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Innovative Diagnostic Tools for Ophthalmology in Low-Income Countries

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Abstract

Globally, there are almost 300 million people blind and visually impaired and over 90% live developing countries. The gross disparity in access to ophthalmologists limits the ability to accurately diagnose potentially blinding conditions like cataract, glaucoma, trachoma, uncorrected refractive error and limits timely initiation of medical and surgical treatment. Since 85% of blindness is preventable, bridging this chasm for care is even more critical in preventing needless blindness. Many low-income countries must rely on community health workers, physician assistants, and cataract surgeons for primary eye care. Ophthalmology in low-income countries (LIC) is further challenging due to complexities brought from tropical climates, frail electric grids, poor road and water infrastructure, limited diagnostic capability and limited treatment options. Vision 2020 set the goal of eliminating preventable blindness by 2020 despite formidable obstacles. Innovative technologies are emerging to test visual acuity, correct refractive error quickly and inexpensively, capture retinal images with portable tools, train cataract surgeons using simulators, capitalize on mHealth, access ophthalmic information remotely. These advancements are allowing nonspecialized ophthalmic practitioners to provide low-cost, high impact eye care in resource-limited regions around the world.

Keywords: Vision 2020, preventable blindness, smartphone photography, mHealth

1. Introduction

When refractive error and presbyopia are included, more than 1.6 billion people suffer from some form of visual impairment worldwide [1]. Unfortunately, the greatest burden of visual blindness and impairment falls to the poor who are living in LIC where access to resources and eye care providers is scarce. According to a published report in 2010, the leading causes of blindness (defined as visual acuity in the better eye less than 3/60) were cataracts (33% of total cases of blindness), uncorrected refractive error (21% of cases), and macular degeneration (7% of cases) [2]. The leading causes of moderate and severe vision impairment (defined as visual acuity in the better eye less than 6/18 but at least 3/60) were uncorrected refractive error (53% of cases), cataract (18%), and macular degeneration (3%). However, these causes varied widely by region. Avoidable vision loss, due to conditions such as uncorrected refractive error, cataract, etc., which are treatable, is

still a major problem worldwide. It accounts for 85% of all cases of vision loss. The number of avoidable cases of blindness is also increasing over time. By 2020, there will be a projected 76 million blind individuals globally.

The prevalence of childhood blindness and vision impairment (CBVI) varies based on socioeconomic development. For example, in high-income countries (HIC), the prevalence of blindness is 0.3 per 1000 children, while in LICs it is 1.5 per 1000 children. The number of blind children is estimated to be 1.4 million, with up to three-quarters of the blind children living in the poor regions of Africa and Asia. Some of the major causes of blindness and visual impairment in children of LIC include vitamin A deficiency, rubella cataracts, corneal scarring from measles, the use of harmful toxic eye remedies and ophthalmia neonatorum [3]. Immunizations and vitamin A supplements are proven, cost-effective preventions.

Despite these challenges, significant technological innovations provide an optimistic view for ending preventable blindness. This chapter will discuss the innovative devices that are currently being tested and used in order to promote eye health worldwide and help achieve the goals set forth by Vision 2020. These include low-cost, portable means of detecting refractive error and imaging the fundus, self-refracting glasses that do not require an eye care specialist, simulators to teach cataract surgery more efficiently, artificial intelligence that diagnose disease, and portable auto-phoropters. Future studies to validate these new innovations will be an important field of research.

2. Vision 2020

In 1999, the World Health Organization (WHO) launched an initiative called Vision 2020: The right to sight [4]. The objective of the initiative was to eliminate avoidable causes of blindness around the world and prevent the projected increase of avoidable visual impairment cases worldwide. Since then more than 90 nongovernmental organizations, agencies, institutions, and corporations have pledged their support of this initiative. If successful, this would reduce the cases of blindness from 76 million to below 25 million. The program is based on several core principles: human resource development, infrastructure and technology development, disease control, advocacy, and collaboration among stakeholders in eye health.

A 2014 study assessed the progress of 21 sub-Saharan African (SSA) countries toward the specific goals placed by the Vision 2020 [5]. The results were not encouraging. First, the authors noted that it was exceedingly difficult to access information on human resources for eye health within the study population, a necessary set of data in order to assist Vision 2020 planning. Secondly, the study found that few of the 21 countries met the human resources goals for the 2011 benchmark: only five countries met the goal for the number of ophthalmologists/cataract surgeons, four countries for ophthalmic nurses, and only two countries for cataract surgical rates (cataract surgeries as a ratio of operations per million population per year). No country met the goal target for number of optometrists, even when other personnel who perform refraction were considered. Overall, sub-Saharan African met three-quarters of its target for number of ophthalmologists, but only one-quarter of its goal for the number of ophthalmic nurses. Thirdly, the study found significant geographic inequities with higher concentrations of human resources in urban cities, seemingly at the expense of rural areas. As a result, there is still significant progress to be made. Compounding these existing provider shortages are increasing clinical care needs due to infectious epidemics, such as Ebola and Zika, and noncommunicable diseases, diabetes and hypertension, which pose a different epidemic threat level by 2030.

3. Innovative technologies

3.1 Refractive error testing kits

Uncorrected refractive error is the most common cause of preventable visual impairment worldwide [6]. The measurement of refractive error typically requires an eyecare specialist, a limiting factor in the provision of eyeglasses in LICs. One study in rural India found that more than 65% of a population with high rates of refractive error correctable with glasses were not wearing them due to inadequate access [7]. While in the U.S., there is approximately one eyecare professional for every 5500 people, that figure is only one per 1 million in certain parts of Africa [8, 9]. Such disparity has negative implications on sustaining educational and occupational productivity of these affected communities. The annual loss in global GDP due to distance visual impairment caused by uncorrected refractive error was an estimated \$202 billion in 2007. In this section, we review various new technological innovations that are able to measure refractive error in a mobile, low-cost manner with limited personnel.

The Portable Eye Examination Kit (PEEK) solutions are built on smartphone technology which includes visual acuity apps and hardware, PEEK Retina. The smartphone app, Peek Acuity Pro, allows users to go through a brief tutorial and then tests visual acuity through a gamelike environment using a tumbling E (<https://mts.intechopen.com/download/index/process/335/authkey/4eb406caf486438fcbbf872a81061e61>). Peek Acuity has been shown to be an accurate and validated method to quickly test visual acuity [10]. Readings can be obtained in Imperial (20/20), Metric (6/6) or LogMar (0) for clinical research. The measured visual acuity can be simulated with a split screen view of a classroom chalkboard on one side compared to 20/20 view on the opposite side. The PEEK Retina allows fundus photography of the optic nerve and macula using a smartphone hardware attachment (**Figures 1 and 2**).

A qualitative study [11] in the Nakuru district of Kenya assessed the usability and acceptability of PEEK for providing eye care. In a region with a lack of adequate eye care services, patients found the PEEK system highly practical, as it allowed health practitioners to visit them in their own rural areas. This is particularly significant in regions with poor infrastructure and roads that can make transportation difficult. The PEEK system was also able to save patient time, overcoming the challenge of taking time off work and losing potential income. In regions where



Figure 1.
The peek retina device.



Figure 2.
Peek retina can be attached to a smartphone for portable fundal examinations.

eye problems are not perceived to be serious enough to warrant travel for care, barriers such as transportation become significant obstacles in providing eye care services. Patients and PEEK-trained healthcare workers appeared to have positive attitudes toward using mobile health technology, referring to it as “innovative” and “new.” Many patients thought it to be efficient and cost-saving. Reasons for preferring PEEK were shorter exam times, simplicity, being seen at home, and increased ability to cover the population in need. However, some patients did prefer the traditional examination due to the ease of reading larger letters.

Another study [12] investigated whether a PEEK-based system could increase hospital follow-up for school aged children who were screened for visual impairment. Subjects in the experimental group determined to have visual impairment were shown their simulated sight on a smartphone and given a printout of this simulation. This simulation was then shared with the subjects’ teachers and parents on a handout, which also included a written hospital referral letter. Parents in the experimental group were also sent regular SMS reminders to attend their follow-up appointment at the hospital. Compared to a control group which only received a referral letter without any simulation or SMS follow-up, the study found that visually impaired subjects in the PEEK group were significantly more likely to follow up at the hospital versus the control group with an odds ratio of 7.35 (95% CI 3.49–15.47). While the SMS reminders may have played a significant role in these results, future studies should analyze the effect of the simulation alone in increasing referral follow ups. However, one potential problem of increased screenings and referrals with PEEK or similar devices would be the inability of providers to handle the increased caseload. Nevertheless, PEEK have played a major role in addressing the shortage of vision care in underprivileged communities worldwide.

EyeNetra Inc. (Cambridge, MA) produces similar smartphone-based autorefractors for refractive error measurements (**Figure 3**). The autorefractor, NETRA, measures sphere, cylinder, axis, and pupillary distance in a virtual reality environment similar to that of PEEK. The age range for the NETRA is 10–65 years. The process takes 2 minutes and requires no power source. The company claims to be as accurate as autorefractors that cost \$45,000, with its own product priced at \$1290. Its system has an accuracy of 0.35D and comes with an extended battery for 2 days of testing without requiring a charge. It can withstand a drop from 1 m without breaking or losing accuracy, a convenient feature for users intending on traveling extensively with the device. EyeNetra also has a lensometer, called the Netrometer, that costs \$975, and a phoropter, called the Netropter, which costs \$699. The



Figure 3.
 The EyeNetra system includes an autorefractor, lensometer, and a phoropter (shown adjacent to a standard near card for size comparison).

combination of the three products can fit within a small suitcase to set up a mobile clinic virtually anywhere and provide all the tools needed to prescribe eyeglasses. The complete kit costs \$2990. The EyeNetra products have been deployed in more than 90 countries worldwide.

In a study sponsored by EyeNetra, Inc., NETRA was compared with Zeiss iProfile Plus and subjective refraction on teenagers of age ranging from 14 to 18 years [13]. When NETRA was compared with subjective refraction, the average absolute difference in sphere was 0.48D, cylinder was 0.30D, and axis was 7.32°. On the other hand, when Zeiss iProfile Plus was compared with subjective refraction, the average absolute difference in sphere was 0.29D, cylinder was 0.45D, and axis was 11°.

Other handheld autorefractors include Retinomax 3, HAR 800/880, QuickSee, PlusOptix, Suresight, SVOne, WA Spot, and 2Win. Retinomax K-plus3, developed by Righton, is a handheld autorefractor and keratometer. It weighs around 1 kg and is able to perform keratometer and refraction measurements in around 0.34 seconds. Its battery life is around 80 minutes. The age range of Retinomax K-plus3 is 5–50 years old with a sphere range of -18.00D to $+23.00\text{D}$. However, pricing can be an issue to certain eyecare providers as it is priced around USD 11,000. HAR-800/880, developed by MOPTIM Imaging Technique Co. (Shenzhen, China), is a portable autorefractor that weighs approximately 0.9 kg with a battery life of 6 hours. The intended patient age range is 10–65 years with the sphere range of -6.0D to $+8.0\text{D}$. HAR-800/880 is priced at USD 4300. QuickSee is an autorefractor developed by PlenOptika (Massachusetts, USA). It is priced around USD 6000. It weighs around 1 kg and is able to perform refraction in 10 seconds. Its intended patient age is 5–85 years with spherical range of -10D to $+10\text{D}$. The battery life is approximately 6–8 hours. QuickSee has already been compared to experienced refractionists in rural south India, which found only small benefit to using subjective refraction over autorefraction [14]. More than half of the patients reported either no preference or preferred the autorefractor over subjective refraction. SVOne, developed by Smart Vision Labs (New York, NY), is a handheld autorefractor that weighs around 0.5 kg and costs USD 10,000. The intended patient age is 5–50 years with spherical range of -14D to $+14\text{D}$. It has been tested in LICs like Bolivia by the Friends of Bolivia Foundation, Inc. PlusOptix, WA Spot and 2Win are handheld autorefractors intended for patients under the age of eight. The price of these autorefractors range from USD 6000–8000.

3.2 Self-adjustable glasses

Self-adjustable glasses are a recent innovation in the realm of optics and refractive error treatment. Also known as self-refraction, self-adjustable glasses look

like any other set of glasses. A well-known set of self-adjustable glasses, Adspecs (Adaptive Eyecare, Oxford, UK), were developed by Professor Joshua Silver in conjunction with Dow Corning and Center for Vision in the Developing World (CVDW). Adspecs use lenses that are composed of two flexible membranes capable of moving inward or outward depending on the amount of silicone solution contained between them (**Figure 4**). The amount of the solution can be altered by the user using a syringe which moves fluid into or out of each lens. When fluid is pumped in, the curvature and power of the lens is increased. The user adjusts the amount of fluid until proper vision is attained, thereby correcting myopia or hyperopia. Another type of self-refracting glasses, USee, work by using pop-in best-sphere lenses (**Figure 5**). On the other hand, a design known as Alvarez optics uses two lens systems that move relative to each other in a spectacle frame, causing changes in lens power. Types of glasses that use this design are the FocusSpecs, Adlens, and Eyejusters.



Figure 4.
Adspecs glasses can quickly adjust refractive power based on the amount of silicone solution injected into the spectacles.

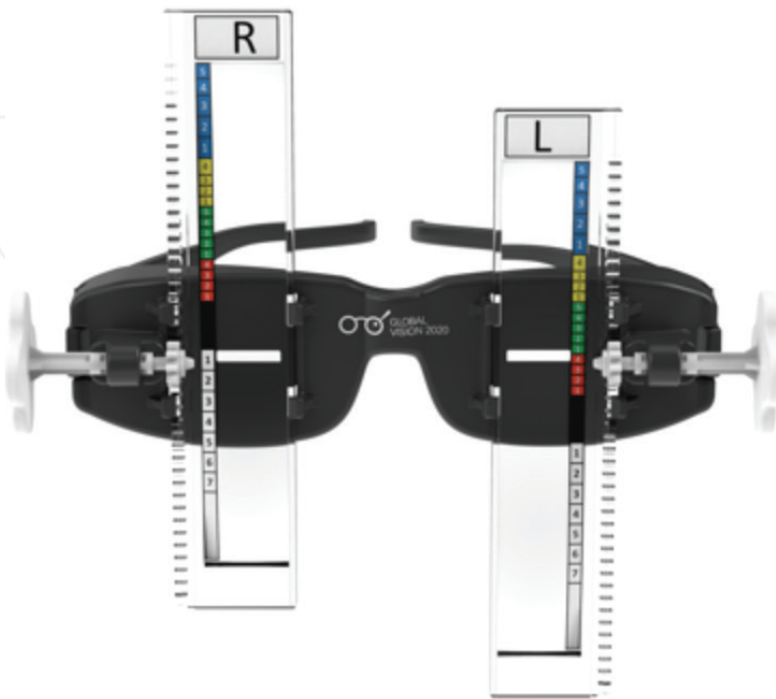


Figure 5.
USee glasses adjust refractive power by using pop-in, best-sphere lenses.

The first iteration of the Adspecs glasses cost between \$18 and 19 to produce and the price has been decreasing ever since [15]. Studies have shown that Adspecs could lead to excellent visual outcomes [16]. A study in rural China found that, while visual acuity was slightly worse with self-refraction versus automated or subjective refraction, acuity was still very good [17]. Moreover, a study in urban Chinese children similarly found good visual acuity with self-refraction, but greater spherical and cylindrical refractive errors were associated with less accurate results as the range for the devices are limited to -6 to $+6$ D. Additionally, the adjustable glasses could not correct astigmatism [18]. Adjustable glasses are easy to use as is evident in a study that looked at users of USee which found positive results in 95% of the users [19].

Concerns regarding self-refracting glasses include the cosmetic appearance, the limited range of correction, inability to correct astigmatism, and compliance with international standards. The Adspecs have the additional limitation that once the glasses are self-adjusted and the power is fixed, they are unalterable. Despite being less expensive than traditional spectacles, cost is still a major barrier to self-adjustable glasses. One study in East Timor showed that nearly half the population was not willing to pay more than \$1 for a pair of glasses [20]. Thus further reductions in cost are paramount for making the glasses affordable to worldwide.

3.3 Smartphone applications

Many iOS and Android applications exist for use in eye care and represent another low-cost tool for providing eye care globally. They generally fall within three categories: patient assessment tools, patient education tools, and health-care reference tools [21]. Many of the applications have redundant functions. For example, countless applications are available to visual acuity. Validation in a low-income setting is critical to compare applications to gold standard methods which can rely on calibration, optotype, distance, lamination and cultural settings. Applications also differ in the number of features they offer, price point, quality of user interface, and, perhaps most importantly, whether they continue to be supported by the developer over time. An analysis of the iTunes store shows that multiple applications from previous reviews [21] are no longer supported by the developers. This demonstrates that ophthalmic applications are part of a dynamic market that is ever-changing, with new applications entering the market each year with older applications exiting the marketplace. This presents the need for users to focus on applications that continue to be upgraded with subsequent iOS and Android updates.

The Eye Handbook (Cloud Nine Development) is the smartphone application currently most highly recommended by the authors for use in LICs (**Figure 6**). It is the most popular and successful application available in eye care [22]. As of 2018, it had over 2 million downloads. The Eye Handbook (EHB) is being used worldwide with 50% of downloads in North America, 20% in Europe, and 10% in each Asia and Australia [23]. While there are surely multiple equality applications that currently exist, the EHB has several significant advantages. First, it has shown to stand the test of time. EHB was developed in 2010 and continues to be supported and upgraded by the developers. Second, EHB is a free application thus making it ideal for use in LICs. Many other applications with similar features charge several dollars (USD), which can be a significant expense for practitioners worldwide. Third, EHB is a comprehensive resource with multiple features, allowing users to avoid downloading several different applications. It includes many different calculators (i.e. IOL calculators, glaucoma risk, etc.), patient assessment tools (amsler grid, visual acuity testing, OKN drum, etc.), medication information (indications, dosing, etc.),

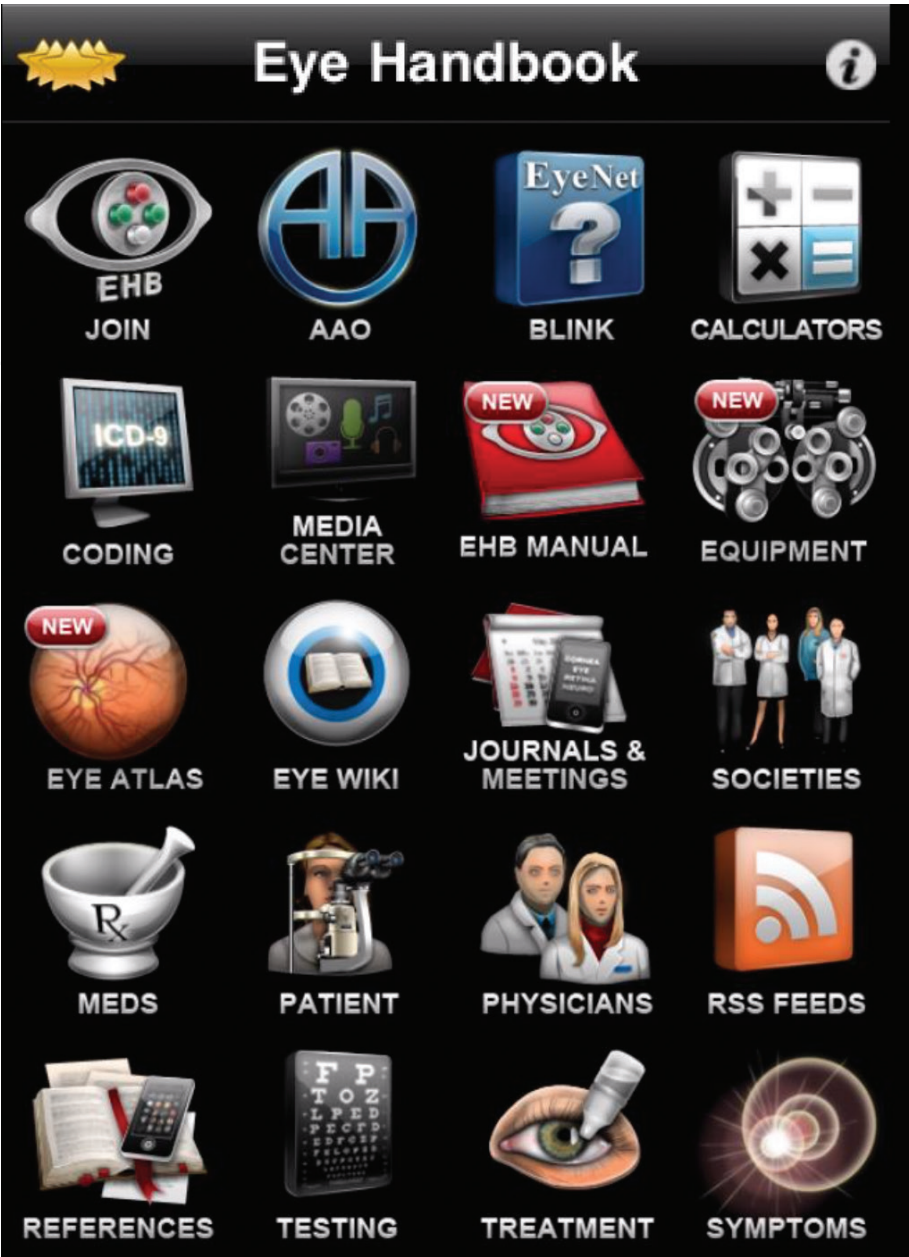


Figure 6.
Menu of The Eye Handbook smartphone application.

and much more. EHB also contains a comprehensive manual of different diseases and includes their epidemiology, pathophysiology, signs and symptoms, differential diagnosis, workup, treatment, and follow up – all of which can be incredibly useful for eye care professionals with limited ophthalmic training in LICs.

3.4 Smartphone-assisted fundoscopy

In addition to the scarcity of ophthalmologists globally, another challenge facing the fight against global blindness is the lack of ophthalmic equipment needed for proper eye care. Given the explosion of mobile phones that 96% of the world’s population now owns, the innovations in fundus photography highlight the ability of smartphones to photograph the fundus [24] and use the smartphone in combination with a 20D condensing lens to capture wider field images of pathology [25].

Traditional ophthalmic equipment, such as office-based cameras are expensive, bulky, immobile and unsuitable for reaching patients in rural areas. Newer developments in technology are replacing our reliance on large equipment and allowing us

to visualize the eye in a mobile and more cost-efficient manner. Smartphone-based technologies can now act as slit lamps, direct ophthalmoscopes, and indirect ophthalmoscopes. **Table 1** lists some of the products currently available. While these images will not be as sharp as those achieved with traditional cameras, they are of adequate resolution for interpretation. This development will allow eye care providers to have more access to imaging technologies, which provide imaging of harder-to-reach patients in rural areas with geo-tagging and wireless transfer of results to distantly-located specialists for appropriate management. One study found that even nonophthalmologists can be trained to effectively capture fundus images in a rural area [26]. This section draws greatly from the 2018 literature review by Barikian et al. [27].

Disadvantages of smartphone-based imaging are the high intensity of the phone light source, which constricts the pupil. However, applications such as Shutter can be used to tailor the intensity and exposure time of the flash for optimal illumination. Another disadvantage is achieving proper beam alignment.

In addition to smartphone-based imaging, standalone handheld camera technologies also allow portable image capture. These cameras are lightweight and capture quality retinal images. Examples of such devices include the Panoptic (Welch Allyn, Skaneateles Falls, NY), Volk Pictor (Volk Optical, Mentor, OH),

Category	Device	Manufacturer	Validated in LIC?	FoV	Pupillary dilation	Cost (USD)
Slit lamp imaging	EyePhotoDoc	EyePhotoDoc (Fullerton, CA)	No	N/A	Required	\$300
	Portable Slit Lamp iPhone 4 Image Adapter	Keeler (Broomall, PA)	No	N/A	Required	\$203
	SteadyPix Telescope Photoadapter	Orion (Cupertino, CA)	No	N/A	Required	\$48
	Zarf iPhone Adapter	Zarf (Spokane, WA)	No	N/A	Required	\$520
	Create-your-own adapter	www.instructables.com www.eyewiki.aao.org	No	N/A	Required	N/A
Direct ophthalmoscopy	iExaminer	Welch Allyn (Skaneateles Falls, NY)	No	25°	Optional	\$800
	D-Eye Adapter	D-EYE (Padua, Italy)	No	20°	Optional	\$435
	PEEK Retina	Peek Vision (London, UK)	Yes [28]	20–30°	Optional	\$245
	Ocular Cellscope	University of California (Berkeley, CA)	No	55°	Required	N/A
	Remidio FOP	Remidio Innovative Solutions (Bangalore, India)	No	45°	Required	\$6500
Indirect ophthalmoscopy	Smartphone and lens	Multiple	No	50°	Required	\$200
	MII Ret Cam	MII Ret Cam (Coimbatore, India)	No	40–50°	Required	\$350
	oDocs	Open source	No	40°	Required	\$0
	Volk iNview	Volk Optical (Mentor, OH)	No	50°	Optional	\$995

Table 1.
Products available for smartphone-based imaging.

VersaCam (Nidek, Gamagori, Japan), Horus Scope (JedMed, St. Louis, MO), and Smartscope (Optomed, Oulu, Finland). A limitation of such devices is the need for proper manual alignment of the illuminating beam with the optical axis for good-quality images. They also lack the ability to integrate with various apps as smartphone-based cameras and tend to be fragile. More importantly, these devices are cost-prohibitive for LICs.

3.5 Ultrasound

VuPad (Sonomed Escalon) and Accutome offer the only portable laptop size ultrasounds that can be used in low-income countries. They are expensive at over \$10 k and do not yet accommodate smart phone utilization. Ultrasound (US) is a noninvasive, very easy to operate tool that plays an important role in clinical ophthalmology. It is used for the visualization of anatomy and various ocular pathology such as retinal detachment and intraocular tumors. Ultrasound becomes especially important if visualization of fundus becomes obscured by opaque elements including vitreous hemorrhage or dense mature cataracts commonly encountered in LIC. Butterfly iQ is the first portable US probe that can be plugged directly into a smartphone to visualize various parts of the body but is not yet approved for the eye (**Figure 7**). The probe uses a single silicone chip that replaces traditional transducer system. Clinicians can switch between various types of transducers, such as linear, curved or phased, without the need of switching probes. Moreover, the Butterfly iQ application allows clinicians to organize and remotely access imaging studies through the Butterfly Cloud. The Butterfly Cloud is HIPAA compliant and the application is developed in a way that makes it easy to share studies between various clinicians across the globe. Butterfly iQ weighs around 0.7 lbs. and is small enough to fit in pants pocket and costs about \$2000. Butterfly iQ is being utilized for point of care ultrasound by physicians and emergency room physicians but could evolve as the first smartphone based ocular ultrasound. It has future potential to be used by visual care providers in resource poor areas for diagnosing ocular pathology.



Figure 7. *Butterfly iQ is a portable ultrasound probe that can be plugged into any smartphone to visualize various anatomical features, including the eye.*

The Clarus Portable Ultrasound is palm sized, connects to a wireless smartphone or tablet, but is not yet marketed for ophthalmology use. Its rugged, portable and waterproof design makes it ideal for global health (relief camp settings/medical missions) where it has been used for ophthalmology as part of a FAST exam.

A group from the University of Arizona assessed a new ultrasound system, the Vevo 2100 (VisualSonics, Toronto, Ontario, Canada) and its ability to examine structures of the anterior and posterior segments [28]. This system is unique in that it was able to implement high-frequency (>20 MHz) linear ultrasonic arrays that were not previously available in ophthalmic practice. Previous ultrasound technologies used single-element transducers, while the Vevo 2100 uses linear array technology with more than 100 piezoelectric elements packed into the face of the transducer probe. The new technology allows users to examine the eye quickly (approximately 10 seconds) with high resolution (30–60 μm). Additionally, it allows the scan to be shown in three-dimensions at different planes with sagittal, transverse, and coronal sections. This allows users to measure the location, dimensions, and volume of lesions or parts of the eye, which could be useful for providing information on the growth of lesions over time. The technology could also be used to determine the extent of traumatic injury and location of foreign bodies. A doppler function also allows examination of the temporal artery as well as vessels of the optic nerve head. However, despite the accurate images, the Vevo 2100 provides the anterior and posterior segments, and its high cost makes it a limiting factor for use in LIC.

3.6 mHealth in LICs

Mobile health, also referred to as mHealth, refers to the use of short messaging service (SMS), wireless data transfer, voice calling, and smartphone applications to transmit health-related information or direct medical care. A thorough 2013 systematic review by Betjeman et al. [29] found that mHealth can be a valuable tool in sub-Saharan Africa (SSA) to monitor patients, increase medication adherence, promote healthcare worker communication, and assist with disaster response. One of the key factors of mHealth is the prevalence of mobile phones even within LICs: penetration rates of mobile phones are greater than 70% in SSA [29].

mHealth has been shown to be a cost-effective means of improving medication adherence in LICs [29]. A study of 155 patients in South Africa tested the utility of SIMpill, a medication dispensing system that uses a SIM card to send an SMS text to a central server each time the medication bottle is opened (**Figure 8**). If the server does not receive an SMS before a preset time, a reminder text message is sent to the patient's mobile phone. If there is no response from the patient, an SMS is sent to the patient's healthcare provider for direct follow up. One study found that the SIMpill system increased medication adherence rates from 22–60 to 94% [30]. The WelTel Kenya study found that even weekly SMS text messages inquiring about patient wellbeing is sufficient to increase self-reported medication adherence and HIV viral suppression [31]. The system deployed in this study cost under \$8 USD per patient per year. Another study in Kenya used a combination of video messages and text messages, having the patient's friends or relatives capture video images of the patient taking their medication which is reviewed by nurses for follow up if there is low medication adherence. This study found that 50% of the messages were not received, mostly due to technical issues [32]. This demonstrates the need for a strong technological infrastructure in regions that mHealth is being deployed. Based on the results of these studies, mHealth can be an effective and cost-effective means to increase medication adherence in LICs with wireless network coverage.

mHealth can also be a means of increasing community health worker (CHW) access to health information, access to health information, decision making, and



Figure 8.

The SIMpill system sends an SMS message to centrally-located servers, recording each time a patient takes their medication.

logistical support [29]. A study in Malawi found that CHWs most often used SMS to report supply shortages, communicate information with other CHW, and facilitate emergency communication [33]. Importantly, this study found that the average cost per communication using SMS was one-fifth the cost of communication in areas without SMS access. SMS communication took approximately 9 minutes, compared to 24 hours in areas without SMS access [33]. Another study found that common uses of SMS by CHW were patient referral, drug dosing information, emergency support, and reporting patient mortality. This study found that the efficiency of SMS communication substantially increased free time of hospital staff, allowing staff to treat more patients. These studies show that mHealth can significantly increase CHW efficiency while reducing overall healthcare costs in LICs.

mHealth could potentially be used to facilitate health education among patients in LICs [29]. One study sent an SMS quiz on HIV awareness to 10,000 cell phone subscribers and found significant challenges associated with the use of mHealth as a patient education tool [34]. First, the study found that individuals tended to only respond to questions for which they knew the correct answer, while skipping other questions. This demonstrates that it may be difficult to use mHealth to transmit new information to patients. Second, and perhaps more importantly, the study found that respondents were more likely to be men. The authors postulated this to be due to men having higher rates of mobile phone ownership and literacy. This could indicate future difficulty for mHealth to be used as an education tool for women in LICs.

3.7 Remote database access

Rapid Assessment of Avoidable Blindness (RAAB) is a survey system that estimates prevalence of avoidable blindness in a population over age 50. The data gathered from these surveys are stored in a repository, which not only details the prevalence of eye diseases and their causes but also the quality of eye services, resources and barriers to care in a specific geographical area. This resource is invaluable to researchers and country ministries of health, as it grants them easy access to data. Moreover, it allows agencies and eye care providers to focus their efforts on regions with the greatest medical need with optimal utilization of limited resources. These RAAB surveys can also be completed using a smartphone application developed by the PEEK Vision project called mRAAB [35]. The mRAAB application has increased the quality and efficiency of data entry by allowing the data to be entered while the examiner is still with the patient. It has been tested successfully

in countries such as Tanzania, the Maldives, Madagascar, Uganda, Zimbabwe, and Nigeria. The future goal of mRAAB is to integrate PEEK functions such as visual acuity assessments and ocular photography with the surveys.

The Open Data Kit is another mobile data collection application that has facilitated the collection, management, and access to data in remote and resource-limited regions. It is a free and open-source software that is already being used by organizations such as the WHO, Red Cross, and Red Crescent [36]. Similar to the mRAAB, this is a great resource that allows various eye care organizations and providers to collect and share data that can increase the effectiveness of their efforts.

Poor cataract outcomes are often detected in RAAB surveys of cataract patients in sub-Saharan Africa. The WHO recommends Better Operative Outcomes Software Technology (BOOST) to track cataract surgery cases for quality assessment and improvement. BOOST is an application developed by several nongovernmental organizations and the Aravind Eye Hospital (Madurai, India) which allows cataract surgeons to measure and benchmark their surgical results against others in a cloud-based database. It also provides advice on how to improve outcomes [37]. The app uses two rounds of data collection. First, users measure visual acuity of patients the day after surgery to measure the proportion of patients with good (defined as $>6/18$) and bad (defined as $<6/60$) visual acuity. Second, for patients returning 6 weeks postoperatively with vision less than 6/60, users choose from among three reasons for poor vision outcomes (refractive problems, surgical misadventure, presence of ocular comorbidity). The app then suggests changes in practice for users to help improve their most common causes of poor vision.

3.8 Simulations in cataract surgery

Simulation-based training for cataract surgery is an innovation with substantial promise for treating global blindness in LIC. Cataracts account for nearly half of all cases of global blindness, the majority being in the developing world [38]. While many of these cases can be cured with inexpensive surgical procedures, there is a shortage of surgeons to handle the caseload. Trainees in developing countries face a lack of equipment and teaching personnel. Simulation-based training could help alleviate this shortage of surgeons by providing practice cases without the requirement for actual patients. Several simulators currently exist on the market, including HelpMeSee (HelpMeSee, New York), Eyesi (VRmagic, Mannheim, Germany), MicroVisTouch (ImmersiveTouch, Chicago), and Phacovision (Melerit Medical, Linköping, Sweden), among others.

The Eyesi is the most prevalent of commercially available simulators in U.S. and European ophthalmology residency programs [39]. It is a high-fidelity phacoemulsification simulator. The hardware consists of a mannequin headpiece with a mechanical eye, which is wired to a computer interface and a microscope, allowing the trainee to assume the most realistic posture (**Figure 9**). Eyesi also includes surgical instruments and foot pedals. The system allows users to watch previous surgeries to review and improve upon. It consists of different learning modules, including anti-tremor training, bimanual training, capsulorhexis, cracking and chopping training, forceps training, hydro-dissection maneuvers, intraocular lens insertion, irrigation and aspiration, navigation training, and phacoemulsification training. VRmagic also produces Eyesi indirect and direct ophthalmoscopes for simulation-based training in ophthalmoscopy (**Figures 10 and 11**). The HMS system includes a platform similar to the Eyesi system with a microscope, monitor, and instruments attached to robotic arms (**Figure 12**). The MicroVisTouch system includes a blunt-tip handpiece attached to a robotic arm, with a mannequin headpiece to practice proper hand placement. The handpiece serves as the appropriate

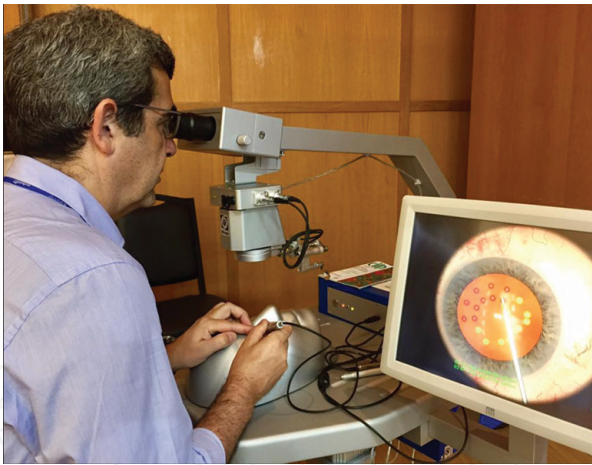


Figure 9.
The VRmagic Eyesi surgical simulator allows users to go through modules of high fidelity simulations of phacoemulsification and vitreoretinal surgery steps.



Figure 10.
The VRmagic direct ophthalmoscope allows users to develop the skillset for direct ophthalmoscopy by progressively moving through skill modules and case pathology.



Figure 11.
The VRmagic indirect ophthalmoscope allows users to develop the skillset for binocular indirect ophthalmoscopy with a 20D and 28D lens and records the percentage of the retina visualized in focus by the examiner.



Figure 12.
The HelpMeSee simulation system allows users to practice small incision cataract surgery (SICS).

instrument based on the stage of surgery being performed, from a keratome to forceps. The system also includes haptic feedback, a relatively new addition to the market for surgery simulators.

A 2015 systematic review of by Thomsen et al. found the overall evidence of research in the use of simulators as both training and assessment tools to be inadequate [40]. Another recent study by Thomsen [41] tested the Eyesi as a training method of 18 surgeons of varying levels of experience. Each surgeon was graded based on a previously-validated testing tool for cataract surgery (Objective Structured Assessment of Cataract Surgical Skill). The study found that novice surgeons benefited by training on the Eyesi, while more experienced surgeons did not. Compared with no intervention, simulation-based training has been shown to have large improvements in user knowledge, skills, and behaviors, along with moderate improvements in patient outcomes across many surgical and medical fields [42]. Given the lack of training institutions, wet labs, etc., in LICs, the use of simulators can play a key role in training future cataract surgeons.

3.9 The HelpMeSee approach to cataract-induced blindness

A 2013 review by Broyles et al. explains that HMS is doing more than simply creating cataract simulation technology. Despite the aforementioned shortcomings in the research of simulators, the organization is creating training centers around the world that incorporate surgical simulation as well as traditional learning methods, centered around a textbook written at an 8th grade English level. Their goal is to fight global blindness caused by cataracts. These training centers will be located within LICs such as Asia, Africa, and Latin America. The intended trainee will include health care professionals and individuals without medical training in order to create the manpower necessary to meet the global need for surgeons. However, HMS predicts that 60% of the trainees will be physicians. Each center will have the capacity to train approximately 1000 trainees per year. Only those who successfully complete the cognitive training will move forward to surgical training, where they will be trained in manual small incision cataract surgery (MSICS), a safe, low-cost, and rapid method for surgical cataract removal compared to other costlier methods.

The graduates then become part of a network of independently-functioning MSICS practitioners that are responsible for seeking out treatable cataract cases in their practicing area, providing surgical care on a fee-for-service basis, and reporting quality metrics via electronic photographs to HMS. The practitioners will live and work in the underserved areas HMS hopes to serve. By focusing only on cataract surgery, the intention is to create high surgical volumes per practitioner in order to drive unit costs of surgery sufficiently low and maintain surgeons' skills. Depending on uptake of surgical services, the cost per surgery could be as low as \$69 in southeast Asia. Better skill and outcomes will then drive local credibility and encourage uptake of the program by locals.

The review forecast that the HMS is able to train 30,000 new surgeons. It also models different levels of uptake of HMS surgeries: low (20% of cataract-caused visually impaired individuals not operated on elsewhere are operated on by HMS), medium (50% operated on by HMS), and high (80% operated on by HMS). With these assumptions, the model predicts that the projected 134 million individuals with cataract-caused blindness in the four identified regions can be reduced to 21 million individuals in the case of high uptake (80%). The reductions are more modest in the medium and low uptake assumptions. The economic effect, with visually-impaired individuals now able to work, would mean an additional \$52 billion of GDP in the Western Pacific Region (i.e., China) if the high scenario is met. The increase in GDP would be \$18 billion in Southeast Asia and \$9 billion in the Africa region. However, once the cataract surgery backlog is eliminated, there will likely be an oversupply of surgeons. The timeframe depends on the uptake of surgical services by region but could be as soon as 2021 in the African region. After that point, surgeons would rely on new cases of cataracts for business. Surgeons could then possibly serve as referral sources for broader ophthalmic services to larger care organizations.

The HMS system faces several obstacles. First, training a new cohort of high-quality cataract surgeons in an efficient manner will likely pose many challenges. Second, it may be challenging for local practitioners to educate patients on the need for surgery and bring in sufficient volumes of cases to drive the unit cost sufficiently low. It will also be difficult for surgeons to have the high surgical load and make time for patient screening and outreach. Third, it may be difficult for individuals to travel the distance required to have the surgery. While the surgeons will live in the regions they serve; patients living in rural will likely still need to travel significant distances for care. This challenge could be reduced by providing transportation services at the time of screening by other qualified medical staff. Fourth, patients with non-cataract pathologies could be disappointed by the inability of practitioners to treat their disease. This could discourage local credibility and would require the practitioner to market their services appropriately. Fifth, it will be challenging for HMS to monitor quality of care provided due to the volume of surgeons operating in multiple different regions worldwide. This increases the need for technology-driven quality monitoring via sophisticated imaging.

4. International organizations promoting visual health

There are several leading global organizations dedicated to providing vision care. Vision Springs, Eyelliance, Eyesee and Vision for a Nation are some of the organizations that focus on providing eyeglasses to low-income countries. Vision Springs is an organization that relies on a high-volume low margin business model. It employs optical shops in communities with limited access to eye care services. These optical shops provide eye exams and low-cost prescription glasses

to the community. Vision Springs also partners with local NGOs and businesses to distribute eyeglasses using their already established distribution channels. This model allows them to distribute glasses to areas in need while keeping the cost as low as possible. Eyelliance and Vision for a Nation follow a similar model. Eyesee is a student-run organization based in the U.S which collects used eyeglasses and distribute them to the poor regions. Since its establishment in 2008, the organization has delivered free recycled glasses to countries such as Haiti, Nigeria, Uganda, Honduras, and Cambodia.

Another leading organization in global vision care is ORBIS. It is a non-profit organization based in New York that operates the Flying Eye Hospital. This mobile hospital is the only one of its kind in the world that provides eye restoration interventions in addition to education and training of local ophthalmic communities throughout low-income countries. The organization has been successful in establishing educational programs in countries such as Bangladesh, Ethiopia, India, and Vietnam. These programs have since provided treatments and prevention of various ocular diseases like cataracts and trachoma to their communities. ORBIS also launched a telemedicine initiative in 2003 called Cybersight. Through Cybersight, ophthalmologists in the U.S. are able to connect 24/7 with local community physicians worldwide to offer them with professional consultation and education on various surgical techniques and patient cases.

The International Agency for the Prevention of Blindness (IAPB), established in 1975, is one of the major organizations that leads international endeavors toward blindness intervention. Through its efforts, Vision 2020 was able to be formed in collaboration with the WHO. The organization's goal in the years between 2013 and 2017 was to promote access to eye health particularly in the most marginalized regions of the world. As a result, IAPB sponsors variety of global initiatives such as Seeing is Believing, the DR Barometer Project, Our Children's Vision, The Rotary International Service Partnership, and the Vision Alliance [43].

5. Future prospects

One of the most exciting emerging frontiers in ophthalmology is the ability of automated devices to diagnose and treat various ocular diseases through artificial intelligence (AI). Giant technology companies such as Google and IBM have dedicated plenty of resources to developing their own version of AI systems. Such systems have shown great promise in playing an important role in patient care. For example, Google Brain (AI system developed by Google) was able to detect the spread of breast cancer by examining microscopic specimen images of lymph nodes. In fact, Google Brain's performance was comparable and, in some cases, superior to that of human pathologists [44]. Similar developments are occurring in ophthalmology, in particularly the field of retinal diseases. In 2016, Google Brain's AI system through machine learning was able to "learn" how detect diabetic retinopathy and diabetic macular edema from fundusoscopic photographs [45]. New systems are currently being developed to evaluate other ophthalmic disorders such as cataract, glaucoma and keratoconus.

These intelligent systems could prove invaluable in global health with the potential to improve health care affordability, efficiency and accessibility. The system can act as an adjunct for eye care capacity building. For example, it could enable non-medical personnel with a few hours of training to diagnose ocular disease without physicians' interpretation, in turn, expanding medical care to remote regions without practicing ophthalmologists. In addition to serving as a solution to the increased shortage of ophthalmologists in low-income countries through simplifying the

process of diagnosing ocular diseases, ocular pathology can be diagnosed at earlier stages. Diagnosing diseases at earlier stages will allow for earlier intervention and in turn yielding better medical outcomes. Moreover, with identification of populations with greater disease burden, resources can be focused on those areas for treatment to maximize its utility.

The US Food and Drug Administration has recently made history by approving the first AI retinal diagnostic system called IDx-DR. The system specializes in autonomously detecting diabetic retinopathy, one of the major causes of vision loss and blindness worldwide. For example, in India, the WHO estimates that around 32 million people were affected by diabetes mellitus (DM) in 2000. We expect the epidemiologic curve to shift from infectious, communicable diseases to non-communicable diseases in the next decade. By 2030, in India alone, these figures are expected to increase to around 80 million people vulnerable to developing diabetic retinopathy [46]. Vision loss, as result of this disease, can be easily controlled with early detection and management; however, most patients with diabetes in low-income countries end up without any eye care. However, IDx-DR currently is only validated and approved by the FDA for use in the US.

IDx-DR could be a future health solution to identify patients with greatest risk early in the disease process, in turn maximizing limited physician resources by focusing on patients who need advanced care. Using a fundus camera, an operator, who does not require previous ophthalmology knowledge, captures two images per eye (**Figure 13**). These images are automatically sent to a computer system that analyzes the images for any signs of diabetic retinopathy. In less than a minute the computer stratifies eyes into two groups. Group 1 contains eyes that are negative or demonstrate mild diabetic retinopathy while Group 2 contains eyes with stages more advanced than mild diabetic retinopathy. Group 1 can be retested in 12 months while group 2 is referred to an eye care specialist. A recent study demonstrated IDx-DR to have similar sensitivity in detecting diabetic retinopathy to human experts [47].

With future system improvement, the integration of this intelligent screening system in a portable fundus camera or a smartphone will greatly improve its accessibility to remote regions. Moreover, having the ability to diagnose diabetic retinopathy (and other ocular diseases in the future) in a matter of few seconds will provide the efficiency to screen larger populations. This new emerging AI technology is a major breakthrough in global health and will serve to positively impact the visual health of millions of patients.

Another major cause of visual impairment worldwide is uncorrected refractive error. In fact, it is considered to be the leading cause of visual impairment worldwide, as more than 650 million people suffer from lack of adequate refractive error



Figure 13.
IDx-DR uses artificial intelligence to detect diabetic retinopathy without the need for experienced ophthalmologic personnel.

correction [48, 49]. It is estimated that the resulting visual impairment contributes to more than 250 billion dollars in productivity loss [48]. This loss of income can be very detrimental, especially to low-income countries where individuals make less than one dollar a day. Providing adequate vision screening and refractive error correction can be very cost effective. A study called PROductivity Study of Presbyopia Elimination in Rural-dwellers (PROSPER), was published in 2018 showed a clear link between refractive error correction and productivity increase [50]. The study conducted in India looked at tea pickers with uncorrected refractive error. It found that providing workers with corrective lenses improved their productivity by 21.7%. Therefore, providing adequate screening and eyeglasses offers an easy solution for the reversal of low vision and blindness, leading to improved quality of life and economic development worldwide. In fact, the WHO considers refractive error as one of the priority eye diseases that it aims to combat globally.

Phoropter is the most widely used tools by ophthalmologists and optometrists to measure patients' refractive error and determine the eyeglass prescription strength. It relies on a heavy set of numerous spherical and cylindrical lenses of various powers. A large number of lenses is required for examination since, eyecare providers must cover the refractive error conditions such as myopia, hyperopia, and astigmatism, along with their respective degree of impairment. This can make mobility of eye care personnel and transportation of equipment between sites a burdensome task, especially in remote areas where road systems are underdeveloped. Moreover, the process of finding the proper prescription strength requires constant patient feedback in order to determine the lens power that provides the sharpest image. It is a very time-consuming process that can limit the number of patients seen by an eye specialist. Moreover, the communication element can be very challenging in certain populations such as children and elderly or patients with mental disabilities or cognitive impairments. It also requires either the eyecare providers speak the language of their patients or the availability of an interpreter in order for the test to be completed. This can force providers to avoid regions where language is a barrier.

A solution to the aforementioned limitations is currently being developed by a team from Tucson, Arizona called the auto-phoropter [51]. The auto-phoropter is a low-cost handheld device that is able to measure a patient's refractive without the need of patient's feedback. In contrast to the already available autorefractors, the auto-phoropter does not require fine tuning of patient's refractive error measurement with an additional exam using lens trials. The special system of lenses and sensors in the auto-phoropter make measuring the refractive error possible. The device contains three separate fluidic lenses, two cylindrical lenses that are placed 45° with respect to each other for astigmatism correction and a spherical lens for myopia/hyperopia. Through pressure induced deformation by the liquid that is pumped in and out of the lens, the power of the fluidic lens can be tuned in increments of 0.1 diopters. With a special wavefront sensor which measures the infrared wavefront coming from the eye called Shack-Hartmann, the refractive error can be calculated in matter of seconds. As a result, the device portability, lack of patient's subjective feedback and the prompt corrective error measurement, the auto-phoropter will allow large patient population screening without the need of trained eye specialists.

According to one estimate, there are more than 1 billion people above the age of 35 that are suffering from uncorrected presbyopia while more than 200 million people suffer from moderate and severe vision impairment (<6/18 but better than 3/60) [52]. Giving patients eyeglasses after vision testing will ensure that they receive the appropriate intervention instead of solely providing them with a prescription. There are various of factors that might impair patients from following up and getting their custom-made glasses. These factors include cost and lack of perceived benefit to name

a few. Therefore, as expected, it will be much more likely that patients wear eyeglasses if offered for free, rather than for purchase [50]. For this reason, we recommend that screening programs carry both reading and prescription glasses to cover the whole spectrum of refraction errors, especially in areas that lack the appropriate facilities and resources.

Nevertheless, being able to carry large number of glasses can be challenging both logistically and financially. Ordering eyeglasses in bulk will help lower their individual cost. We found that in some factories in China, manufacturing a pair of reading glasses can cost as little as USD 0.50 while a prescription glasses for myopia can cost around USD 1.50. Adjustable glasses can be a solution to reducing the number of eyeglass carried by screening programs. However, this advanced type of eyeglasses is more expensive, as a pair can cost around USD 19.

6. Conclusion

This chapter outlined various emerging diagnostic tools and resources that aim to assist in the fight against preventable blindness and achieve the mission of Vision 2020. From Web-based databases and global organizations to smartphone applications and diagnostic devices, eye care providers have emerging diagnostic tools to promote visual health and increase access in global underserved areas. We hope that with the continual evolution of technology, and with improved accessibility and affordability of visual care, preventable blindness can be 1 day eliminated worldwide.

Acknowledgements

The authors would like to thank the Global Retina Institute, Scottsdale, Arizona (USA) for research funding and special thanks to VRmagic (Mannheim, Germany) and Peek Vision Ltd. (England) for use of images.

Conflict of interest

The authors have no conflict of interest.

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