use AI in ophthalmology, including understanding how the integration of AI supports medical professionals while changing the emphasis on the skill set required in the field. The critical evaluation criteria appear to be AI algorithms' diagnostic accuracy and performance (sensitivity and specificity) in diagnosing specific eye diseases, such as diabetic retinopathy, glaucoma, age-related macular degeneration, and others. AI allows for greater integration with various imaging technologies, such as optical coherence tomography, fundus photography, and retinal imaging, which can provide hybrid image interpretation and analysis methods. In this situation, clinical trials and validation studies will be needed to assess the usefulness of AI in clinical practice [54–56].

Further research will show where it is worth developing new AI/ML approaches better suited to ophthalmology's needs and the shape medical professionals want to give it as a mid-21st-century science.

CONCLUSIONS

Taking into account research in recent years, one can conclude that AI is the future of medicine, especially ophthalmology, and could have a breakthrough in disease diagnosis. A comprehensive review of existing AI applications in ophthalmology shows how AI is already or can be used for prevention, diagnosis, disease prediction, treatment planning and monitoring, and subsequent cyclical evaluation of changes. More comprehensive implementation of AI technology in ophthalmology can improve early lesion detection, reduce misdiagnosis, and contribute to better overall patient care.

It is worth emphasizing that AI algorithms/systems need trained optometrists and ophthalmologists, because although the basis for diagnoses made by AI algorithms is computational, some human intervention is necessary for further interpretation.

The broader use of AI/ML holds the promise of transforming different areas of ophthalmology, from early disease detection to personalized treatment and surgical support, thereby improving patient outcomes and increasing the efficiency of ophthalmic care delivery. However, it is imperative to ensure that these AI technologies are rigorously validated, responsibly integrated into clinical practice, and used in conjunction with human expertise to deliver the best possible patient care.

Author contributions

M.M. and K.W. chose the topic and developed a concept of the paper. A.K.-S. wrote the main core of the manuscript. D.M. and E.M. improved the manuscript. All authors have read and accept the paper in its form.

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Conflict of interest

The authors declare no conflict/competing interests.

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