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ARTIFICIAL INTELLIGENCE–ENHANCED RETINAL IMAGING IN DIABETIC RETINOPATHY: OPPORTUNITIES AND LIMITATIONS

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ABSTRACT

Background: Diabetic retinopathy (DR) remains a leading cause of vision loss worldwide, making early detection and effective screening essential for preventing irreversible complications. Traditional imaging methods, such as fundus photography and optical coherence tomography (OCT), identify established retinal lesions but often fail to capture subtle early microvascular changes.
Objective: This review examines current retinal imaging techniques and evaluates the integration of artificial intelligence (AI) to enhance the detection of DR.
Methods: The analysis focuses on studies investigating AI applications with fundus photography, OCT, and optical coherence tomography angiography (OCTA), highlighting their diagnostic performance and potential to improve screening programs.
Results: OCTA enables high-resolution, non-invasive visualization of retinal and choroidal vasculature, allowing early detection of microaneurysms, capillary non-perfusion, and other biomarkers. AI integration improves diagnostic accuracy, sensitivity, and specificity, reducing the burden on clinicians. However, clinical adoption is limited by small, homogeneous datasets, lack of standardized imaging protocols, and limited explainability of AI algorithms.
Conclusion: AI-enhanced retinal imaging shows significant promise for early detection and improved management of DR. Future efforts should focus on multicenter validation, data standardization, and development of explainable AI models to enable safe, effective, and equitable implementation in routine clinical practice.

KEYWORDS

Diabetic Retinopathy, Artificial Intelligence, OCTA, Screening

CITATION

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Introduction

Diabetic retinopathy (DR) is the most common complication of diabetes. It affects over 30% of patients with diabetes and is the leading cause of blindness worldwide. Over the past twenty years, the prevalence of blindness associated with DR has increased to 19%. Currently, it affects approximately 463 million people, and forecasts indicate that by 2045 the number of affected individuals may rise to 700 million. The early stages of the disease are often asymptomatic, which makes detection difficult, while early diagnosis is crucial for effective treatment [1,7,15,16].

Currently, diagnostics and screening for diabetic retinopathy rely mainly on fundus examination and retinal imaging techniques. Although these methods are valuable, they allow the disease to be recognized only in its more advanced stages, which limits the effectiveness of therapy and usually allows only for slowing its progression with minimal improvement in vision [2].

The use of artificial intelligence enables earlier disease detection, increases the accuracy and consistency of examinations, and reduces human error, while supporting a more personalized therapeutic approach [3]. Due to the numerous benefits of its use, the application of artificial intelligence in the diagnosis and treatment of diabetic retinopathy has increased significantly, ranking it as the second most commonly used medical procedure in the United States, second only to coronary artery disease treatment [4].

Pathomechanism

Diabetic retinopathy is a chronic disease of the retinal blood vessels caused by long-term hyperglycemia. Clinically, two forms are distinguished: non-proliferative (NPDR), characterized by microvascular damage, hemorrhages, and retinal edema, and proliferative (PDR), characterized by the formation of pathological blood vessels that may lead to vitreous hemorrhages and irreversible vision loss [5]. The pathogenesis of diabetic

retinopathy involves not only progressive microangiopathy but also early retinal neurodegeneration, in which ganglion cell dysfunction and disturbances in the neurovascular unit appear even before visible vascular changes—highlighting the need for therapies targeting early neurovascular pathways [6].

Since proliferative diabetic retinopathy and macular edema often develop without symptoms, only their identification during screening creates an opportunity for early intervention—including laser photocoagulation and intravitreal anti-VEGF injections—which can prevent vision loss [8].

Screening

Screening for diabetic retinopathy has so far been performed mainly manually, using various fundus imaging techniques carried out by experienced specialists. These included fundus photography, slit-lamp examination, and direct ophthalmoscopy [9,10]. These methods allow for the identification of basic retinopathic changes, such as microaneurysms (small, round dots), hemorrhages (irregular spots), hard exudates (yellow, well-defined lesions), and soft exudates (white, oval changes) [11].

In clinical practice, fundus photography is considered the primary and most reliable screening method in the diagnosis of diabetic retinopathy [8,12]. It enables detection of clear, macroscopic retinal changes, but does not allow for the assessment of subtle damage, such as early ischemia of the inner layers, small exudates, microhemorrhages visible only in histological examinations, or changes within the retinal pigment epithelium [6,11].

Despite its widespread use, this method remains burdened by significant limitations. The most important include image deformations and artifacts, e.g., caused by eyelashes, insufficient image resolution, and the limited ability to assess peripheral retinal vessels and areas resulting from the narrow field of view. Obtaining diagnostic material of good quality often also requires taking multiple images of the macula [13].

These factors limit the effectiveness of classical techniques in identifying the earliest disease changes, which justifies the need to supplement them with more advanced imaging methods. An additional problem is the time-consuming nature of traditional procedures, the need for specialized equipment, and the involvement of qualified personnel, which reduces accessibility. Moreover, methods relying on manual image evaluation are prone to variability and errors resulting from the observer's subjective interpretation [9,14].

Additional Diagnostic Methods

FFA (Fluorescein Fundus Angiography)

FFA is a classical method of retinal vessel imaging used in ophthalmology to assess blood flow and vascular abnormalities. It involves intravenous administration of fluorescein followed by illumination of the retina with blue light. Fluorescein emits green-yellow light, which is recorded by a camera, creating an image of the retinal vessels and detecting areas of leakage or ischemia [13]. Fluorescein angiography enables detection of more abnormalities present in the fundus than standard color fundus photographs. However, it is a time- consuming and invasive method and is not optimal for routine clinical use [6]. The contrast agent used may cause adverse effects such as nausea and vomiting, allergic reactions, or seizures [17].

OCT (Optical Coherence Tomography)

OCT is a non-invasive, contactless imaging technique performed through the pupil that has revolutionized ophthalmic diagnostics, enabling cross-sectional imaging of the macula with quality comparable to histological images. The examination allows for precise, objective measurement of retinal thickness and assessment of the structure at the vitreoretinal interface [6]. However, OCT does not allow for assessment of blood flow or full visualization of retinal vessels; its limitations include the lack of angiographic information, inability to detect ischemia and therapeutically relevant abnormalities, as well as limited visibility of deeper vessels and analysis restricted to two-dimensional superficial structures [13].

OCTA (Optical Coherence Tomography Angiography)

OCTA is an extension of OCT that enables visualization of blood vessels and blood flow in the retina and choroid without the use of contrast (unlike FFA), making it a less invasive examination. The method has high sensitivity and specificity, allowing the detection of neovascularization even in the presence of blood flow. Due to its ability to precisely visualize key changes associated with diabetic retinopathy—including microaneurysms, ischemic areas, IRMA (Intraretinal Microvascular Abnormalities), and neovascularization—OCTA has been identified in expert guidelines as an important complementary tool supporting clinical evaluation and treatment planning. This examination has higher resolution than FFA, and when combined with artificial intelligence (AI), OCTA gains expanded diagnostic, evaluative, and prognostic capabilities in the assessment of DR [17].

Despite numerous advantages, OCTA has important technical and diagnostic limitations, including a limited field of view, inability to visualize certain characteristic diabetic retinopathy features such as vascular leakage, susceptibility to motion artifacts, and failure to detect very slow blood flow [13]. Additionally, the lack of definitive diagnostic markers, difficulties in standardizing data between devices, and limitations in image resolution and quality hinder precise assessment of microstructures and the complete architecture of retinal vessels in DR [17].

UWF-OCTA (Ultra-Widefield Optical Coherence Tomography Angiography)

UWF-OCTA is a newer version of classical OCTA that allows imaging of a significantly larger portion of the retina, covering up to 80% of its surface in a single image without pupil dilation [4]. It offers advantages over traditional fundus photography; however, its high cost limits use in low- and middle-income countries. The extended image acquisition time may lead to more artifacts and reduced image quality and sharpness [17].

The synergistic benefits of multimodal imaging are well documented, and combining OCTA with other imaging techniques—such as fundus photography, OCT, or UWF-FA—as well as with clinical and demographic patient data shows high diagnostic effectiveness and potential to enhance the comprehensive evaluation of diabetic retinopathy [18].

Methodology

This review was developed based on a systematic analysis of scientific literature available in PubMed, Scopus, Web of Science, and Google Scholar, covering the years 2023–2025. The search included publications in English, including prospective studies, systematic reviews, and meta-analyses, using keywords such as diabetic retinopathy, artificial intelligence, OCT angiography, pathophysiology, and screening. The selection criteria included works concerning the diagnosis of diabetic retinopathy, with particular focus on the use of artificial intelligence in improving the accuracy, consistency, and accessibility of screening as well as optimizing clinical outcomes. The literature analysis focused on identifying current trends, limitations of traditional methods, and the potential of new technologies to enhance disease detection and treatment.

Artificial Intelligence

Artificial intelligence systems in the diagnosis of diabetic retinopathy are divided into machine learning (ML) systems and deep learning (DL) systems. ML is characterized by high sensitivity (87–95%) but low specificity (49.6–68.8%) and a large number of false-positive results, which limits cost-effectiveness. In contrast, DL systems require less supervision and allow for detection and classification of DR, increasing specificity to 59.4–98% and reducing false positives [8,19].

In imaging diagnostics, including diabetic retinopathy, AI uses various models that differ in their learning methods and pattern recognition. The most commonly used include CNN (Convolutional Neural Networks), ANN (Artificial Neural Networks), other neural network variants (Other-NN), fuzzy machine learning (Fuzzy ML), as well as classical models such as SVM (Support Vector Machines) and RF (Random Forest) [11].

Deep learning (DL) systems enable automatic analysis of large image datasets, significantly reducing the workload of medical personnel and facilitating large-scale screening programs [18]. Moreover, the literature review indicates that there are DL models optimized for computational efficiency, allowing rapid and scalable implementation in real-world screening programs, even with limited hardware resources [20]. Their advantage over earlier machine learning (ML) methods results primarily from the lack of necessity for manual selection of OCTA image features, which in traditional models limited accuracy and increased the risk of missing important information. In contrast to ML, deep learning networks—especially CNNs—can autonomously extract key diagnostic features, resulting in high effectiveness: for example, the VGG16 architecture achieves 90.84% accuracy and 95.83% specificity. Multilayer neural networks (ANN) can reach accuracy levels of 97.78%, while newer and more advanced DL models, such as DcardNet-36 or Vision Transformers (ViT), often exceed 95% accuracy and in some cases even 99%. The use of attention mechanisms and ensemble methods further enhances the ability of models to identify subtle image changes. The newest generation of DL tools consists of Vision Transformers (ViT), which analyze the image globally, allowing incorporation of the context of the entire retinal structure and further increasing classification accuracy [18].

Implications for practice and society

Recent advancements in artificial intelligence applied in ophthalmology have enabled technological integration of image analysis, acquisition, and OCTA data processing. Machine learning–based methods perform particularly well when working with the large datasets generated by OCTA. AI can transform the imaging process from traditional motion-contrast capture into an image-processing task, opening the possibility of reducing artifacts typical of classical OCTA methods [17].

To evaluate the diagnostic effectiveness of artificial intelligence systems in screening for diabetic retinopathy, their results were compared with physicians' assessments using MetaDiSc software to analyze diagnostic accuracy. The results were as follows: for AI, sensitivity and specificity were 0,877 (95% CI: 0.870–0.884) and 0.906 (95% CI: 0.904–0.908), respectively, while for physicians: 0.751 (95% CI: 0.736–0.766) and 0.941 (95% CI: 0.936–0.946) [14]. In the 43 analyzed studies evaluating 15 deep learning (DL) systems and 4 machine learning (ML) systems, it was demonstrated that artificial intelligence achieves high sensitivity in detecting diabetic retinopathy (≥85% for all disease stages), while specificity was more variable and fell below 80% for all ML systems and in 6 out of 31 studies involving DL systems. Seven studies found that AI algorithms had higher sensitivity than traditional human assessment, although specificity was slightly lower, indicating an advantage of AI in detecting disease changes at the cost of more false-positive results [21].

Numerous clinical and population studies—including RAIDERS, ACCESS, and trials conducted in Tanzania, the USA, China, Spain, Mexico, and Sub-Saharan Africa—have evaluated the effectiveness of artificial intelligence systems in screening for diabetic retinopathy. The results consistently show that AI algorithms achieve high sensitivity and specificity, often matching or surpassing ophthalmologists, while significantly increasing screening completion rates and adherence to referral recommendations [10].

Cost-effectiveness analyses have also been conducted to evaluate AI-based screening in comparison with traditional ophthalmic methods. In a study carried out in rural China, AI-based screening increased QALY (Quality-Adjusted Life Year) by 0.16 at an additional cost of USD 180.19 compared to no screening, while the ophthalmologist-based approach proved both less effective and more expensive [14].

Artificial Intelligence Systems

Various artificial intelligence systems have been evaluated in diabetic retinopathy screening to identify patients requiring further diagnostics and to assess disease severity.

The DAIRET system has demonstrated promising results, effectively identifying all patients requiring further ophthalmic evaluation or treatment. The algorithm classifies patients as eligible or not eligible for referral to an ophthalmologist. Despite its high sensitivity, DAIRET is characterized by low specificity (40.9%), which results from a large number of false-positive outcomes caused by imaging artifacts and coexisting ocular conditions such as glaucoma, age-related macular degeneration, or choroidal nevi [8].

The IDx-DR system (Digital Diagnostics, Coralville, IA, USA) is the first FDA-approved system for detecting diabetic retinopathy. It is used to identify and assess the severity of the disease [6,7,22]. A key component of IDx-DR is its advanced imaging system, which, through techniques such as OCT and fundus photography, generates detailed images of the retina. These images allow for the evaluation of blood vessels, microaneurysms, exudates, and other changes associated with diabetic retinopathy. High-quality images form the basis of AI analysis, increasing the accuracy and reliability of diagnosing different stages of the disease [22]. Studies show that the system achieves high sensitivity in detecting diabetic retinopathy, confirming its usefulness in screening applications, particularly in primary care settings [6,22]. In studies by Van der Heijden and colleagues, sensitivity was 68% and specificity 86%; Abramoff and team reported sensitivity of 87.2% and specificity of 90.7%; and Shah and collaborators reported sensitivity of 100% and specificity of 82%. Ting and co-authors reported sensitivity of 90.5% and specificity of 91.6% for general retinopathy, and sensitivity of 100% and specificity of 91.1% for vision-threatening retinopathy, while Peris-Martínez and team reported sensitivity of 100% and specificity of 81.8% for all cases and sensitivity of 100% and specificity of 94.6% for the vision-threatening form. Across the studies analyzed, the IDx-DR system showed a tendency to classify some fundus images into higher severity categories of diabetic retinopathy compared to the reference standard [22]. False-positive results were also observed, leading to patients being referred for further diagnostics despite the absence of changes requiring intervention [22,23]. For comparison, the RetCAD system offers more balanced results, combining high sensitivity (88.0%) with substantial specificity (94.7%), reducing the risk of excessive patient referrals for further evaluation [23].

In a study conducted in the United States, it was shown that implementing the IDx-DR system in diabetic retinopathy diagnostics could increase clinic efficiency by up to 40% in the care of patients with diabetes [4].

Another FDA-approved system is EyeArt, which achieves a sensitivity of 96% and specificity of 88% in detecting mild diabetic retinopathy, and a sensitivity of 92% and specificity of 94% for vision-threatening diabetic retinopathy (VTDR). Its algorithm can analyze data from 100,000 individuals in approximately 45 hours [15]. In a clinical study comparing EyeArt results with the assessment of a certified retinal specialist, overall diagnostic agreement was 81%, and agreement regarding referral decisions was 83%. Additionally, for referral decisions, the system's sensitivity was 74%, specificity 87%, positive predictive value 72%, and negative predictive value 88%, indicating substantial consistency with expert evaluation and usefulness in screening-based diagnostic programs [24].

Telemedicine

Telemedicine is defined as the use of information and communication technologies for diagnosing, treating, and preventing diseases, with its main goal being to overcome barriers resulting from geographical distance. In this context, artificial intelligence demonstrates increasing potential in the diagnosis of diabetic retinopathy, enabling automatic assessment of retinal images and supporting effective screening in various clinical settings. A mobile tool for the automatic evaluation of retinal images has been developed, using deep learning (DL) methods. The algorithm performs binary classification, indicating which images may suggest the presence of diabetic retinopathy and require further diagnostics. The system was evaluated on more than 200,000 images by a team of specialists and engineers, demonstrating high flexibility and ease of use in diverse clinical environments [6,25]. A meta-analysis of 34 other studies showed high effectiveness of various retinal imaging methods—from tabletop cameras to smartphones—in screening for diabetic retinopathy, with an overall sensitivity of 94% and specificity of 89%, comparable to specialist assessment [4].

Because some artificial intelligence systems require continuous internet access, work is underway to develop solutions that can operate offline, increasing their applicability in resource-limited settings. An example of such technology is Remidio Medios, in which retinal imaging is performed using the portable Remidio Non-Mydriatic Fundus on Phone camera; the obtained image is displayed on a smartphone, and the system achieves 98% sensitivity and 86% specificity [6].

Discussion

Artificial intelligence (AI) has become a promising method for automating screening for DR, offering improved efficiency, precision, and overall accessibility of diagnostics. With the increase in computational power, deep learning techniques have established themselves as the key AI approach in the detection and screening evaluation of diabetic retinopathy [14].

Data from the reviewed studies indicate that AI-based tools achieved very good performance in detecting changes characteristic of diabetic retinopathy in many analyses. For both dilated and non-dilated images, AI algorithms demonstrated sensitivity and specificity comparable to manual evaluation, confirming their potential as tools supporting the diagnostic process [9]. Available evidence also suggests that AI systems can effectively identify different stages of diabetic retinopathy based on fundus photography, achieving results comparable to physician assessment. The incorporation of retinal imaging devices equipped with built-in algorithms may significantly reduce the burden on clinicians and improve diagnostic consistency [28].

In diabetic patients who do not yet show clinical signs of retinopathy, quantitative OCTA vascular parameters—such as vessel density or morphological features—are valuable tools for early screening and monitoring of retinal status. The integration of AI techniques for analyzing these parameters has made it possible to identify specific indicators that may serve as new imaging biomarkers supporting early diagnosis of diabetic retinopathy [17]. As a result, it becomes possible not only to detect existing changes but also to predict the risk of disease progression, increasing the preventive and clinical value of screening efforts.

A review of the literature also highlights the easy scalability of AI systems, their lower cost, and their ability to improve the availability of screening in resource-limited areas, contributing to more equitable access to ophthalmic care worldwide [14]. Despite the proven effectiveness of regular screening for diabetic retinopathy—national and international guidelines recommend that individuals with diabetes undergo such examinations every one or two years—patient participation in screening programs for diabetic retinopathy remains insufficient [10,16]. The low participation rate may result from the asymptomatic course of the disease in its early stages, patients' reluctance to undergo dilated fundus examinations, the mistaken belief that good glycemic control eliminates the risk of retinopathy, as well as long waiting times for ophthalmology appointments, which reduce motivation to participate in screening [15]. The use of fundus photography together with remote image evaluation by ophthalmologists significantly increases patient participation in

screening programs and, as available data confirm, represents a cost-effective solution. Additionally, the integration of artificial intelligence further enhances this effect: the RAIDERS study demonstrated that immediate feedback generated by AI significantly improves adherence to referral recommendations, encouraging patients to pursue further diagnostics more promptly [10]. Similar conclusions were drawn from the ACCESS study, conducted in the United States among adolescents with diabetes, which confirmed that autonomous AI systems can effectively increase the rate of completed screenings in primary care settings [29]. Moreover, in experimental studies, autonomous AI systems achieved a full, 100% completion rate of screening in patients with type 1 diabetes, far exceeding the results achieved with standard care [30].

In the context of telemedicine, AI-OCTA systems can increase access to screening, reduce inequalities in healthcare, and improve population-level management of diabetic retinopathy. Compared with traditional manual assessment methods, which require substantial time investment and specialized expertise, AI-assisted analysis of OCTA images enables rapid and objective data processing, shortening diagnostic time and increasing efficiency [18].

However, it is important to note that the diagnostic parameters of individual systems are not identical and may vary depending on the device type, image quality, or local working conditions. These observations indicate that although AI solutions—especially those based on images obtained without pupil dilation—represent valuable clinical support, they require further standardization and cross-center validation [9].

Challenges and Limitations

Despite the growing use of artificial intelligence (AI) in OCTA image analysis in studies on retinal responses to visual stimuli in diabetic retinopathy (DR), a standardized Computer-Aided Detection (CAD) system has not yet been developed, and the lack of clearly defined criteria for evaluating machine learning models limits the consistency of results. Differences in diagnostic thresholds, diversity of training data, and varying reference standards in manual assessment—from individual specialists to expert panels—lead to substantial heterogeneity in outcomes and variable performance of AI systems. Additionally, variability in imaging techniques, including both two- and five-field retinal photography performed with or without pupil dilation, OCT and OCTA imaging, as well as differences in device protocols and specifications, further increase inter-study inconsistency. The lack of complete data in some publications, such as the number of participants, makes it difficult to assess the quality of analyses and compare the effectiveness of different systems [9,14,17].

The implementation of deep learning models also encounters limitations related to the lack of transparency in decision-making ("black box"), which weakens clinicians' trust. A solution may lie in explainable artificial intelligence (XAI) methods, such as attention mechanisms in Vision Transformers, which visualize important image regions, enabling evaluation of model decisions and building trust in clinical practice [18].

The main challenges for AI in OCTA include the high cost of creating large, annotated datasets, limited generalizability of models trained on homogeneous populations, susceptibility to imaging artifacts, failure to account for the influence of patient age, and variability resulting from methodological differences across studies. The deployment of such systems in clinical practice is also accompanied by ethical and regulatory challenges, including patient privacy protection, the risk of algorithmic bias, the need to ensure informed consent, and the lack of uniform standards and guidelines necessary for the safe and reliable use of AI in diagnostics. Standardization of metrics and transparent reporting may increase the credibility of AI in clinical practice and support diagnostic decision-making [8,9,14,17,18,26].

The implementation of telemedicine may also be difficult for individuals without access to modern technologies or adequate digital skills, as well as in regions with poor infrastructure, which limits access to healthcare among underrepresented populations [27].

Conclusions

Diabetic retinopathy progresses through various stages, each characterized by distinct retinal changes, which are often difficult to clearly differentiate even for experienced clinicians [5]. With the increasing number of diabetic retinopathy cases, the importance of early diagnosis and regular screening becomes crucial, as timely recognition and treatment can prevent or delay over 95% of vision loss associated with this disease [18]. In response to these growing needs, modern technologies—including artificial intelligence–based systems—are being dynamically developed, offering promising opportunities for enhancing and automating DR screening [6,22].

Artificial intelligence technologies, particularly deep learning models, enable automatic interpretation of retinal images and detection of changes characteristic of diabetic retinopathy. Their performance in terms of accuracy often matches that of specialist evaluations. AI systems can not only identify the presence of retinopathy but also assess its severity, making them a valuable tool in large-scale population programs. The implementation of such technologies may significantly streamline the diagnostic process, reduce its costs, and increase access to screening in resource-limited settings [9].

Future development directions include creating interpretable models that account for age, standardization and multicenter validation, improved artifact correction, and the deployment of unified CAD systems. Despite these challenges, the combination of AI and OCTA can significantly enhance precise diagnosis and monitoring of DR, with AI supporting—not replacing—clinical decision-making [14,17]. Before implementing AI systems, the risks of malfunction and the operational conditions of devices must be considered. Although such systems can reduce staff workload and improve screening efficiency, their clinical effectiveness requires ongoing evaluation and refinement [9,14].

Artificial intelligence in combination with teleophthalmology demonstrates high agreement with specialist fundus examinations and has the potential to expand the reach of screening programs while triaging patients with urgent needs. Further development of these technologies should focus on improving image quality, reducing artifacts, and integrating AI into routine screening programs [31].

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