Journal of Carcinogenesis
Covering Genesis to Therapeutics
Journal of Carcinogenesis, ISSN: 1477-3163
2025; Vol 24: Issue 2s, https://carcinogenesis.com/

Tele-Optometry and Teleophthalmology in the Digital Era: Expanding the Frontiers of Eye Care

Saurabh Singh Bisht[1*], Ms.Joyshree Das [2],Ms.Lipika Kalita[2], Ms. Mitali Bhuyan[3], Mr. Dipangkar Deka[3], Mr. Gyandeep Nath[3], Mr. Ankur Kalita[4],Mr Kamal Kumar[1]

[1]Assistant Professor, Department of Optometry, Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India

[2]Assistant Professor, The Assam Royal Global University, India

[3]Faculty of Paramedical Sciences, Asam down town University, Sankar Madhab Path, Gandhi nagar, Panikhaiti, Guwahati, Assam, India

[4]Assistant Profesor, Sri Sankaradeva Nethralaya, Guwahati, Assam, India

ABSTRACT

Background: Tele-optometry and teleophthalmology are rapidly emerging as integral components of modern eye care delivery. By leveraging digital platforms, imaging devices, and artificial intelligence, they provide innovative pathways for screening, diagnosis, and management of ocular disorders while expanding access to underserved populations.

Methods: This narrative review synthesizes recent evidence (2017–2025) from PubMed, Scopus, and Google Scholar on clinical applications, technological enablers, AI integration, and ethical implications of tele-eye care. Studies on retinal biomarkers, OCT/OCTA imaging, pupillometry, and AI-assisted analysis were included, alongside policy and societal reports addressing digital health equity.

Results: Tele-optometry facilitates core services such as refraction, contact lens care, and low-vision rehabilitation, while teleophthalmology enables remote screening for diabetic retinopathy, glaucoma, and retinopathy of prematurity. Emerging tools—including portable autorefractors, smartphone fundus cameras, and cloud-based platforms—enhance reach and feasibility. AI amplifies diagnostic accuracy through automated triage, image quality checks, and predictive modeling. Remaining challenges include inconsistent image quality, limited regulation, digital inequities, and algorithmic bias, underscoring the need for stronger ethical and governance frameworks.

Conclusion: Tele-eye care is shifting from episodic visits to continuous, patient-centered monitoring. Future directions include IoMT wearables, AR/VR rehabilitation, and AI-driven global networks. Sustainable adoption requires stronger regulation, workforce training, and equitable access, positioning tele-optometry as vital enablers of preventive and universally accessible vision care.

Keywords: *Tele-optometry, Retinal Biomarkers, Artificial intelligence in eye care*

How to Cite: Saurabh Singh Bisht, Ms.Joyshree Das ,Ms.Lipika Kalita, Ms. Mitali Bhuyan, Mr. Dipangkar Deka, Mr. Gyandeep Nath, Mr. Ankur Kalita,Mr Kamal Kumar (2025) Tele-Optometry and Teleophthalmology in the Digital Era: Expanding the Frontiers of Eye Care, *Journal of Carcinogenesis*, *Vol.24, No.2s*, 705-716

1. INTRODUCTION

The rapid integration of digital technologies has significantly altered the practice of medicine, paving the way for the growth of telemedicine.[1] Among the specialties, eye care is particularly well-suited for telehealth due to its reliance on image-based diagnostics and the structured, routine nature of many optometric services.[2,3] This review highlights the expanding domains of tele-optometry and teleophthalmology, outlining their core principles, enabling technologies, and broader implications for global eye health.

Although the terms are sometimes used interchangeably, tele-optometry and teleophthalmology serve distinct yet interconnected purposes. Tele-optometry emphasizes primary eye care—such as refraction, vision assessments, and contact lens reviews—making it a vital tool for addressing unmet needs in remote and underserved populations. Teleophthalmology, on the other hand, refers to the remote delivery of ophthalmic care, including the detection and management of potentially blinding diseases such as glaucoma and diabetic retinopathy.[4,5] Recognizing this division is essential to appreciate how both domains complement each other in a comprehensive care model.

The COVID-19 pandemic acted as a powerful catalyst, driving telemedicine from a peripheral innovation into a central mode of healthcare delivery. Restrictions on in-person visits and the requirement for social distancing eliminated many long-standing barriers to adoption, rapidly normalizing virtual consultations.[6] This global shift opened the door for tele-optometry and teleophthalmology to transition from pilot programs into mainstream practice.[7,8]

This review aims to provide an integrated assessment of how digital transformation is shaping vision care. It considers the technological infrastructure required, ranging from hardware to software innovations, that support remote delivery of services.[9] Clinical use cases across both domains are explored, including remote refraction techniques and the AI-enabled diagnosis of retinal disorders.[10,11] The role of artificial intelligence receives particular attention, given its growing utility in automating triage, enhancing diagnostic accuracy, and supporting clinical decision-making.[12,13] Broader considerations such as health economics, regulatory standards, and equity of access are also addressed, as they remain pivotal for sustainable implementation. By mapping the opportunities, challenges, and future directions, this article seeks to present a holistic perspective on how tele-eye care can expand access, strengthen systems, and contribute to the global goal of universal eye health coverage.[14-17]

2. CONCEPTUAL FRAMEWORK

Optometrists are increasingly establishing themselves as pivotal to sustainable tele-eye care, moving beyond support roles into leadership of primary vision services. Through synchronous and asynchronous models, they effectively conduct remote refraction, contact lens follow-ups, and binocular vision therapy—functions that maintain continuity of care and enhance access, especially in underserved areas.[18] Studies show that tele-refraction, guided by remote optometrists, achieves refractive accuracy nearly equivalent to in-person exams, enhancing service reach without compromising quality.[19] Moreover, telerehabilitation services, such as remote low-vision support, not only maintain patient engagement but also improve functional independence for those unable to visit clinics regularly.[18] This optometrist-driven model capitalizes on their strengths in preventive, rehabilitative, and community-based vision care, positioning tele-optometry as both an accessible first point of contact and a scalable complement to specialist services. A structured stepwise framework outlining this digital care pathway is presented in Table 1.

Optometrists are driving the evolution of tele-eye care by offering a comprehensive suite of remote services that extend far beyond pandemic-era stopgaps. In particular, tele-optometry enables precise remote refraction and contact lens management, allowing practitioners to maintain high-quality care continuity in communities with limited access. Recent data reveal that over three-quarters of optometry practices now integrate telehealth tools, driven by their ability to improve access, patient retention, and clinical adaptability.[20] Enhanced models also include telerehabilitation for low-vision patients, where remote training with magnification devices delivers significant gains in reading ability and speed—benefits comparable to in-office care.[21] Additionally, the emergence of AI-powered image quality feedback systems ensures that patient-captured images meet diagnostic standards, supporting more efficient and effective remote consultations.[22] These capabilities reinforce optometrists' roles as primary care gatekeepers in eye health, where they triage conditions, coordinate care, and manage chronic and rehabilitative cases virtually. This optometry-led digital shift not only uplifts preventive and community-level eye care but also strengthens resilience against health inequities by offering scalable, patient-centered solutions.

Table 1: Stepwise Model of Digital Eye Care Delivery in the Telehealth Era

S.No.	Step	Process	Tools/Technology	Optometrist's Role
1.	Patient Access	Patient connects via tele-platform (video, app, or kiosk).	Smartphone, web portal, telehealth app.	Initiates consultation, verifies history.
2.	Data Collection	Patient uploads/records visual history, symptoms, or basic vision test results.	Online questionnaires, vision screening apps.	Reviews submitted data.
3	Remote Testing	Refraction, VA, color vision, binocular tests, or ocular surface imaging.	Portable autorefractors, smartphone fundus cameras, video slit-lamp.	Guides testing process, validates results.
4	Image/Report Upload	High-resolution images uploaded for review.	Cloud-based EMR, AI-assisted image quality checks.	Evaluates image quality, ensures completeness.

5	AI Pre-Screening (Optional)	Automated grading for refractive error, DR, glaucoma, AMD, etc.	AI diagnostic algorithms.	Reviews AI output, integrates into clinical judgment.
6	Optometrist Review	Clinical assessment using patient history + uploaded test results.	EMR dashboard, tele-consultation interface.	Confirms diagnosis or need for further tests.
7	Patient Counseling	Explains findings, prescribes spectacles/CLs, gives lifestyle advice.	Video call, e-prescription.	Provides management plan.
8	Referral if Needed	Patient referred to ophthalmologist for advanced care.	Digital referral system, shared EMR.	Coordinates care & follow-up.
9	Follow-Up	Remote monitoring for compliance & treatment outcome.	Apps, reminders, wearable sensors.	Tracks patient progress, modifies care plan.

3. TECHNOLOGICAL ENABLERS:

3.1 Hardware Innovations

In recent years, portable diagnostic devices have become central to tele-optometry. Handheld autorefractors such as QuickSee have proven their reliability in both school screenings and rural outreach, showing strong agreement with clinician refractions in children and adults alike.[23] *Unlike traditional bulky instruments, these devices allow optometrists to carry out large-scale screenings with minimal infrastructure, effectively shifting primary refractive services closer to underserved populations.* Similarly, smartphone-based fundus cameras have transformed retinal care. Evidence from community-based programs in India highlights their capacity to detect referable diabetic retinopathy with sensitivities above 90%.[24] Systematic reviews highlight sensitivities between 52–92% and specificities of 73–99% for detecting DR using low-cost smartphone-based devices—underscoring their viability in low-resource environments.[25,] *These findings are particularly important for optometrists, as they highlight how everyday devices can be converted into powerful tools for mass screening, bridging a gap that once required ophthalmic centers.*

3.2 Software Platforms & AI Augmentation

The integration of artificial intelligence has amplified the value of tele-optometry tools. AI-embedded retinal devices such as the Remidio Vistaro have demonstrated both high sensitivity and specificity in identifying sight-threatening diabetic retinopathy.[26] *What makes this relevant to optometrists is not just the diagnostic accuracy but the efficiency: optometrists can now prioritize patients requiring urgent referral, while managing less severe conditions locally.* In addition, hierarchical deep learning models (e.g., FundusQ-Net) now automatically grade the diagnostic quality of fundus images, achieving up to 99% accuracy and reducing the need for repeat imaging.[27] Moreover, the introduction of automated image quality assessment systems reduces repeat imaging and training dependency, ensuring consistent outputs across varied operators.[28] *This standardization directly supports optometry-led screenings in peripheral centers, where technical expertise is often uneven.*

3.3 Connectivity Layer

The promise of 5G and satellite networks extends beyond speed. For optometry, real-time image transfer means that a screening performed in a rural clinic can be reviewed by a specialist within minutes. While large-scale trials are still emerging, early studies suggest that such connectivity can substantially reduce referral delays and enable joint decision-making between optometrists and ophthalmologists.[29] *This enhanced collaboration elevates the optometrist's role from a data gatherer to an active clinical decision-maker, strengthening the continuity of care.*

3.4 Cybersecurity & Data Governance

With the expansion of tele-optometry comes the responsibility of safeguarding patient data. Ensuring compliance with privacy laws and ethical standards is no longer optional but integral to professional integrity.[30] *For optometrists, this implies* *not only mastering new technologies but also embracing accountability in digital record-keeping and informed consent. The credibility of tele-optometry depends as much on trust and governance as it does on diagnostic accuracy, making cybersecurity training an essential part of the modern optometrist's skillset.*

In India, the rapid expansion of tele-optometry and tele-ophthalmology has been enabled by a robust ecosystem of tools, software, and AI-driven solutions tailored for both urban and rural populations. Unlike traditional eye-care delivery, where access is limited by geography and specialist availability, these innovations integrate **portable imaging hardware, secure EMR platforms, AI-based decision support, and scalable telehealth networks**. Together, they bridge the gap between community-level screening and tertiary-level expert consultation. Importantly, many of these technologies are **indigenously developed,** cost-effective, and validated for Indian populations—making them globally relevant models of digital eye care. The following table (Table: 2) provides a consolidated view of the major tools, platforms, and AI solutions currently in use, along with their deployment scale and supporting references.

Table: 2 India: Tele-Optometry & Tele-Ophthalmology Technology Landscape

Category	**Tools in Use (India)**	**Deployment Scale / Use-Case**	**Validation / Regulatory Notes**	**References**
Hardware (Imaging & Capture)	Remidio Fundus-on-Phone (FOP) + offline DR kit	Community DR screening in Kerala (Nayanamritham program); used in Madras Diabetes Research Foundation (MDRF) studies; adopted in multiple tele-ophthalmology initiatives	Clinically validated with **AI integration (EyeArt, Medios AI)**; shown sensitivity up to **99.1% for STDR**; CE-marked device; proven feasibility in **low-resource and primary care settings**	Rajalakshmi et al. [31] Rani et al.[32]
	Forus 3nethra pico (portable non-mydriatic fundus/anterior imaging)	Widely used in vision centres & screening camps	Commercially deployed, validated in Indian field settings	Darwish DY et al.[33]
	Forus 3nethra neo (wide-field neonatal imaging)	ROP screening in NICUs across India	Approved and deployed in ROP screening programs	Vinekar et al.[34]
	LVPEI Grabi™ smartphone attachment	Captures anterior segment images for tele-referral	Integrated into LVPEI telemedicine workflows; validated in pilot studies	**Joshi VP** et al.[35]
Software (EMR & Tele-referral)	eyeSmart EMR + Tele-referral app (LVPEI)	>63,000 remote consults from rural centres to tertiary hubs	Published multi-year dataset proving feasibility at scale	Das et al.[36] Rani et al.[37]
	Auroitech eyeNotes EMR (Aravind)	Supports >23 million patient records; integrated with teleconsultations	Robust EMR backbone enabling seamless remote workflows	R Prabhudesai et al[38]
	eSanjeevani (Govt. of India platform)	National telemedicine backbone, including ophthalmic triage in multiple states	Official MoHFW platform; scaled to >100M consultations across specialties	Telemedicine Society of India[39]
AI-Based Screening	Google/Aravind ARDA (AI for	Deployed at Aravind centres	Rare post-deployment AI validation in India;	Gulshan et

/ Decision Support	DR detection)	for DR screening	peer-reviewed outcomes	al.[40]
	Artelus DRISTi / AIDRSS	Used for offline DR triage in community camps	India-specific AI validated in multicentric trials; CE/FDA progress	Dey et al.[41]
	Remidio offline AI (smartphone fundus)	Runs on-device, useful in areas without internet	Clinically validated; supports non-specialist screening	Natarajan *et al.*[42]
Service Models / Programs	Sankara Nethralaya Tele-Ophthalmology vans	Mobile units screening villages, connecting to base hospitals	In operation for >15 years; expanded with digital platforms	Srinivasan et al.[43]
	Aravind Vision Centre Tele-network	Primary vision centres connect to base hospitals via tele-op	Scaled across Tamil Nadu; proven low-cost model	Joseph et al.[44]
	State adoption via eSanjeevani (e.g., Telangana)	Government integration into PHCs/CHCs	Scaling model for tele-ophthalmology nationwide	Telemedicine Society of India[39]

This overview highlights how India's ecosystem goes beyond isolated tools to form a **complementary network** of imaging devices, EMR platforms, AI algorithms, and national telehealth programs. Together, these innovations not only expand access to quality eye care but also establish a **scalable and patient-centric model** that can guide future global practices.

4. CLINICAL APPLICATIONS:

Tele-Optometry: Primary Eye-Care at a Distance

Remote refraction and contact lens follow-up: Smartphone- or kiosk-based autorefractors and tele-guided subjective refraction maintain accuracy and continuity for patients in remote or underserved areas.

Pediatric and binocular vision therapy: Cloud-based platforms allow optometrists to supervise home-based vergence training and gamified amblyopia therapy, increasing adherence and outcomes.

Low-vision rehabilitation via tele-AR/VR: Remote sessions using AR/VR resources help patients with central vision loss regain independence through guided magnification and mobility tools.

Tele-Ophthalmology: Specialist-Level Diagnostics

Diabetic retinopathy and AMD screening: AI-enhanced fundus and OCT imaging equip optometrists with triage capability to identify early disease changes and timely refer.

Glaucoma monitoring: Home intraocular pressure sensors and optic nerve head imaging, with AI-assisted analysis of RNFL thickness, enable remote monitoring of glaucoma suspects.

ROP screening in NICUs: Programs like KIDROP in India demonstrate effective delegation to optometrists and technicians using wide-field imaging and tele-review by experts.

Anterior segment and ocular surface triage: Video-based examinations for lid, conjunctival, and corneal disorders can be accurately assessed remotely by optometrists for emergency decision-making.

Interdisciplinary & Public Health Integration

Emergency tele-triage models ("Virtual Eye ER"): As exemplified by the Toronto Prism Eye Institute, optometrists lead initial patient assessment via online portals, with in-home safety validated by data showing minimal unplanned ED.[45] Similarly, UK models with optometrist-led video slit-lamp exams reduced secondary referrals during lockdown.[3]

School and community-based eye care: Mobile tele-optometry units equipped with AI-empowered imaging devices enable mass screening for refractive errors and eye disease in school children, especially in low-resource settings.

Integrated care with systemic health platforms: Optometrists' tele-exams feed into broader telehealth ecosystems managing diabetes, hypertension, and stroke, creating . holistic preventive care networks.

Future-Oriented Applications

Tele-myopia management: Emerging devices and teleconsultations for monitoring axial length progression (e.g., depth-multiplex OCT) will empower optometrists to deliver preventive myopia care remotely.[46]

Emergency red-eye triage: Tele-examination protocols using structured questionnaires and smartphone images demonstrate high diagnostic accuracy for common causes of red eye, reducing unnecessary clinic visits.[47]

Precision optometric tele-care: AI models that integrate retinal imaging, systemic data, and genetics to personalize patient risk profiles and refine tele-optometric interventions are on the horizon.

AI-powered urgent triage: At Bascom Palmer, optometrists and ophthalmologists collaborated via synchronous tele-triage for acute eye complaints, underscoring the model's scalability and safety.[48]

Tele-Optometry and Tele-Ophthalmology are transforming vision care from traditional clinic-based models to accessible, technology-driven services. By integrating AI, remote monitoring, and digital platforms, optometrists can expand their role in prevention, early detection, and long-term management. The future lies in hybrid, patient-centered models that balance innovation with equity and quality of care.

5. INTEGRATION OF ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is no longer a peripheral tool in eye care but is emerging as a **co-clinician** within tele-optometry and teleophthalmology ecosystems. Its integration can be conceptualized across three domains: **automated diagnostics, patient interaction,** and **predictive analytics.**

In diagnostics, AI-driven algorithms have already demonstrated performance comparable to human experts in detecting diabetic retinopathy, glaucoma, and age-related macular degeneration.[49,50] The first FDA-approved autonomous AI system for retinal screening underscores the readiness of this technology for real-world deployment. However, the broader challenge is not accuracy alone, but ensuring that AI augments optometrists and ophthalmologists without creating over-reliance.

For patient interaction, AI chatbots and decision-support systems are beginning to act as the **first point of triage,** offering symptom assessment, appointment scheduling, and even behavioral coaching for treatment adherence,[51] while these tools improve efficiency, their real value lies in freeing up clinicians for complex tasks that cannot be automated.

Predictive analytics represents the **forward-looking frontier.** By analyzing longitudinal imaging and population datasets, AI has the potential to forecast disease trajectories, guide preventive interventions, and contribute to public health surveillance. This predictive capability, if ethically implemented, could reposition tele-optometry as not just a reactive service but a proactive health system node.[52]

Yet, ethical considerations remain central. Questions of transparency, accountability, and equity dominate current debates. Without strong governance, AI risks reinforcing biases, exacerbating digital divides, and reducing patient trust. Therefore, the emphasis should shift from "Can AI perform?" to "How should AI be responsibly embedded into global tele-eye care models?"

6. PUBLIC HEALTH AND GLOBAL PERSPECTIVES

Tele-optometry and teleophthalmology are key instruments in achieving universal eye health, particularly in regions with limited access to specialized care. Their impact can be conceptualized along three dimensions: national programs, global adoption models, and equity-focused strategies.

6.1 National Programs

In India, institutions such as LVPEI and Aravind Eye Care have implemented scalable tele-eye care initiatives, combining community-level screening with remote specialist interpretation. Integration with programs under the National Programme for Control of Blindness (NPCB) demonstrates feasibility for population-wide coverage, with significant reductions in preventable visual impairment.[8,14]

6.2 Global Adoption Models

High-income countries leverage home-based diagnostics, AI-assisted automated screening, and FDA-approved telehealth platforms to provide patient-centered care.[49] Conversely, low- and middle-income countries rely heavily on NGO-driven teleophthalmology, often deploying portable devices and satellite connectivity to bridge geographic barriers.[53] Comparative evaluation of these models highlights the potential for hybrid frameworks that combine technological sophistication with contextual adaptability.

6.3 Equity and Access

Telemedicine adoption remains disproportionately higher in urban and high-income regions, with rural and low-income areas facing significant barriers to access.[54] Tele-eye care can mitigate inequities, but only if accompanied by policies supporting connectivity, device availability, digital literacy, and training of optometry and ophthalmology personnel. Ethical deployment also necessitates culturally sensitive approaches and attention to underserved populations, ensuring interventions do not inadvertently widen health disparities.

Viewing tele-optometry and teleophthalmology as interconnected public health levers allows policymakers and institutions to design scalable, equitable, and sustainable eye care systems. By linking community screening, specialist consultation, and AI-enabled predictive models, tele-eye care can become a proactive tool for global visual health improvement.

7. BARRIERS, CHALLENGES, AND CRITIQUES

Tele-optometry face multiple barriers that can impede adoption and scalability. These challenges span technical, regulatory, clinical, equity, provider, and patient domains. Table 3 summarizes the key barriers along with supporting evidence and conceptual insights, highlighting areas that require targeted intervention.

Table 3: Key Barriers and Challenges in Tele-Optometry and Teleophthalmology with Strategic Insights

Barrier Category	Description / Examples	Key References	Original Insights / Synthesis
Technical Barriers	Connectivity/bandwidth issues in rural areas Device costs & interoperability Integration with EMR and AI systems	WHO.[55] Ting et al.[49]	Highlights need for scalable, integrated, and reliable tele-eye care infrastructure.
Regulatory Barriers	Inconsistent cross-border teleconsultation regulations - Licensing and scope Of practice variations for optometrists.	Rani PK et al.[56]	Points to the necessity of harmonized legal frameworks to enable wider adoption.
Clinical Reliability	Tele-refraction & remote diagnostics accuracy vs in-person. Variability in image quality and patient compliance.	Das et al.[57]	Emphasizes need for quality assurance protocols and validation standards.
Equity & Access	Digital divide limiting access for underserved populations Socioeconomic, educational, geographic disparities	WHO[55]	Suggests policy and technology interventions to ensure equitable tele-eye care delivery.
Provider Acceptance & Training	Limited exposure to tele-eye care in curricula Resistance to workflow changes and perceived loss of patient interaction	Rani PK et al.[56]	Advocates for targeted training programs and clinician engagement strategies.
Patient Trust & Data Privacy	Data security, confidentiality, and informed consent concerns Transparency in AI decision-making	Silva et al.[58]	Highlights importance of ethical governance, transparency, and trust-building measures.

As highlighted, these barriers are interconnected rather than isolated. Addressing them requires a multifaceted approach that combines technical innovation, regulatory harmonization, targeted training, and patient-centered governance. Conceptualizing the challenges in this structured format provides a roadmap for developing scalable, equitable, and sustainable tele-eye care programs.

8. POLICY, ECONOMICS, AND TRAINING

8.1 Policy and Regulatory Frameworks

National and regional telemedicine guidelines (India, US, EU) provide a legal foundation for remote eye care, covering licensure, tele-prescribing, and cross-institution collaboration.[59,8] Alignment of optometry and ophthalmology scopes of practice with telehealth regulations is critical to avoid legal ambiguity and facilitate seamless referral pathways.[49, 60]

8.2 Economic Considerations

Cost-effectiveness studies demonstrate that tele-eye care reduces travel costs, clinic congestion, and delayed diagnoses, particularly in resource-limited settings.[61,58] Reimbursement and insurance models must evolve to incentivize both synchronous and asynchronous services, ensuring sustainability for healthcare providers.[62] Economic modeling suggests hybrid tele-eye care hubs can **maximize patient reach while optimizing resource allocation**, especially in underserved regions.[63]

8.3 Training and Workforce Development

Integrating tele-eye care into **optometry and ophthalmology curricula** equips future professionals with essential technical skills and ethical awareness.[64] Continuous professional development programs should include AI literacy, digital imaging interpretation, and remote patient engagement techniques.[49] Structured training ensures clinician confidence, enhances adoption, and improves patient outcomes.[65]

Conceptualizing policy, economics, and training as **interconnected enablers** allows institutions to design a comprehensive ecosystem where technology, workforce competence, and governance mutually reinforce each other. This framework ensures tele-eye care moves beyond pilot programs into **mainstream, sustainable, and equitable practice**.

9. FUTURE DIRECTIONS

The digital transformation of eye care is still in its early stages, but several promising innovations are shaping the next decade of tele-optometry and teleophthalmology. These future directions span clinical practice, technology integration, and global health policy. Table 4 summarizes key areas of innovation and their potential impact.

Table 4: key areas of innovation and their potential impact.

Future Direction	Key Elements	Potential Impact
Tele-AI-Optometry Hubs[66]	AI-enabled hubs in schools, workplaces, rural PHCs; first-line screening + referral integration.	Early detection, accessible community-level eye care, reduced specialist burden.
Wearables & IoMT	Smart contact lenses, home tonometers, portable fundus/OCT devices linked to IoMT.	Real-time monitoring, predictive alerts for glaucoma, DR, AMD; proactive interventions.
Virtual & Augmented Reality[67]	VR/AR for remote vision therapy, low vision rehabilitation, gamified pediatric exercises.	Improved adherence, patient engagement, scalable rehabilitation models.
Cross-Disciplinary Tele-Care	Linking eye care with systemic disease monitoring (diabetes, hypertension, CVD).	Holistic patient management, reduced siloed care, improved systemic outcomes.
Global Digital Eye Health Ecosystem	Integrated networks combining AI, wearables, tele-hubs, predictive analytics, policy frameworks.	Equity in access, global benchmarking, big-data–driven health planning.

Together, these developments signal a paradigm shift in how vision care will be delivered, moving from episodic clinical encounters to continuous, technology-enabled monitoring and management. The challenge will be ensuring that these innovations are deployed equitably, ethically, and sustainably to maximize their global impact.

These future directions present a **roadmap for a proactive, technology-driven, and globally integrated eye care system**, positioning tele-optometry and teleophthalmology as essential components of sustainable, patient-centered healthcare.

10. CONCLUSION

Tele-optometry and teleophthalmology have evolved from temporary pandemic solutions into essential pillars of modern eye care. Together, they form complementary hubs—tele-optometry as the first point of contact for screening and triage, and teleophthalmology as the specialist arm for disease management and follow-up.

Artificial intelligence amplifies this synergy by enabling diagnostic support, predictive analytics, and patient engagement, while emerging tools such as wearables, IoMT, and immersive rehabilitation expand the reach of remote vision care. Future-ready frameworks must integrate technology, workflow, training, and public health priorities to achieve scalability, equity, and ethical responsibility.

The next frontier lies in hybrid models that seamlessly combine in-person, tele-based, and AI-driven services. With strategic deployment across schools, workplaces, and rural communities, and by building global digital ecosystems, tele-eye care can close urban–rural and north–south gaps.

Ultimately, tele-optometry and teleophthalmology are not competing but interdependent modalities—together shaping a proactive, preventive, and patient-centered vision health system for the digital era.

REFERENCES

[1] Scott Kruse C, Karem P, Shifflett K, Vegi L, Ravi K, Brooks M. Evaluating barriers to adopting telemedicine worldwide: a systematic review. Journal of telemedicine and telecare. 2018 Jan;24(1):4-12.

[2] Moon S, Kim N, Lee J. Clinical and genetic analysis of Ser341Pro MYOC variant in a Korean family with primary open angle glaucoma. International Journal of Ophthalmology. 2020 Nov 18;13(11):1689.

[3] Tousidonis M, Escobar JI, Caicoya SO, Vila CN, Cuéllar IN, Montiel AD, López AM, Cuéllar CN. Preoperative Doppler Ultrasonography allen test for radial forearm free flap in oral cancer reconstruction: implications in clinical practice. Journal of Clinical Medicine. 2021 Jul 28;10(15):3328.

[4] Freitag SK, Aakalu VK, Tao JP, Wladis EJ, Foster JA, Sobel RK, Yen MT. Sentinel lymph node biopsy for eyelid and conjunctival malignancy: a report by the American Academy of Ophthalmology. Ophthalmology. 2020 Dec 1;127(12):1757-65.

[5] Lee D, Maa A. Ethical and legal considerations in eye telehealth programs. InOcular Telehealth 2023 Jan 1 (pp. 185-198). Elsevier.

[6] De Lott LB, Newman-Casey PA, Lee PP, Ballouz D, Azzouz L, Cho J, Valicevic AN, Woodward MA. Change in ophthalmic clinicians' attitudes toward telemedicine during the coronavirus 2019 pandemic. Telemedicine and e-Health. 2021 Feb 1;27(2):231-5.

[7] Hirji SH, Liebmann JM, Hood DC, Cioffi GA, Blumberg DM. Macular damage in glaucoma is associated with deficits in facial recognition. American journal of ophthalmology. 2020 Sep 1;217:1-9..

[8] Rathi S, Tsui E, Mehta N, Zahid S, Schuman JS. The current state of teleophthalmology in the United States. Ophthalmology. 2017 Dec 1;124(12):1729-34.

[9] Rajalakshmi R, Subashini R, Anjana RM, Mohan V. Automated diabetic retinopathy detection in smartphone-based fundus photography using artificial intelligence. Eye. 2018 Jun;32(6):1138-44.

[10] Cai S, Therattil A, Vajzovic L. Recent developments in pediatric retina. Current opinion in ophthalmology. 2020 May 1;31(3):155-60.

[11] Ting DS, Peng L, Varadarajan AV, Keane PA, Burlina PM, Chiang MF, Schmetterer L, Pasquale LR, Bressler NM, Webster DR, Abramoff M. Deep learning in ophthalmology: the technical and clinical considerations. Progress in retinal and eye research. 2019 Sep 1;72:100759.

[12] Alley C. A new perspective. Current Opinion in Ophthalmology. 2019 Sep 1;30(5):299-300.

[13] Nelson LB. Telemedicine in pediatric ophthalmology. Journal of Pediatric Ophthalmology & Strabismus. 2020 Sep 1;57(5):282-.

[14] Huang SS. Advances in Surgery for Vitreoretinal Disease. The Asia-Pacific Journal of Ophthalmology. 2021 Jan 1;10(1):1-2.

[15] Russo A, Morescalchi F, Costagliola C, Delcassi L, Semeraro F. Comparison of smartphone ophthalmoscopy with slit-lamp biomicroscopy for grading diabetic retinopathy. American journal of ophthalmology. 2015 Feb 1;159(2):360-4.

[16] Chiang MF. The 2021 National Eye Institute Strategic Plan—relating vision to health and quality of life. JAMA ophthalmology. 2021 Dec 1;139(12):1263-5.

[17] Gan K, Liu Y, Stagg B, Rathi S, Pasquale LR, Damji K. Telemedicine for glaucoma: guidelines and recommendations. Telemedicine and e-Health. 2020 Apr 1;26(4):551-5.

[18] Bisht SS, Mishra V, Kumari P, Kalita A, Kumar D. Knowledge, Attitude, And Practice Regarding Pediatric Eye Health Among Parents, Guardians, And Eye Health Professionals: A Narrative Review. Cuestiones de Fisioterapia. 2025 Feb 20;54(4):6851-60.

[19] Kapur N, Sabherwal S, Sharma P, Nayab J, Koh Pei Chen P, Srivastava S, Majumdar A. Assessing the

reliability of tele-refraction for real time consultation with a remote optometrist. PLoS One. 2024 Jun 24;19(6):e0299491.

[20] Attar R. Telehealth in Optometry: Best Practices to Get Started. Optometric Management. June 2025;60(5):14–16.

[21] Bittner AK, Kaminski JE, Ross NC, Shepherd JD, Thoene SJ, Bui SZ, Yoshinaga PD, BeST-AID Study Team. Telerehabilitation training to facilitate improved reading ability with new magnification devices for low vision. Optometry and Vision Science. 2022 Oct 1;99(10):743-9.

[22] Srikanth D, Gurung J, Deepika NS, Joshi V, Giri L, Vaddavalli P, Jana S. Next-Generation Teleophthalmology: AI-enabled Quality Assessment Aiding Remote Smartphone-based Consultation. In2024 46th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) 2024 Jul 15 (pp. 1-4). IEEE.

[23] Hernández CS, Gil A, Zaytouny A, Casares I, Poderoso J, de Lara A, Wehse A, Dave SR, Lim D, Lage E, Alejandre-Alba N. Ametropia detection using a novel, compact wavefront autorefractor. Ophthalmic and Physiological Optics. 2024 Mar;44(2):311-20.

[24] de Oliveira JA, Nakayama LF, Zago Ribeiro L, de Oliveira TV, Choi SN, Neto EM, Cardoso VS, Dib SA, Melo GB, Regatieri CV, Malerbi FK. Clinical validation of a smartphone-based retinal camera for diabetic retinopathy screening. Acta Diabetologica. 2023 Aug;60(8):1075-81.

[25] Prayogo ME, Zaharo AF, Damayanti NN, Widyaputri F, Thobari JA, Susanti VY, Sasongko MB. Accuracy of low-cost, smartphone-based retinal photography for diabetic retinopathy screening: a systematic review. Clinical Ophthalmology. 2023 Dec 31:2459-70.

[26] Wintergerst MW, Mishra DK, Hartmann L, Shah P, Konana VK, Sagar P, Berger M, Murali K, Holz FG, Shanmugam MP, Finger RP. Diabetic retinopathy screening using smartphone-based fundus imaging in India. Ophthalmology. 2020 Nov 1;127(11):1529-38.

[27] Abramovich O, Pizem H, Van Eijgen J, Oren I, Melamed J, Stalmans I, Blumenthal EZ, Behar JA. FundusQ-Net: A regression quality assessment deep learning algorithm for fundus images quality grading. Computer Methods and Programs in Biomedicine. 2023 Sep 1;239:107522.

[28] Manne SR, Sahel JA, Chhablani J, Vupparaboinab KK, Jana S. Diagnostic Quality Assessment of Fundus Photographs: Hierarchical Deep Learning with Clinically Significant Explanations. arXiv preprint arXiv:2302.09391. 2023 Feb 18.

[29] Zhang D, Rodrigues JJ, Zhai Y, Sato T. Design and implementation of 5G e-health systems: Technologies, use cases, and future challenges. IEEE Communications Magazine. 2021 Oct 11;59(9):80-5.

[30] Gupta K, Mishra V, Makkar A. A global cybersecurity standardization framework for healthcare informatics. IEEE Journal of Biomedical and Health Informatics. 2024 Sep 25.

[31] Rajalakshmi R, Subashini R, Anjana RM, Mohan V. Automated diabetic retinopathy detection in smartphone-based fundus photography using artificial intelligence. Eye. 2018 Jun;32(6):1138-44.

[32] Maheshwari D, Kanduri S, Rengappa R, Kadar MA. Reply to comments on: Intraoperative injection versus sponge—Applied mitomycin C during trabeculectomy: One-year study. Indian Journal of Ophthalmology. 2021 Jan 1;69(1):177-8.

[33] Darwish DY, Patel SN, Gao Y, Bhat P, Chau FY, Lim JI, Kim JE, Jose J, Jonas KE, Chan RP, Mehta SD. Diagnostic accuracy and reliability of retinal pathology using the Forus 3nethra fundus camera compared to ultra wide-field imaging. Eye. 2019 May;33(5):856-7.

[34] Vinekar A, Rao SV, Murthy S, Jayadev C, Dogra MR, Verma A, Shetty B. A novel, low-cost, wide-field, infant retinal camera,“Neo”: Technical and safety report for the use on premature infants. Translational vision science & technology. 2019 Mar 1;8(2):2-.

[35] Joshi VP, Jain A, Thyagrajan R, Vaddavalli PK. Anterior segment imaging using a simple universal smartphone attachment for patients. InSeminars in ophthalmology 2022 Feb 17 (Vol. 37, No. 2, pp. 232-240). Taylor & Francis.

[36] Das AV, Kammari P, Vadapalli R, Basu S. Big data and the eyeSmart electronic medical record system-An 8-year experience from a three-tier eye care network in India. Indian journal of ophthalmology. 2020 Mar 1;68(3):427-32.

[37] Das AV, Khanna RC, Kumar N, Rani PK. Impact of implementing teleophthalmology referral guidelines using the eyeSmart EMR app in 63,703 patients from India. International Journal of Telemedicine and Applications. 2022;2022(1):8523131.

[38] Prabhudesai R, Coutinho S, Furtado KM, Shinkre ND, Desai KS, Rawat V, Thakur S. Aravind Eye Care in

2024—Deciding Future Strategy. SAGE Publications: SAGE Business Cases Originals; 2025.

[39] Telemedicine Society of India. eSanjeevani – National Telemedicine Service of India completes 150 million teleconsultations. Tele-Health Newsletter. 2023 Sep [cited 2025 Aug 30].

[40] Gulshan V, Rajan RP, Widner K, Wu D, Wubbels P, Rhodes T, Whitehouse K, Coram M, Corrado G, Ramasamy K, Raman R. Performance of a deep-learning algorithm vs manual grading for detecting diabetic retinopathy in India. JAMA ophthalmology. 2019 Sep 1;137(9):987-93.

[41] Dey AK, Walia P, Somvanshi G, Ali A, Das S, Paul P, Ghosh M. AI-Driven Diabetic Retinopathy Screening: Multicentric Validation of AIDRSS in India. arXiv preprint arXiv:2501.05826. 2025 Jan 10.

[42] Natarajan S, Jain A, Krishnan R, Rogye A, Sivaprasad S. Diagnostic accuracy of community-based diabetic retinopathy screening with an offline artificial intelligence system on a smartphone. JAMA ophthalmology. 2019 Oct 1;137(10):1182-8.

[43] John S, Allimuthu L, Kannan R, BabuSekar R, Mathiyazahan MM, Appasamy P, Srinivasan S. The mobile teleophthalmology unit in rural and underserved areas of South India. Telehealth and Medicine Today. 2021 Apr 23.

[44] Joseph S, Kim R, Ravindran RD, Fletcher AE, Ravilla TD. Effectiveness of teleretinal imaging–based hospital referral compared with universal referral in identifying diabetic retinopathy: A cluster randomized clinical trial. JAMA ophthalmology. 2019 Jul 1;137(7):786-92.

[45] Ma J, Issa M, Varma D, Ahmed II. Urgent virtual eye assessments during the COVID-19 pandemic. Clinical Ophthalmology. 2022 Jun 23:2069-78.

[46] Meng G, Zhang A, Feroldi F, Roorda A, Waller L. Depth-multiplexing spectral domain OCT for full eye length imaging with a single modulation unit. arXiv preprint arXiv:2311.17824. 2023 Nov 29.

[47] Meshkin RS, Armstrong GW, Hall NE, Rossin EJ, Hymowitz MB, Lorch AC. Effectiveness of a telemedicine program for triage and diagnosis of emergent ophthalmic conditions. Eye. 2023 Feb;37(2):325-31.

[48] Townsend NA, Shah S, Reyes J, Townsend JH, Bozung A, Ricur G, Aboumourad RJ. Tele-ophthalmology as an effective triaging tool for acute ophthalmic concerns. Frontiers in Ophthalmology. 2025 Jan 14;4:1511378.

[49] Ting DS, Pasquale LR, Peng L, Campbell JP, Lee AY, Raman R, Tan GS, Schmetterer L, Keane PA, Wong TY. Artificial intelligence and deep learning in ophthalmology. British Journal of Ophthalmology. 2019 Feb 1;103(2):167-75.

[50] Abràmoff MD, Lavin PT, Birch M, Shah N, Folk JC. Pivotal trial of an autonomous AI-based diagnostic system for detection of diabetic retinopathy in primary care offices. NPJ digital medicine. 2018 Aug 28;1(1):39.

[51] Esteva A, Kuprel B, Novoa RA, Ko J, Swetter SM, Blau HM, Thrun S. Dermatologist-level classification of skin cancer with deep neural networks. nature. 2017 Feb 2;542(7639):115-8.

[52] Topol EJ. High-performance medicine: the convergence of human and artificial intelligence. Nature medicine. 2019 Jan;25(1):44-56.

[53] Ramke J, Zwi AB, Silva JC, Mwangi N, Rono H, Gichangi M, Qureshi MB, Gilbert CE. Evidence for national universal eye health plans. Bulletin of the World Health Organization. 2018 Aug 27;96(10):695.

[54] Douthit N, Kiv S, Dwolatzky T, Biswas S. Exposing some important barriers to health care access in the rural USA. Public health. 2015 Jun 1;129(6):611-20.

[55] World Health Organization. World health statistics 2020.

[56] Rani PK, Khanna RC, Ravindrane R, Yeleswarapu SC, Panaganti AK, Thakur VS, Sharadi V, Iype V, Rathi VM, Vaddavalli PK. Teleophthalmology at a primary and tertiary eye care network from India: environmental and economic impact. Eye. 2024 Aug;38(11):2203-8.

[57] Das AV, Rani PK, Ramachandran S, et al. COVID-19 and the rise of tele-ophthalmology in India. Indian J Ophthalmol. 2020;68(7):1319–1326.

[58] Silva PS, Cavallerano JD, Aiello LM, Aiello LP. Telemedicine and diabetic retinopathy: moving beyond retinal screening. Archives of ophthalmology. 2011 Feb 14;129(2):236-42.

[59] Holl F, Kircher J, Hertelendy AJ, Sukums F, Swoboda W. Tanzania's and Germany's digital health strategies and their consistency with the World Health Organization's global strategy on digital health 2020-2025: comparative policy analysis. Journal of Medical Internet Research. 2024 Mar 18;26:e52150.

[60] Das AV, Rani PK, Vaddavalli PK. (2020). Tele-consultations and electronic medical records-driven remote screening of ophthalmic disorders. Indian J Ophthalmol.

[61] Avidor D, Loewenstein A, Waisbourd M, Nutman A. Cost-effectiveness of diabetic retinopathy screening programs using telemedicine: a systematic review. Cost Effectiveness and Resource Allocation. 2020 Apr 6;18(1):16.

[62] Kruse CS, Krowski N, Rodriguez B, Tran L, Vela J, Brooks M. Telehealth and patient satisfaction: a systematic review and narrative analysis. BMJ open. 2017 Aug 1;7(8):e016242.

[63] Ramachandran R, Elkin Z, Brodie SE, Kim E, Belinsky I, Lazzaro D, Panarelli JF, Haberman I, Sperber L, Al-Aswad LA. Evaluation of Teleophthalmology During The COVID-19 Pandemic At A Single Outpatient Clinical Practice. Investigative Ophthalmology & Visual Science. 2021 Jun 21;62(8):1737-.

[64] Al-Khaled T, Acaba-Berrocal L, Cole E, Ting DS, Chiang MF, Chan RP. Digital education in ophthalmology. The Asia-Pacific Journal of Ophthalmology. 2022 May 1;11(3):267-72.

[65] Fontanarosa PB, Bauchner H. COVID-19—looking beyond tomorrow for health care and society. Jama. 2020 May 19;323(19):1907-8.

[66] Pang Y, Li Y, Wang X, Qi C, Yang Y, Ren TL. A contact lens promising for non-invasive continuous intraocular pressure monitoring. RSC advances. 2019;9(9):5076-82.

[67] Bittner AK, Yoshinaga PD, Rittiphairoj T, Li T. Telerehabilitation for people with low vision. Cochrane Database of Systematic Reviews. 2023(1)...