Portable hardware & software technologies for addressing ophthalmic health disparities:
A systematic review

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Abstract
Vision impairment continues to be a major global problem, as the WHO estimates 2.2 billion people struggling with vision loss or blindness. One billion of these cases, however, can be prevented by expanding diagnostic capabilities. Direct global healthcare costs associated with these conditions totaled $255 billion in 2010, with a rapid upward projection to $294 billion in 2020. Accordingly, WHO proposed 2030 targets to enhance integration and patient-centered vision care by expanding refractive error and cataract worldwide coverage. Due to the limitations in cost and portability of adapted vision screening models, there is a clear need for new, more accessible vision testing tools in vision care. This comparative, systematic review highlights the need for new ophthalmic equipment and approaches while looking at existing and emerging technologies that could expand the capacity for disease identification and access to diagnostic tools. Specifically, the review focuses on portable hardware- and software-centered strategies that can be deployed in remote locations for detection of ophthalmic conditions and refractive error. Advancements in portable hardware, automated software screening tools, and big data-centric analytics, including machine learning, may provide an avenue for improving ophthalmic healthcare.

Keywords
Portable, vision, machine learning, blindness, digital health, prevention, chronic disease, vision screening, eye exams, global health, eyecare access

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Introduction
Three key factors contributing to global disparities in access to vision care are per capita income, healthcare coverage, and geographic location.¹ Current estimates suggest that 89% of those currently affected by visual impairment live in low- and middle-income countries, making affordable care a widespread global health issue.² In West Africa, a study of uveitis cases linked to the Ebola outbreak showed that, due to inadequate access to comprehensive care and timely treatment, 40% of affected individuals developed severe complications of this treatable eye condition resulting in blindness.³,⁴ The outcomes were attributed to the inability to access vision screening in time.

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Vision care disparities related to lower screening rates within the United States have led to Hispanic women receiving disproportionately lower cataract care than their white counterparts. Furthermore, African American individuals have a lower rate of dilated fundus examinations despite a higher risk for diabetic retinopathy. They are twice as likely to develop preventable blindness from diabetic retinopathy than their white counterparts, with the gap increasing.

Another important aspect of vision care is continuous monitoring of progressive ophthalmic conditions, such as glaucoma and macular degeneration, to identify gradual changes and hasten interventions. The overall capital cost to battle the need for more new interventions and provide relief to areas with the most need. The overall capital cost to battle the need for more refractive error centers, including education and training, in the region of Americas is approximately $4.1 million, where $374,595 is a one-time cost of establishing and equipping new facilities with bulk-purchasing of refractive, ocular health screening, ocular dispensing, and business tools.

Many endeavors have been made to achieve universal eye care by expanding equipped vision facilities, hiring more trained personnel, and purchasing more vision screening tools to increase patient throughput. Chou et al. argue that system-wide differences and disparate coverage across states should force policymakers and physicians to look for new interventions and provide relief to areas with the most need. The overall capital cost to battle the need for more refractive error centers, including education and training, in the region of Americas is approximately $4.1 million, where $374,595 is a one-time cost of establishing and equipping new facilities with bulk-purchasing of refractive, ocular health screening, ocular dispensing, and business tools.

Integrating portable, low-profile technologies, such as those depicted in Figure 1, presents a promising solution for overcoming vision inequities, thereby improving vision care in marginalized communities. Several healthcare facilities, including generalist locations, have initiated the adoption of these technologies with early success in the identification and treatment of diabetic retinopathy and pediatric vision deficits.

In this review, “portable” refers to technologies that are entirely handheld, whereas “semi-portable” refers to technologies that are partially handheld and tethered to mobile components such as a wheeled stand or table.

**Portable hardware ophthalmic solutions**

**Aberrometers**

The demand for portable and quantitative refractive error measurement in mobile healthcare settings has propelled the field towards smaller and more automated devices.

Netra (EyeNetra Inc., Cambridge, MA) is a smartphone-based subjective refraction system with variable lenses and a binocular-style headset. The refractometer relies upon Scheiner principles, which is the concept that refractive error can be determined using double pinhole apertures with a Shack-Hartmann wavefront sensor. Through its binocular fixation system, Netra measures both eyes simultaneously and can calculate interpupillary distance. With the help of verbal instructions from the device, the patient is tasked with aligning red and green lines oriented at different angles, eliminating the need for literacy. Netra measures sphere from −12 to +5.5 diopters in 0.25 diopter increments, cylinder from −7 to 0 diopters in 0.25 diopter increments, and axis to 1°. In a cross-sectional study of 87 subjects (152 eyes) that compares Netra with subjective refraction, Jeganathan et al. found a mean relative difference in spherical equivalent of −0.27 diopters.

The SVOne (Smart Vision Labs, New York, NY) is a portable Shack-Hartmann wavefront aberrometer that attaches to a smart phone to measure ocular aberrations and refractive error of each eye independently. By taking the required images and averaging five measurement readings over a five-second period, the device uses Zernike decomposition to convert the wave aberration data into conventional sphere, cylinder, and axis measurements, measuring refractive errors within a range of ±10 diopters and ±5 diopters of sphere and cylinder, respectively.

In a prospective study on 50 subjects, Ciuffreda et al. investigated the SVOne’s use as an objective autorefractor in a comparison with retinoscopy, subjective refraction, and two commercially available autorefractors, Topcon KR-1W wavefront analyzer (Topcon Corp, Tokyo, Japan) and Righton Retinomax-3 handheld autorefractor (Righton Ophthalmic Instruments, Tokyo, Japan). The SVOne measurements were not significantly different across all instruments. In a pediatric analysis of 40 subjects between 5 and 17 years old, Rosenfield et al. showed no significant difference between the spherical equivalent refractive error measured by the SVOne and subjective techniques.

In an analysis of astronauts comparing Netra and SVOne, Masterova et al. found that SVOne had a tendency toward better intrasession repeatability, likely because the SVOne device has no subjective aspect of measurement. Furthermore, SVOne captured measurements significantly faster than Netra, completing autorefraction in approximately 6 min compared to 12 min for Netra. One drawback for the SVOne was that it consistently provided more negative refractive errors compared to the clinical autorefractor, while the Netra produced measurements better aligned with the clinical autorefractor. SVOne was also compared to Retinomax-3, WAM-5500 (Grand Seiko Co. Ltd, Hiroshima, Japan) and Topcon KR-1W autorefractors in pediatric and adult populations, with one cycloplegic subgroup, alongside subjective refraction, showing no difference in refractive assessment. Overall, subjects reported that the SVOne was preferred to Netra because of its easy-handling, audio feedback, and user confidence in their ability to make correct measurements.
The QuickSee/e-see or QuickSee (PlenOptika, Cambridge, MA) is a novel handheld wavefront autorefractor that is independent of a laptop or smart device, implementing an open-view wavefront aberrometer that eliminates the use of relay lenses. With a larger measurement range, the device uses optimized image processing to produce real-time refractive error measurements and includes a pupillary distance adjustment mechanism, controlled with a thumb wheel on the side of the device. The current model uses a 785 nm laser that delivers less than 40 μW of power to the eye, allowing for measurement of spherical and cylindrical refraction error of ±10 diopters and ±6 diopters, respectively. Wavefront images are processed at eight frames per second using a customized algorithm that tracks patient-device alignment and accommodation. The device then synthesizes these dynamic measurements through a proprietary statistical algorithm and presents the final refractive measurement to the user. Though the device has a binocular design, it records monocular measurements. Measurement in the opposite eye requires the device to be inverted. The device has been recently released in India and surrounding countries at one-third of the cost of commercial desktop autorefractors. The console’s compact design and portability make it an enticing tool for clinicians in need of a mobile, easy-to-use diagnostic tool for refractive error.

In a comparison of the QuickSee and desktop autorefraxion followed by subjective refraction, the spherical equivalent and the cylindrical components of the power vectors measured with the QuickSee agreed within 0.25 diopters of the subjective refraction. Visual acuity achieved by QuickSee was not significantly different; compared to Netra and SVOne, the QuickSee produced significantly smaller deviations from subjective refraction, undercorrecting by 0.09 diopters.

**Fundoscopic imaging**

Damage to the retina and optic nerve is the basis of many leading causes of vision loss, including diabetic retinopathy, macular degeneration, and glaucoma. This section focuses on portable fundoscopy cameras that are stand-alone and adaptable to smartphones (Table 1).
The SmartScope (OptoMed, City, Finland) is a handheld digital fundoscope with a non-mydriatic camera. Mydriatic and non-mydriatic versions of this technology demonstrated non-inferiority when compared against a mydriatic TRC-50DX (Topcon, Tokyo, Japan) table-top.21 Smartscope is overall highly gradable; however, the presence of vitreous hemorrhages or advanced cataracts significantly decreases gradability, necessitating ophthalmic experience to determine the quality of images.22

The 3nethra neo (Forus Health, Bengaluru, India) is a mydriatic, wide-field digital fundoscope that is semi-portable by being tethered to a central module connected to a laptop. The study showed that 3nethra neo was well tolerated for ROP screening, with comparable view to the RetCam3 tabletop on initial cases (Natus Medical, Pleasanton, CA).23

Pictor (Volk Optical Inc., Mentor, OH) is an FDA-approved portable, non-mydriatic camera that permits posterior pole imaging with a 40° field view as well as non-contant anterior segment imaging using a cobalt blue LED to detect dry eye syndrome and corneal trauma. A prospective study in which non-ophthalmologists used this technology to screen infants resulted in successful identification of type 1 ROP.24

The NM-200D (Nidek, Hiroishi, Japan) is another example of a semi-portable handheld, non-mydriatic fundus camera. This device successfully generated normative data for cup-to-disc, a common metric for detection and monitoring of glaucoma, and arteriole-to-venule ratios in a pediatric population used in monitoring microvascular disease.25

The Retinal Plenoptoscope (Queensland UoT, Queensland, AU) is a non-mydriatic fundus camera that utilizes novel image rendering against corneal backscatter to achieve high-depth resolution. This strategy allowed for a higher degree of stereopsis (3D retinal renderings by imaging via two slightly modified pupilar light paths) and improved, glare-free image quality that has been a challenge with other portable fundoscopic devices.26

Stereopsis is regarded as an advantage of slit lamp fundoscopy and is relied on for assessment in glaucoma and macular edema as a gold standard.

Several successful models of smartphone add-ons have recently been introduced to digital fundoscopy. Russo et al. demonstrated that non-mydriatic smartphone fundoscopy using the D-Eye add-on (D-EYE S.r.l., Padova, Italy) was not significantly different from dilated slit-lamp fundoscopy in detecting macular edema, although limitations with smartphone imaging emerge in patients with small pupil size and cataracts.27

According to Ryan et al., pairing smartphone with a diopter condensing lens without additional hardware has low sensitivity in detecting diabetic retinopathy in mydriatic eyes when compared to the FF450 Plus (Carl Zeiss Meditec, Dublin, CA).28 However, comparing mydriatic slit-lamp microscopy to mydriatic smartphone imaging with a D-Eye add-on produced 85% accuracy.27 D-Eye is able to intentionally reduce the magnitude of reflection from retinal structures that occurs during image acquisition, enabling improved non-mydriatic imaging. Some of its shortcomings include a single-image retinal view of 20°, requiring iterative imaging to achieve 90°.29

RetinaScope (University of Michigan, MI) adapted a handheld ophthalmoscope apparatus to a smartphone, capturing 50° of retina within a single image. Individual images are automatically stitched on the smartphone to generate a 100° field of view. Patel et al. recently demonstrated a 96% agreement rate in the identification of pediatric retinal disorders such as retinoblastoma and optic nerve hypoplasia when interpreting images captured with the RetinaScope versus the RetCam3 (Clarity Medical Systems, Pleasanton, CA) and the Optos 200Tx (Optos, Marlborough, MA).30 31

Finally, RETeval (LKC Technologies, Gaithersburg, MD) is a portable, non-mydriatic version of an electroretinography (ERG) that allows for evaluation of achromatopsia, cone receptor dysfunctions, retinitis pigmentosa, choroidal dystrophy, autoimmune retinopathy, and juvenile macular degeneration.32 33 The device also showed promising results in detecting vision-threatening diabetic retinopathy.34 While earlier generation ERG devices were semi-invasive and required the use of special contact electrodes on the surface of the eye, RETeval uses skin-contact electrodes placed on the lower orbit.

**Perimetry**

In examining visual function, the most common method of quantitative, functional assessment are visual fields (VFs), which allow for static and dynamic targets to determine pattern and degree of vision loss. The current in-office gold standard is the Humphrey Visual Field Analyzer (HVFA) (Carl Zeiss Meditec, Dublin, CA), a table-mounted technology that uses proprietary algorithms to provide a detailed map of VF perimetry, as well as reliability metrics such as fixation deviation. HVFA is entirely reliant on a technician to run the test, making it susceptible to subjective technician bias and patients may find the machine overall uncomfortable.35 Recently, several tablet- and virtual reality (VR)-based adaptations of perimetry examinations have emerged, introducing the possibility of vision screening in non-vision specialist locations including rural clinics or the home. These technologies are essential for longitudinal monitoring of diseases like diabetic retinopathy, glaucoma, and macular degeneration, particularly in regions where vision care is limited.

Several studies have demonstrated a high degree of comparability between tablet-based perimetry (TBP) and the HVFA. Prea et al. and Kong et al. found that the Melbourne Rapid Fields (MRF) (M&S Technologies, New York, NJ) was not significantly different from HVFA.36 37
| Name of device | Field of view | Non-mydriatic Smartphone attachment | Glare reduction | Condition tested | Clinical use paper without comparison to gold standard | Comparison to tabletop fundus photography | Comparison to slit lamp or indirect ophthalmoscopy | Clinical outcome for comparison to gold standard |
|----------------|--------------|-----------------------------------|----------------|-----------------|---------------------------------------------------|----------------------------------------|------------------------------------------|--------------------------------------------------|
| Retinal Plenoptoscope (Queensland UoT, Queensland, AU) | 32° | | | Healthy controls | × | × | × | |
| SmartScope (OptoMed, Oulu, Finland) | 45° | | | Diabetic retinopathy | × | | | Vision threatening diabetic retinopathy (VTDR) |
| 3nethra Neo (Forus Health, Bengaluru, India) | 120° | | | Retinopathy of prematurity | × | | | Safety for infant |
| Pictor™ (Volk Optical Inc., Mentor, OH) | 45° | | | Retinopathy of prematurity | × | | | |
| NM-200D (Nidek, Hiroishi, Japan) | 30° | | | Glaucoma, diabetic retinopathy | × | | | |
| RetinaVue 100 (Welch Allyn, Skaneateles Falls, New York) | 45° | | | | | | | |
| D-Eye Smartphone Attachment (D-Eye) | 20° | | | Cup-to-disk ratio, diabetic retinopathy | × | | | Vertical cup-to-disk ratio, diabetic retinopathy clinical diagnosis, VTDR |
| RetinaScope (CellScope, Berkely, CA) | 50° | | | Pediatric ophthalmological conditions, diabetic retinopathy staging | | | | Diabetic retinopathy staging, referral-warranted diabetic retinopathy |

**RWDR = moderate NPDR or greater severity OR presence of macular edema.**
Niles, IL) app on an iPad (Apple, Cupertino, CA) was equal in speed to the HVFA 24-2 SITA-fast algorithm and significantly faster than the 24-2 SITA-standard algorithm without sacrificing accuracy or longitudinal repeatability in a glaucomatous patient population. 36, 37 MRF showed higher fixation loss compared to the HVFA 24-2 SITA-standard. 38

Similarly, Jones et al. demonstrated that Eyecatcher (UCL Institute of Ophthalmology, London, England), another TBP, was reliable in terms of mean deviation scores and concordance between identified locations of VF loss when compared to the HVFA 24-2 SITA-standard. 39 Anderson et al. discovered that home glaucoma monitoring with MRF TBP can allow for the identification of rapid field loss with an 80% sensitivity, 18 months faster on average than 6-month clinic testing, even when accounting for moderate at-home compliance. 40

In a study of the Visual Fields Easy (George Kong SOFTWARE, Melbourne, Australia) iPad app in rural Nepal, early VF loss was not consistently detected due to a high false positive rate, although most cases of moderate and advanced VF deficits were concordant with 24-2 SITA standard HVFA findings. 41

TBP continues to evolve in speed, accuracy, and interactivity. The PERformance Centered Portable Test (PERCEPT) (University of California, San Diego, CA) is an interactive TBP that dynamically increases visual task difficulties in order to identify central and peripheral VF losses. Rosen et al. demonstrated that this app was able to detect glaucoma and accurately predict one’s previous history of motor vehicle crashes or falls based on traumatic impact that resulted in characteristic visual deficits. 42

Recently emerging VR advancements allow for unique vision screening opportunities. VR offers eye-tracking, allowing to measure degrees from fixation due to the potential for insertion of convex lenses or the manipulation of test software to create “virtual spheres.” Erichev et al. used the latter approach for the P-VRD (Total Vision, Russia), allowing for a screening range of 30° from fixation, with similar outputs to that of a HVFA 30-2. 43 VR perimetry also allows for unique methods of unbiased examinations, such as a randomized presentation of stimuli to either eye without occlusion and thus inability of the patient to know which eye is being tested. Matsumoto et al. found high comparability between the iVue+ iStand (Optovue, Fremont, CA), a semi-portable spectral-domain OCT (SD-OCT) was able to identify fine retinal signatures, such as foveal contour, that are predictive of successful ROP management with bevacizumab (an anti-VEGF therapy). Interestingly, Rothman et al. used the Envisu semi-portable SD-OCT system (Biotigten, Research Triangle Park, NC) to successfully identify macular edema within infant eyes as a predictive measure for future visual or central nervous system deficits. 51

Another study in ROP patients showed that handheld OCTA can capture retinal structures that can screen for disease severity. This included peripapillary and foveal microvasculature, epiretinal membrane (ERM), hyperreflective punctate vitreous opacities, and tractional vitreous bands. 52

Maloca et al. demonstrated an intersection between sparse OCT and telemedicine with the MIMO_02 prototype (MIMO AG, Bern, Switzerland). 53 In this study, the authors demonstrated a potential for increased test speed and portability if one sacrificed high resolution. Despite this loss in functionality, MIMO_02 had central retinal thickness measurements comparable to the Spectralis OCT, a key parameter for monitoring AMD progression. The device may therefore allow for at-home monitoring of retinal disorders.

Optical coherence tomography

Optical Coherence Tomography (OCT) uses low-coherence near-infrared light scatter to visualize a cross-section of the retina, allowing for analysis of the retina’s thickness and fine anatomical structures. The technology has, until recently, been limited to expensive tabletop devices with costs of up to $150,000. 49 However, the important role of OCT in making definitive diagnoses has driven adaptation toward more portable and cost-effective devices that cost as low as $7200. 49

Song et al. published a study utilizing an early iteration of the semi-portable QQ Labscope (Lumedica, Durham, NC) OCT that demonstrated a contrast-to-noise ratio comparable to the tabletop Spectralis OCT (Heidelberg Engineering, Heidelberg, Germany). 48, 50

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Recently, a standard SD-OCT device has improved in portability and accommodation of different examination positions with the introduction of the Spectralis Flex (Heidelberg Engineering, Heidelberg, Germany), although the device is still likely limited to in-office use due to its integration with a wheel-based stand. However, even with these adjustments, the Spectralis Flex was able to detect retinoblastoma through identification of hyperreflective vitreous opacities in a recent case study.54

**Tonometry**

Tonometry involves either physical or non-contact perturbation of the eye in order to measure IOP and is critical for evaluating patients at risk of glaucoma.55 Goldmann applanation tonometry (GAT) is considered the gold standard for IOP measurements,55, 56 although it has several limitations that include requiring the use of fluorescein dye, topical anesthetics, and a slit-lamp arrangement, thus requiring a trained provider to operate it and to calibrate monthly.57 However, there are numerous commercially available portable tonometers. These products range from contact devices, requiring topical anesthetics for direct corneal contact, as well as non-contact tonometers (NCTs) that measure IOP over the eyelid, with air puffs or other methods.58 It is important to note that portable tonometers uniformly overestimate IOP measurements compared to GAT.

The Schiotz tonometer (Medical Technologies, New Dehi, India) was the most widely used portable tonometer due to its lower cost and not requiring batteries, until GAT took over in the last quarter of the 20th century.59, 60

The iCare contact tonometer (Tiolat Oy, Helsinki, Finland) is a portable rebound device that correlates metallic probe deceleration against the eye with IOP.56, 61 Conversely, the Pulsair (Keeler, Malvern, PA) is a semi-portable NCT that determines IOP based on air application of the cornea, which may be more ideal for use with non-vision specialist locations and does not rely on topical anesthetics.56 Prabhakar et al. demonstrated that the Pulsair showed better agreement with the Perkins Applanation Tonometer (PAT) and excellent comparability with GAT.56, 62

Accordingly, the PT100 and Tono-Pen AVIA (Reichert, Depew, NY) are fully portable tonometers with a reported high ease of handling that is particularly suitable for facilities that lack trained individuals.57, 62, 63 Hubanova et al. demonstrated a weaker agreement of PT100 with GAT readings in hypertensive patients compared to the Pulsair Intellipuff.62

**Software-based technologies**

As portable ophthalmic technologies become more widely utilized, particularly in settings without specialists who can interpret test results, and as the adoption of teleophthalmology practices has been slow to gain momentum, machine learning (ML) shows promising potential to provide fast and reliable clinical information in the near future (Figure 2).

Deep learning (DL) models, a subset of ML involving the computation of multi-layer neural networks, use OCT data for algorithm training in the detection of glaucoma and/or prediction of its progression. The high accuracy of DL approaches in predicting glaucomatous eyes makes it a promising avenue for robust, scalable, and cost-saving diagnosis of glaucoma and other ocular abnormalities.

**OCT- & Fundus image-dependent machine learning applications for unstructured data**

Most ML applications in ophthalmology use high-dimensional data, such as imaging, to predict ocular health and function. In particular, DL methods applied to data from OCT and fundus imaging have been shown to be high performing.

Thompson et al. employed an algorithm that leveraged SD-OCT data to predict glaucomatous neuroretinal damage through the measurement of the minimum rim width relative to Bruch’s membrane opening (BMO-MRW) on fundus images. This parameter has been shown to correlate well with glaucomatous VF loss.64 The BMO-MRW model predictions from all optic disc photographs in their test set were highly correlated with the observed values from SD-OCT (Pearson’s r = 0.88; R^2 = 77%).64

Alternatively, studies quantified glaucomatous structural damage on optic disc photographs using RNFL thickness by initially training with SD-OCT data.65, 66 Ultimately, the RNFL model was able to infer RNFL values from optic disc images that correlated strongly with SD-OCT-retrieved RNFL values (Pearson r = 0.832; R^2 = 69.3%).65 Similarly, Asaoka et al. strongly correlated RNFL and ganglion cell complex layer thickness with early-stage glaucoma, showing sensitivity and specificity of 82.5% and 93.9%, respectively.67

In comparing various ML classifiers and algorithm types, Silva et al. found that a random forest model produced the most accurate prediction of glaucomatous eyes based on SD-OCT and standard automated perimetry data.68

Furthermore, the area under the receiver operating curve (aROC) curve, an indication how accurate a model’s classification is, for differentiating glaucomatous eyes from healthy ones was greater than or equal to 0.94 in all models previously described.64–68

Some examples of successful DL models include the detection of ERM, detection of pathologic lesions including intraretinal fluid, subretinal fluid, pigment epithelial detachment, and subretinal hyperreflective material, estimation of
refractive error, estimation of visual acuity, and drusen quantification from OCT imaging. Additionally, DL had enabled the extraction of accurate estimations of refractive error and visual acuity.

A DL algorithm trained on fundus photographs in a retrospective cohort of ROP patients demonstrated variability between and within clinician grading in assigning ROP severity scores. This points toward the need of looking at other objective clinical features for identifying plus disease that could play a role in influencing treatment decisions.

ML has also been used to accurately differentiate between optic neuropathies and pseudopapiledema by using fundus photography.

Deep learning-based techniques using structured data: EHR, visual field, and other sources

In addition to imaging, a number of ML applications in ophthalmology also leverage the growing amount of structured data from electronic health records (EHR) and VFs. In these applications, ML models use structured data to predict progression of disease and to classify diagnoses. For example, Wen et al. used unfiltered real-world data sets to develop a DL model that generated predictions for future Humphrey VFs by up to 5.5 years. Some examples of successful models include neural networks that differentiate between glaucomatous from non-glaucomatous VFs, unsupervised ML detection of VF deterioration in glaucoma, and a random forest ML model of glaucoma diagnosis using RNFL and VF.

DL models that do not use VF in differentiating glaucoma status have also been explored. Oh et al. designed an artificial neural network with nine non-categorized factors including IOP, vertical cup-to-disk ratio, sex, and age, that was able to predict open angle glaucoma with relatively high accuracy (84%), sensitivity (78.3%), and specificity (85.9%). Scanning laser polarimetry-variable cornea compensation measurements have also been used to improve the differentiation between glaucomatous and normal eyes using an artificial neural network with high accuracy (aROC = 0.95). Kalman filtering, a type of ML technique, forecasted accurate mean deviation values of IOP for patients with normal tension glaucoma.

Bach et al. used an ML approach to achieve comparable or better accuracy for visual acuity. In another study, Rohm et al. implemented ML algorithms to successfully predict visual acuity at 3 and 12 months in patients treated for neovascular age-related macular degeneration. Finally, Gramatikov et al. created an artificial neural network to classify retinal birefringence scanning data in the pediatric diagnosis of amblyopia with comparable results to classical statistical methods.
Non-machine learning-based computational techniques: statistical models, glaucoma progression analysis

Using a variety of statistical analyses, combined VF and OCT methods were found to have a more accurate and faster identification glaucoma progression than VF-only ones.\textsuperscript{90} Serial analysis of combined wide-field OCT maps for detection of structural progression in early glaucoma showed strong agreement between glaucoma specialists (wide-field OCT thickness map: $\kappa = 0.649$; wide-field OCT deviation map: $\kappa = 0.833$).\textsuperscript{91} However, a comparison of Glaucoma Progression Analysis (GPA, Carl Zeiss Meditec, Dublin, CA), a proprietary software analysis tool, showed only a fair level of agreement upon initial review ($\kappa = 0.52$) and re-evaluation ($\kappa = 0.62$).\textsuperscript{92}

In order to address the subjectivity of characterizing ocular pathology, Castro \textit{et al.} developed a freeware program, Halo v1.0 software that measures and calculates a visual-disturbance index, a parameter used to quantify the discrimination capacity of peripheral stimuli in the presence of visual disturbances like age-related macular degeneration or keratitis.\textsuperscript{93} The Halo v1.0 software used the Strehl ratio, a measure of overall optical quality, to show that the pathologies previously mentioned had greater ocular scattering compared to healthy eyes.\textsuperscript{93}

Discussion

As the global demand for ophthalmic care continues to grow, with current estimates suggesting 5\% compound annual growth rate over the next 5 years, portable technologies have become increasingly important in addressing the needs of patients in resource-limited and resource-rich communities.\textsuperscript{101} The increased demand for early detection and treatment is one of the key drivers of the market, indicating a clear need for more equitable, accessible, sustainable, comprehensive, and portable vision screening.\textsuperscript{1} Early detection can be longitudinally more cost-effective according to a study that used a Markov simulation model on 1000 patients who received tonometry screening irrespective of glaucoma risk factors.\textsuperscript{102}

Portable solutions can allow for increased sustainability and scale of impact given lower capital investment and feasibility of adaptation. One example of large-scale implementation is GoCheckKids (GoCheck, USA), which is a smartphone photo screening platform for amblyopia detection that has been adopted by 6500 pediatricians as of May 2020.\textsuperscript{102} Such tools allow for increased triage at the level of primary care and early referral identification. Furthermore, the adoption of the SPOT Vision Screener (Welch Allyn, USA) in 19 pediatric facilities resulted in increased screening implementation, from 65.3\% to 86.5\% of patients just 12 weeks after implementation.\textsuperscript{13}

In addition to improving overall screening, these technologies have potential benefits for school vision screenings, nursing homes, and homeless shelters, where convenience and user-friendliness are highly important. Changes in healthcare policy and insurance models that are increasingly recognizing telehealth and mobile medicine models will certainly prompt further development of these technologies. These models are particularly important in the times of a COVID-19 pandemic with increased efforts for remote access and telemedicine for long-range delivery of medical care.

Some barriers to the adoption of portable technology are low levels of eye disease awareness in patients since early, disease-related changes are functionally subtle in most cases. Further barriers to the adoption of novel technologies into existing workflows include deeply ingrained technician or physician habits and strict billing systems. This is especially relevant for vision specialist offices, where a lot of expensive machinery has already been purchased and engrained into clinical practice.

This review has examined the literature that evaluates portable aberrometers, fundoscopy, and OCT and discussed the principles behind their design as well as clinical

Non-machine learning, non-computational based techniques: smartphone applications, mobile games, computer programs, web applications

The visual nature of many ophthalmic exams makes them optimal for the use of smartphones, computer tablets, and web applications.

The \textit{Nintendo 3DS PDI Check} (Nintendo, Kyoto, Japan) is a novel near vision screening game capable of assessing visual acuity, color vision, and stereopsis. Though studies were limited by their sample size, the \textit{PDI Check} was associated with faster testing times compared to conventional testing and had a high specificity.\textsuperscript{94, 95}

A visual acuity Snellen chart (gold standard) and Arabic figures that were administered on an \textit{iPad} (Apple, Cupertino, CA) showed no significant difference from the logMAR visual acuity.\textsuperscript{96} Additionally, the \textit{Mobile Assessment of Vision by intEractive Computer} (MAVERIC) system, which uses a computer tablet and software that collects touch responses from patients to measure low or high contrast visual acuity, exhibited similar high reliability and agreement.\textsuperscript{97} However, mobile applications like \textit{SightBook} produced discrepant visual acuities compared to clinic chart acuities.\textsuperscript{98}

Mobile applications for vision screening have also incorporated an assessment of color vision. Portable games with chromatic contrast sensitivity, tablet versions of Ishihara plates for dyschromatopsia screening, and a web-based color vision test for color vision defects in optic neuritis have all demonstrated high levels of repeatability and comparability with established tests.\textsuperscript{99, 100}
validation, highlighting specific benefits and drawbacks that were identified.

In addition to technologies that are used for structural assessment of the eye, VFs are heavily relied upon for a functional component of the exam. This included adaptations of TBP and VR, both of which show promising results with a difference in fixation-measurements due to VR’s biconcave structural advantage. Additionally, FDT has been considered as a promising tool for testing vision perimetry on a VR platform.

In light of the available portable hardware and software solutions, ML has been considered as the next step in unifying delivery of remote and more frequent eye care. Through the use of both structured and unstructured data that can be collected with portable advancements, the algorithm models can provide disease state predictions and propose recommendations that are non-inferior to those of trained specialists.

Although recent developments are making it possible to monitor vision remotely, there is a need for more cost-benefit analyses to show how access to portable technologies improves outcomes. Recent studies demonstrate that automatic retinal image analysis is a cost-effective solution in primary care settings given a 23.3% reduction in costs after 5 years. One study in South Africa calculated a cost-saving effect of $1206 per blindness case averted due to primary care integration of mobile fundus cameras. In finding ways to implement portable screening tools, it is also essential to identify a platform that can unify the structural screening aspects such as fundoscopy, tonometry, and OCT with functional components of a comprehensive exam like VFs, contrast sensitivity, and visual acuity. This platform can be used to store and collect data to then actively build predictive models by using the established potential of ML, resulting in refer, non-refer recommendations, and ensuring longitudinal patient care. Such improvement in patient outcomes combined with the reductions in cost further encourage efforts toward a value-based and quality-driven eyecare system.

Conclusion

This systematic review analyzed the portable technologies landscape for oculus vision screening that compares most recently clinically tested software, hardware, and machine/deep learning. Given the medical field’s fragmented status and steps towards coupling with tele-health and tele-ophthalmology, portable and remote ophthalmic testing is paramount to the continuity of quality care within our communities. This paper highlighted the most recent advancements and achievements in the last 10 years in the aforementioned topics for a comprehensive review. Professionals should continue monitoring and staying engaged with technologies penetrating the

healthcare market while staying informed regarding clinical validity and adaptation of these products.

Literature search

Review articles retrieved in the systematic search are referenced along with any relevant primary literature. Filtering assumptions limited literature searches from the last 10 years, with the search entered on 21 January 2020. From this search, 1166 total articles were screened from PubMed.gov, and 90 were manually selected based on the inclusion criteria of English language, relevance to global vision frameworks and our criteria for portable and semi-portable devices. Since then, we incorporated additional articles to cover the breadth of newly emerging evidence until the beginning of 2021. The introduction section was not restricted to the systematic analysis approach as it describes a broader framework, making a total of 108 publications on portable technology that emerged within the past 10 years.

For the Introduction section, the search terms ("Vision Tests"[Mesh] OR (Vision AND ("screening" OR test OR "care"))) AND ("Health Status Disparities"[Mesh] OR "Healthcare Disparities"[Mesh] OR ((health* OR economic OR sex OR ethnic OR gender OR racial) AND (disparity OR inequal*))) OR at-risk OR underserved)) were applied. Supplemental searches were added to include quantitative measures of global vision impairment (e.g. economic burden of treatment) as well as information about teleophthalmology.

The Tonometry section included search terms 
(((portable AND ("Vision Tests"[Mesh] OR vision)) AND (hardware OR tonometry OR pressure)) AND (ocular hypertension OR optic disc OR retina OR Cataracts OR Macular degeneration OR Retinopathy OR Retinitis OR Glaucoma OR Strabismus OR Color blindness OR Macular edema OR keratoconus OR Retinal detachment OR Uveitis OR Low vision OR Blindness)). Supplemental studies related to pricing of each device as well as gold standard technologies were added. Finally, information about portable tonometry devices was acquired from Google Patents to determine the landscape of available patents worldwide.

In the Hardware section, we searched (portable AND ("Vision Tests"[Mesh] OR vision)) AND (hardware OR OCT OR optical coherence tomography OR fundoscopy OR infrared) AND (optic disc OR retina OR Cataracts OR Macular degeneration OR Retinopathy OR Retinitis OR Glaucoma OR Strabismus OR Color blindness OR Macular edema OR keratoconus OR Retinal detachment OR Uveitis OR Low vision OR Blindness). For the Software section, the following search terms were used: (((("Vision Tests"[Mesh])) AND (software
OR machine learning OR artificial intelligence OR deep learning OR neural networks) AND (ocular hypertension OR optic disc OR retina OR Cataracts OR Macular degeneration OR Retinopathy OR Retinitis OR Glaucoma OR Strabismus OR Color blindness OR Macular edema OR keratococcus OR Retinal detachment OR Uveitis OR Low vision OR Blindness)). Publications not retrieved from the systematic approach were used for the purposes of providing technological background in each section.

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**Contributorship:** Margarita Labkovich outlined the study, helped with organizing literature review research, worked extensively on introduction and portable hardware solutions sections, and brought the rest of the sections together, including discussion and conclusion. Megan Paul was responsible for sorting through the systematic approach were used for the purposes of providing technological background in each section. Dr. Zhou and Aashay Patel researched literature for the fundoscopy and perimetry sections. Andrew Warburton contributed by organizing citations, editing the aberrometry section, and providing suggestions for the entire manuscript. Randal A. Serafini assisted with organizing and editing the manuscript. Drs. Sklar, Chehins, and Elahi reviewed the entire manuscript and provided their contributions and ophthalmologic expertise by citing additional technologies and bringing their physician perspectives.

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**References**

1. The Global Economic Cost of Visual Impairment: Summary Report. (2010). Retrieved from www.amdalliance.org

2. Ackland P, Resnikoff S and Bourne R. World blindness and visual impairment: despite many successes, the problem is growing. *Community Eye Health* 2017; 30: 71–73.

3. Shantha JG, Crozier I and Yeh S. An update on ocular complications of ebola virus disease. *Curr Opin Ophthalmol* 2017; 28: 600–606.

4. Yeh S, Shantha JG, Hayek B, et al. Clinical manifestations and pathogenesis of uveitis in Ebola virus disease survivors. *Ocul Immunol Inflamm* 2018; 26: 1128–1134.

5. Herren DJ and Kohanim S. Disparities in vision loss due to cataracts in Hispanic women in the United States. *Semin Ophthalmol* 2016; 31: 353–357.

6. Fathy C, Patel S, Sternberg Jr P, et al. Disparities in adherence to screening guidelines for diabetic retinopathy in the United States: a comprehensive review and guide for future directions. *Semin Ophthalmol* 2016; 31: 364–377.

7. Khawaja AP, Cooke Bailey JN, Wareham NJ, et al. Genome-wide analyses identify 68 new loci associated with intraocular pressure and improve risk prediction for primary open-angle glaucoma. *Nat Genet* 2018; 50: 778–782.

8. Hamzah J C, Daka Q and Azuara-Blanco A. Home monitoring for glaucoma. *Eye (London, England)* 2020; 34: 155–160.

9. Burton MJ, Faal HB, Ramke J, et al. Announcing the lancet global health commission on global eye health. *Lancet Global Health* 2019; 7: e1612–e1613.

10. Chou C-F, Barker LE, Crews JE, et al. Disparities in eye care utilization among the United States adults with visual impairment: findings from the behavioral risk factor surveillance system 2006-2009. *Am J Ophthalmol* 2012; 154: S45–S52.e1.

11. Fricke TR, Holden BA, Wilson DA, et al. Coût global de la vision et de la cataracte. *Bull W H O* 2012; 90: 728–738.

12. Tousignant B, Garceau M-C, Bouffard-Saint-Pierre N, et al. Comparing the Netra smartphone refractor to subjective refraction. *Clin Exp Optom.* Epub ahead of print November 2019;103(4): 501–506. doi:10.1111/cxo.13003

13. Vernacchio L, Trudell EK, Nigrosh J, et al. Primary care implementation of instrument-based vision screening for young children. *Clin Pediatr* 2018; 57: 1020–1026.

14. Jeganathan VSE, Valkidath N, Niziol LM, et al. Accuracy of a smartphone-based autorefractor compared with criterion-standard refraction. *Optom Vis Sci* 2018; 95: 1135–1141.

15. Paudel N, Adhikari S, Thakur A, et al. Clinical accuracy of the Nidek ARK-1 autorefractor. *Optom Vis Sci* 2019; 96: 407–413.

16. Ciufridda KJ and Rosenfield M. Evaluation of the SVOne: a handheld, smartphone-based autorefractor. *Optom Vis Sci* 2015; 92: 1133–1139.

17. Rubio M, Hernandez CS, Seco E, et al. Validation of an affordable handheld wavefront autorefractor. *Optometry Vision Sci: Off Publ Am Acad Optometry* 2019; 96: 726–732.

18. Rosenfield M and Ciufridda KJ. Evaluation of the SVOne handheld autorefractor in a pediatric population. *Optometry Vision Sci: Off Publ Am Acad Optometry* 2017; 94: 159–165.

19. Masterova KS, Anderson AP, Cowan DR, et al. Portable autorefractors for detecting axial length changes in space. *Aerosp Med Hum Perform* 2018; 89: 724–730.
20. Bourne RRA, Stevens GA, White RA, et al. Causes of vision loss worldwide, 1990-2010: a systematic analysis. Lancet Global Health 2013; 1: E339–E349. doi: 10.1016/S2214-109X(13)70113-X

21. Sengupta S, Sindal MD, Besiri CG, et al. Screening for vision-threatening diabetic retinopathy in South India: comparing portable non-mydriatic and standard fundus cameras and clinical exam. Eye (Basingstoke) 2018; 32: 375–383.

22. Davila JR, Sengupta SS, Nizioł LM, et al. Predictors of photographic quality with a handheld nonmydriatic fundus camera used for screening of vision-threatening diabetic retinopathy. Ophthalmologica J Int d’ophthalmologique Int J Ophthalmol Z Augenheilkunde 2017; 238: 89–99.

23. Vinekar A, Rao SV, Murthy S, et al. A novel, low-cost, wide-field, infant retinal camera, “Neo”: Technical and safety report for the use on premature infants. Transl Vision Sci Technol Epub ahead of print March 2019; 8(2). DOI: 10.1167/tvst8.2.2

24. Prakalapakorn SG, Freedman SF, Hutchinson AK, et al. Evaluating a portable, noncontact Fundus camera for retinopathy of prematurity screening by nonophthalmologist health care workers. Ophthalmol Retina 2018; 2: 864–871.

25. Mcclelland JF, O’Donohue L, McIntyre M, et al. Cup-to-disc and arteriole-to-venule ratios in children aged 6-7 and 12-13 years. Ophthalmic Physiol Optics 2012; 32: 31–38.

26. Palmer DW, Coppin T, Rana K, et al. Glare-free retinal imaging using a portable light field fundus camera. Biomed Opt Express 2018; 9: 3178.

27. Russo A, Morescalchi F, Costagliola C, et al. Comparison of smartphone ophthalmoscopy with slit-lamp biomicroscopy for grading diabetic retinopathy. Am J Ophthalmol 2015; 159: 360–364.e1.

28. Ryan ME, Rajalakshmi R, Prathiba V, et al. Comparison among methods of retinopathy assessment (CAMRA) study: smartphone, nonmydriatic, and mydriatic photography. Ophthalmol 2015; 122: 2038–2043.

29. Russo A, Morescalchi F, Costagliola C, et al. A novel device to exploit the smartphone camera for Fundus photography. J Ophthalmol 2015; 2015: 5. Article ID 823139. Epub ahead of print 2015. DOI: 10.1155/2015/823139.

30. Patel TP, Kim TN, Yu G, et al. Smartphone-based, rapid, wide-field fundus photography for diagnosis of pediatric retinal diseases. Trans Vision Sci Technol Epub ahead of print May 2019; 8(3): 29. DOI: 10.1167/tvst8.3.29

31. Kim TN, Myers F, Reber C, et al. A smartphone-based tool for rapid, portable, and automated wide-field retinal imaging. Trans Vis Sci Technol 2018; 7: 21.

32. Osigian CJ, Grace SF, Cavuoto KM, et al. Assessing nonseated handheld cone flicker electroretinogram as a screening test in pediatric patients: comparison to sedated conventional cone flicker electroretinogram. J AAPOS 2019; 23: 34.e1–34.e5.

33. Tang J, Hui F, Hadoux X, et al. A comparison of the RETeval sensor strip and DTL electrode for recording the photopic negative response. Trans Vision Sci Technol Epub ahead of print November 2018; 7(6): 27. DOI: 10.1167/tvst7.6.27

34. Al-Otaibi H, Al-Otaibi MD, Khandekar R, et al. Validity, usefulness and cost of RETeval system for diabetic retinopathy screening. Trans Vision Sci Technol Epub ahead of print May 2017; 6(3): 3. DOI: 10.1167/tvst6.3.3

35. Mottolino FG J, Wesselinck C, Gordijn M, et al. Factors that influence standard automated perimeter test results in glaucoma: test reliability, technician experience, time of day, and season. Invest Ophthalmol Visual Sci 2012; 53: 7010–7017.

36. Prea SM, Kong YXG, Mehta A, et al. Six-month longitudinal comparison of a portable tablet perimeter with the Humphrey field analyzer. Am J Ophthalmol 2018; 190: 9–16.

37. Kong YXG, He M, Crowston JG, et al. A comparison of perimetric results from a tablet perimeter and Humphrey field analyzer in glaucoma patients. Transl Vis Sci Technol 2016; 5: 2.

38. Schulz AM, Graham EC, You YY, et al. Performance of iPad-based threshold perimetry in glaucoma and controls. Clin Exp Ophthalmol 2018; 46: 346–355.

39. Jones PR, Smith ND, Bi W, et al. Portable perimetry using eye-tracking on a tablet computer—A feasibility assessment. Trans Vision Sci Technol 2019; 8: 17–17.

40. Anderson AJ, Bedgood PA, George Kong YX, et al. Can home monitoring allow earlier detection of rapid visual field progression in glaucoma? Ophthalmology 2017; 124: 1735–1742.

41. Johnson CA, Thapa S, George Kong YX, et al. Performance of an iPad application to detect moderate and advanced visual field loss in Nepal. Am J Ophthalmol 2017; 182: 147–154.

42. Rosen PN, Boer ER, Gracitelli CPB, et al. A portable platform for evaluation of visual performance in glaucoma patients. PLoS ONE 10(10): e0139426. Epub ahead of print October 2015; 10. DOI: 10.1371/journal.pone.0139426.

43. Erciev VP, Ermolaev AP, Antonov AA, et al. New visual field testing possibilities (a preliminary report). Vestn Oftalmol 2018; 134: 66–71.

44. Matsumoto C, Yamao S, Nomoto H, et al. Visual field testing with head-mounted perimeter ‘imo’. PLoS ONE 11(8): e0161974. Epub ahead of print August 2016; 11. DOI: 10.1371/journal.pone.0161974.

45. Morejon A, Mayo-Iscar A, Martin R, et al. Development of a new algorithm based on FDT matrix perimetry and SD-OCT to improve early glaucoma detection in primary care. Clinical Ophthalmol 2019; 13: 33–42.

46. Terauchi R, Wada T, Ogawa S, et al. FDT Perimetry for glaucoma detection in comprehensive health checkup service. J Ophthalmol 2020; 2020: 4687398. Article ID 4687398. Epub ahead of print 2020. DOI: 10.1155/2020/4687398.

47. Alawa KAR, Nolan RP, Han E, et al. Low-cost, smartphone-based frequency doubling technology visual field testing using a head-mounted display. Br J Ophthalmol 2019; 0: 1–5.

48. Chang R. The evolution of portable visual field testing. Review of Ophthalmology, https://www.reviewofophthalmology.com/article/the-evolution-of-portable-visual-field-testing (2019, accessed 31 December 2021).

49. Kim S, Crose M, Eldridge WJ, et al. Design and implementation of a low-cost, portable OCT system. Biomed Opt Express 2018; 9: 1232.

50. Song G, Chu KK, Kim S, et al. First clinical application of low-cost OCT. Trans Vision Sci Technol Epub ahead of print 2019; 8(3): 61. DOI: 10.1167/tvst8.3.61.
51. Rothman AL, Tran-Viet D, Vajzovic L, et al. Functional outcomes of young infants with and without macular edema. *Retina* 2015; 35: 2018–2027.

52. Moshiri Y, Legocki AT, Zhou K, et al. Handheld swept-source optical coherence tomography with angiography in awake premature neonates. *Quant Imaging Med Surg* 2019; 9: 1495–1502.

53. Maloca P, Hasler PW, Barthelmes D, et al. Safety and feasibility of a novel sparse optical coherence tomography device for patient-delivered retina home monitoring. *Trans Vision Sci Technol* Epub ahead of print July 2018; 7(3): 61. DOI: 10.1167/tvst.7.4.8

54. Finn AP, House RJ, Tammy SH, et al. Hyperreflective vitreous opacities on optical coherence tomography in a patient with bilateral retinoblastoma. *Ophthalmic Surg Lasers Imaging Retina* 2019; 50: 50–52.

55. Schmid U and Kniestedt C. Mobile intraocular pressure measurement. From palpation to initial clinical experience with the handheld dynamic contour tonometer TT - Mobile Augeninnendruckmessung. Von der Palpation bis zu ersten klinischen Erfahrungen mit dem handgehaltenen dynamisch. *Der Ophthalmologe: Z Deutsch Ophthalmologischen Ges* 2010; 107: 676–682.

56. Prabhakar SK, Mahesh BS and Shanthamallappa M. A comparative study of intraocular pressure measurement by three tonometers in normal subjects. *NEPJOPTH* 2013; 5: 201–206.

57. Aziz K and Friedman DS. Tonometers - Which one should I use? *Eye (Basingstoke)* 2018; 32: 931–937.

58. [Contemporary possibilities of intraocular pressure measurement]. - PubMed - NCBI.

59. Chiara GF, Semes LP, Potter JW, et al. Portable tonometers: a clinical comparison ofplanation and indentation devices. *J Am Optom Assoc* 1989; 60: 105–110.

60. Cordero I. Understanding and caring for a Schiotz tonometer. *Community Eye Health* 2014; 27: 57.

61. Mayali H, Tekin B, Kayıkçıoğlu ÖR, et al. Evaluation of the effect of body position on intraocular pressure measured with rebound tonometer. *Turk J Ophthalmol* 2019; 49: –9.

62. Hubanova R, Aplt F, Zhou T, et al. Comparison of intraocular pressure measurements with the Reichert Pt100, the Keeler Pulsair Intellipuff portable noncontact tonometers, and Goldmann applation tonometry. *J Glaucoma* 2015; 24: 356–363.

63. Billy A, David P, Mahabir A, et al. Utility of the tono-pen in measuring intraocular pressure in trinidad: a cross-sectional study. *West Indian Med J* Epub ahead of print May 2015; 64(4): 367–71. DOI: 10.7727/wimj.2014.125

64. Thompson AC, Jammal AA and Medeiros FA. A deep learning algorithm to quantify neuroretinal rim loss from optic disc photographs. *Am J Ophthalmol* 2019; 201: 9–18.

65. Medeiros FA, Jammal AA and Thompson AC. From machine to machine: an OCT-trained deep learning algorithm for objective quantification of glaucomatous damage in fundus photographs. *Ophthalmology* 2019; 126: 513–521.

66. Christopher M, Belghith A, Weinreb RN, et al. Retinal nerve fiber layer features identified by unsupervised machine learning on optical coherence tomography scans predict glaucoma progression. *Invest Ophthalmol Visual Sci* 2018; 59: 2748–2756.

67. Asaoka R, Murata H, Hirasa K, et al. Using deep learning and transfer learning to accurately diagnose early-onset glaucoma from macular optical coherence tomography images. *Am J Ophthalmol* 2019; 198: 136–145.

68. Silva FR, Vidotti VG, Cremasco F, et al. Sensitivity and specificity of machine learning classifiers for glaucoma diagnosis using spectral domain oct and standard automated perimetry. *Arg Bras Oftalmol* 2013; 76: 170–174.

69. Sonobe T, Tabuchi H, Ohsugi H, et al. Comparison between support vector machine and deep learning, machine-learning technologies for detecting epiretinal membrane using 3D-OCT. *Int Ophthalmol* 2019; 39: 1871–1877.

70. Varadarajan AV, Poplin R, Blumer K, et al. Deep learning for predicting refractive error from retinal fundus images. *Invest Ophthalmol Visual Sci* Epub ahead of print 2018; 59(7): 2861–2868. DOI: 10.1167/iovs.18-23887

71. Lee H, Kang KE, Chung H, et al. Automated segmentation of lesions including subretinal hyperreflective material in neovascular age-related macular degeneration. *Am J Ophthalmol* 2018; 191: 64–75.

72. Schmidt-Erfurth U, Bogunovic H, Sadeghipoor A, et al. Machine learning to analyze the prognostic value of current imaging biomarkers in neovascular age-related macular degeneration. *Ophthalmol Retina* 2018; 2: 24–30.

73. Schlegl T, Waldstein SM, Bogunovic H, et al. Fully automated detection and quantification of macular fluid in OCT using deep learning. *Ophthalmology* 2018; 125: 549–558.

74. Aslam TM, Zaki HR, Mahmood S, et al. Use of a neural network to model the impact of optical coherence tomography abnormalities on vision in age-related macular degeneration. *Am J Ophthalmol* 2018; 185: 94–100.

75. Nittal MG, Ruiz-García H and Sadda SVR. Accuracy and reproducibility of automated drusen segmentation in eyes with non-neovascular age-related macular degeneration. *Invest Ophthalmol Visual Sci* 2012; 53: 8319–8324.

76. Ahn JM, Kim S, Ahn KS, et al. Accuracy of machine learning for differentiation between optic neuropathies and pseudopapill edema. *BMC Med* 2017; 1(0024) Epub ahead.

77. Sirin L, Conen D, Patricio VP, et al. Artificial neural network regarding accuracy and certainty in performance of visual field assessment for the diagnosis of glaucoma. *Acta Ophthalmol* 2013; 91: 413–417.
82. Kim SJ, Cho KJ and Oh S. Development of machine learning models for diagnosis of glaucoma. *PloS One* 2017; 12: e0177726.

83. Goldbaum MH, Lee I, Jang G, et al. Progression of patterns (POP): a machine classifier algorithm to identify glaucoma progression in visual fields. *Invest Ophthalmol Visual Sci* 2012; 53: 6557–6567.

84. Oh E, Yoo TK and Hong S. Artificial neural network approach for differentiating open-angle glaucoma from glaucoma suspect without a visual field test *Invest Ophthalmol Visual Sci* 2015; 56: 3957–3966.

85. Huang ML, Chen HY, Huang WC, et al. Linear discriminant analysis and artificial neural network for glaucoma diagnosis using scanning laser polarimetry-variable cornea compensation measurements in Taiwan Chinese population. *Graefe’s Arch Clin Exp Ophthalmol* 2010; 248: 435–441.

86. Garcia GGP, Nitta K, Lavieri MS, et al. Using kalm filter to forecast disease trajectory for patients with normal tension glaucoma. *Am J Ophthalmol* 2019; 199: 111–119.

87. Bach M and Heinrich SP. Acuity VEP: improved with machine learning. *Doc Ophthalmol* 2019; 139: 113–122.

88. Rohm M, Tresp V, Müller M, et al. Predicting visual acuity by using machine learning in patients treated for neovascular age-related macular degeneration. *Ophthalmology* 2018; 125: 1028–1036.

89. Gramatikov BI. Detecting central fixation by means of artificial neural networks in a pediatric vision screener using retinal birefringence scanning. *Biomed Eng Online* Epub ahead of print April 2017; 16(52). DOI: 10.1186/s12938-017-0339-6.

90. Garway-Heath DF, Zhu H, Cheng Q, et al. Combining optical coherence tomography with visual field data to rapidly detect disease progression in glaucoma: a diagnostic accuracy study. *Health Technol Assess* Epub ahead of print January 2018; 22(4). DOI: 10.3310/hta22040.

91. Lee WJ, Kim TJ, Kim YK, et al. Serial combined wide-field optical coherence tomography maps for detection of early glaucomatous structural progression. *JAMA Ophthalmol* 2018; 136: 1121–1127.

92. Tanna AP, Budenz DL, Bandi J, et al. Glaucoma progression analysis software compared with expert consensus opinion in the detection of visual field progression in glaucoma. *Ophthalmology* 2012; 119: 468–473.

93. Castro JJ, Jiménez JR, Ortiz C, et al. New testing software for quantifying discrimination capacity in subjects with ocular pathologies. *J Biomed Opt* 2011; 16: 015001.

94. Martin SJ, Rowe KS, Hser N, et al. Compared near-vision testing with the nintendo 3DS PDI check game on the Thai-Burma border. *Asia-Pacific J Ophthalmol* 2019; 8: 330–334.

95. Smith KA, Arnold AW, Sprano JH, et al. Performance of a quick screening version of the nintendo 3DS PDI check game in patients with ocular suppression. *J Pediatr Ophthalmol Strabismus* 2019; 56: 234–237.

96. Rhiu S, Lee HJ, Goo YS, et al. Visual acuity testing using a random method visual acuity application. *Telemed J e-Health: Off J Am Telemed Assoc* 2016; 22: 232–237.

97. Aslam TM, Parry NRA, Murray JJ, et al. Development and testing of an automated computer tablet-based method for self-testing of high and low contrast near visual acuity in ophthalmic patients. *Graefe’s Archive Clin Exp Ophthalmol* 2016; 254: 891–899.

98. Phung L, Gregori NZ, Ortiz A, et al. Reproducibility and comparison of visual acuity obtained with sightbook mobile application to near card and snellen chart. *Retina (Philadelphia, Pa)* 2016; 36: 1009–1020.

99. Bodduluri L, Boon MY, Ryan M, et al. Normative values for a tablet computer-based application to assess chromatic contrast sensitivity. *Behav Res Methods* 2018; 50: 673–683.

100. Campbell TG, Lehn A, Blum S, et al. Ipad colour vision apps for dyschromatopsia screening. *J Clin Neurosci* 2016; 29: 92–94.

101. Global Eye Care Surgical Market | Estimated to Reach Worth USD 1 - Suncoast News and Weather Sarasota Manatee & Charlotte. (n.d.). Retrieved April 16, 2022, from https://www.snttv.com/story/45912225/global-eye-care-surgical-market-estimated-to-reach-worth-usd-19610-million-compound-annual-growth-rate-cagr-is-51-during-forecast-period-2022-2028.

102. Peeters A, Schouten JSAG, Webers CAB, et al. Cost-effectiveness of early detection and treatment of ocular hypertension and primary open-angle glaucoma by the ophthalmologist *Eye* 2008 2006; 22: 354–362.

103. Sopeyin A, Young BK and Primary OA. Focus: preventative medicine: 2020 evaluation of portable vision Screening Instruments. *Yale J Biol Med* 2021; 94: 107.

104. Fuller SD, Hu J, Liu JC, et al. Five-year cost-effectiveness modeling of primary care-based, nonmydriatic automated retinal image analysis screening among low-income patients with diabetes. *J Diabetes Sci Technol* 2022; 16(2): 415–427: 1932296820967011.

105. Khan T, Bertram MY, Jina R, et al. Preventing diabetes blindness: Cost effectiveness of a screening programme using digital non-mydriatic fundus photography for diabetic retinopathy in a primary health care setting in South Africa. *Diabetes Res Clin Pract* 2013; 101: 170–176.

106. Bourne RRA, Fluxman SR, Braithwaite T, et al. Magnitude, temporal trends, and projections of the global prevalence of blindness and distance and near vision impairment: a systematic review and meta-analysis. *Lancet Global Health* 2017; 5: e888–e897.

107. Fricke TR, Tahhan N, Resnikoff S, et al. Global prevalence of presbyopia and vision impairment from uncorrected presbyopia: systematic review, meta-analysis, and modelling. *Ophthalmology* 2018; 125: 1492–1499.

108. Commercial-in-Confidence The global economic cost of visual impairment AMD alliance international Commercial-in-Confidence. 2010.

109. ASSEMBLY S-FWH. Integrated people-centred eye care, including preventable vision impairment and blindness Global targets for 2030 Draft decision.