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ABOUT THE AUTHOR

Michelle Khan, MD, FRCSC

Dr. Michelle Khan is an oculoplastic, cataract, and refractive surgeon. She completed her residency training in ophthalmology at the University of Toronto, followed by fellowship training in oculoplastics at Moorfields Eye Hospital, London UK. She is a lecturer at the University of Toronto and Staff Ophthalmologist at Trillium Heath Partners. Dr. Khan is co-chair of the bi-annual conference "Artificial Intelligence, Digital Health, and the Eye," which is held in collaboration with Moorfield's Eye Hospital in London, The University of Toronto Department of Ophthalmology and Vision Sciences, and the St. John Eye Hospital Group. She is passionate about international humanitarian work, and is the current Chair of the St. John Ophthalmic Association in Canada.

Affiliations: University of Toronto, Division of Ophthalmology and Vision Sciences, Toronto, ON.

Next-Generation Ophthalmology: How Artificial Intelligence Is Shaping the Future of Eye Care

Michelle Khan, MD, FRCSC

Introduction

When Canada hosted the inaugural "Artificial Intelligence, Digital Health, and the Eye" conference in April 2023, it quietly launched what has become a defining forum at the intersection of technology and vision science in the country. A year later, the conference found a new stage at the Royal Society of Medicine in London, drawing global attention. This was largely because the keynote address was delivered by Professor Geoffrey Hinton, co-recipient of the 2024 Nobel Prize in Physics, and widely regarded as one of the founding fathers of deep learning. As modern medicine continues to be shaped by artificial intelligence (AI), the tone is unmistakably clear: the future is not only digital, but also intelligent.

Few medical specialties are as naturally aligned with AI as ophthalmology. Its high-resolution imaging and quantitative data make ophthalmology particularly well-suited for the integration of AI technologies. Beyond automating image interpretation, AI now holds promise in risk stratification, disease progression modelling, and even in democratizing access to subspecialty-level diagnostics—advances that could meaningfully alter the delivery of eye care across the globe.

Significant strides have been achieved in applying both machine learning (ML) and deep learning (DL) algorithms to major ophthalmic diseases, including diabetic retinopathy, age-related macular degeneration, glaucoma, cataracts, and various corneal pathologies. The U.S. Food and Drug Administration (FDA) has approved several AI-based platforms for clinical use, many of which are showing tremendous potential. Large language model AI systems, such as Generative Pre-Training–Model 4 (better known as GPT-4 by OpenAI), have demonstrated the ability to either match or outperform human ophthalmologists in diagnosing and treating various ophthalmic diseases.[1] This article aims to provide a comprehensive review of the role of AI in ophthalmology, with particular attention to current clinical applications, emerging innovations, and the challenges that lie ahead.

AI Applications in Ophthalmology

1. Diabetic Retinopathy

AI has achieved significant milestones in diabetic retinopathy (DR) screening. FDA-approved systems such as IDx-DR are enabling autonomous detection of referable DR from fundus photographs. In a 2024 study conducted by Abràmoff and colleagues, an AI system achieved 87.2% sensitivity and 90.7% specificity in detecting referable DR.[2] Beyond screening, AI is able to predict DR progression by analyzing longitudinal optical coherence tomography (OCT) data, enabling personalized monitoring intervals.[3] DL algorithms can analyze retinal images with high accuracy, and identify and grade the severity of DR, which allows efficient processing of large volumes of images. These algorithms can further identify microaneurysms, hemorrhages, and exudates with a sensitivity and specificity exceeding 85%. This reduces the dependence on manual grading and has the potential to expand access to screening in primary care settings.[4]

2. Glaucoma

AI offers promising solutions for cost-effective glaucoma screening through automated analysis of fundus and OCT images. AI systems can now detect glaucomatous optic neuropathy with high sensitivity and specificity. Unlike fundus imaging, OCT provides three-dimensional imaging that can detect depth-related structural changes in glaucoma. AI models trained on OCT images have exhibited superior accuracy compared to those trained on fundus images, performing comparably to experienced glaucoma specialists.[5] AI can also predict glaucoma progression by analyzing visual field data, allowing for earlier identification of disease progression than traditional methods. At the recent Heidelberg Engineering Symposium, experts highlighted AI's role in risk stratification, particularly for patients with normal-tension glaucoma, where traditional metrics often fail. These advancements in AI technology enhance early detection and monitoring of glaucoma, facilitating timely interventions and ultimately resulting in better patient outcomes.

3. Age-Related Macular Degeneration and Retinal Imaging

AI has several applications that can potentially transform the diagnosis and treatment of age-related macular degeneration (AMD). AI models are able to detect and predict the progression of AMD, effectively quantifying drusen volumes and geographic atrophy progression using OCT and fundus autofluorescence. DL models can classify disease severity into early, intermediate, and advanced stages with 94% accuracy, offering the potential to customize anti-vascular endothelial growth factor (VEGF) treatment protocols.[6] Generative adversarial networks (GANs), a type of ML model that uses two neural networks to compete against each other, can enhance image resolution, thus enabling the detection of nascent subretinal drusenoid deposits that predict late-stage AMD.[7] In addition, these models can accurately predict visual acuity response to treatment, which may considerably increase patient compliance. Lastly, DL AI models can effectively predict the conversion to geographic atrophy and suggest new biomarkers for AMD conversion.[7]

AI has also shown significant progress in diagnosing and staging retinopathy of prematurity (ROP). These systems are enhancing the efficiency and accuracy of ROP screening, thereby reducing the workload on clinicians and enabling timely interventions for these patients.[8]

4. Anterior Segment Applications

AI technology is showing growing utility in diagnosing and managing a range of ocular surface and corneal diseases. AI models trained on corneal topography, tomography, and anterior segment OCT can detect subclinical keratoconus (forme fruste) and classify disease severity with high accuracy, achieving 98% sensitivity in recent trials.[6] The grading of lens opacities, once a subjective clinical assessment, is now being automated through AI analyses of slit-lamp and fundus images, thereby streamlining cataract evaluations. More recently, smartphone-integrated AI platforms (such as CorneAI), have emerged, with the ability to distinguish between various corneal pathologies via simple slit-lamp photographs. This development holds particular promise in resource-limited settings. Beyond infection and ectasia, convolutional neural networks have also shown success in recognizing subtle patterns associated with Fuchs' endothelial dystrophy, map-dot-fingerprint dystrophy, and Salzmann's nodular degeneration—potentially informing both medical therapy and surgical decision-making.[6,9]

5. Intraocular Surgery

Currently, AI applications in cataract and vitreoretinal surgery focus largely on surgical planning, real-time decision support, and postoperative outcome prediction. ML algorithms, trained on large datasets of biometric and intraoperative parameters, have demonstrated improved accuracy in intraocular lens power calculations. These algorithms outperform conventional formulas, particularly in eyes with atypical anatomy, such as those that have undergone post-refractive surgery or have high axial myopia.[10] In cataract surgery, AI-integrated platforms can predict the likelihood of intraoperative complications such as posterior capsular rupture based on preoperative imaging, and patient-specific variables.[11] In vitreoretinal surgery, AI is being explored for its potential in instrument tracking, surgical phase recognition, and microsurgical skill assessment, enabling objective analysis of surgical videos. This research is laying the exciting groundwork for intelligent robotic assistance and automated training feedback.

6. Telemedicine and Population Health

The COVID-19 pandemic served as a catalyst for the rapid adoption of AI in tele-ophthalmology, particularly in the realms of DR and ROP. At India's Aravind Eye Care System, one of the world's largest eye care networks, autonomous AI implementation has led to a significant reduction in screening costs while maintaining a diagnostic concordance rate of 92% compared to retina specialists.[12] Liu et al. assessed the cost-effectiveness and cost-utility of AI-driven screening for 5 major eye diseases in China, including DR, AMD, glaucoma, cataract, and refractive errors.[13] The study demonstrated that AI-supported telemedicine was the dominant strategy, providing superior cost-effectiveness in 90% of rural and 67% of urban regions. These findings underscore the economic and clinical viability of AI-based screening models, particularly in large-scale public health systems and underserved areas where access to subspecialty care is limited.

Challenges and Limitations

Despite its tremendous potential, the integration of AI into routine clinical ophthalmology faces several challenges. Concerns around model transparency, generalizability across diverse populations, ethical implementation, and regulatory oversight continue to slow widespread adoption.

A critical limitation lies in data heterogeneity and algorithmic bias. Most AI models are trained on datasets derived from high-income countries, which restricts their applicability to broader global populations. For instance, a 2024 study demonstrated that DR algorithms trained on Western cohorts significantly underperformed when applied to African populations, raising concerns about equity and reliability in global deployment.[14]

Generative AI and large language models, while holding great potential, have shown a susceptibility to errors, which introduces significant concerns about accuracy and accountability in clinical practice.

Even in regions where AI technologies have received regulatory approval, clinician skepticism remains a significant barrier. A 2025 study revealed that approximately 45% of ophthalmologists surveyed were unwilling to trust AI-generated recommendations.[15] Furthermore, many current electronic medical record systems are not designed for AI interoperability, which limits seamless usage.

Finally, there is a substantial gap in AI literacy among clinicians, which perpetuates the so-called "black box phenomenon"—wherein providers are hesitant to rely on models whose decision-making processes are not fully understood. This issue, combined with smaller and non-representative training datasets, discrepancies between research and clinical settings, and regulatory uncertainty, underscores the need for clinician education and transparent AI design before full-scale clinical integration can be achieved.

Future Directions

The future of ophthalmology lies in the evolution of multimodal AI systems. These advanced tools are capable of synthesizing complex datasets such as imaging, functional testing, genomics, and longitudinal health records to deliver care that is predictive, personalized, and preventive. AI models offering simultaneous screening for multiple ocular conditions from a single imaging session are already demonstrating significant clinical utility, particularly in diseases such as glaucoma and AMD.

On the surgical front, augmented reality and AI-assisted navigation systems are poised to enhance intraoperative precision by improving tissue visualization and depth perception in real-time. Concurrently, advances in robotic microsurgery, powered by AI-driven feedback loops and real-time data fusion, suggest a future where semi-autonomous surgical systems augment both safety and efficiency in complex procedures.

The deployment of mobile and cloud-based AI platforms in pharmacies, community clinics, and underserved settings is democratizing access to expert-level diagnostics. As AI becomes more seamlessly integrated with electronic medical records and tele-ophthalmology infrastructure, its role in population-level screening, triage, and disease management will continue to expand.

While challenges around transparency, bias, regulations, and clinician trust remain, the convergence of AI and ophthalmology is undeniably transformative. The future will be shaped not only by technological breakthroughs, but also by our collective ability to implement them ethically, equitably, and intelligently. If realized responsibly, AI will not merely enhance eye care—it will redefine its reach, precision, and promise.

Correspondence

Michelle Khan, MD, FRCSC
Email: mkhan@qmed.ca

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