The Role of Smartphones in Eyecare: A Systemic Review

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ABSTRACT

Vision impairment is one of major worldwide public health issues. The demand on eyecare services is increasing. The expensive cost and bulkiness of ophthalmic diagnostic tools and shortage of labour are main barriers for setting an eye clinic, especially in low- and middle-economy countries. Environmental factors, such as COVID-19, cause a restricted number of medical consultations. Besides, people with poor mobility, such as the elderly, are inaccessible to attend eyecare consultation. An alternative to the existing eye clinic setting is necessary.

As smartphone technologies advance, smartphones have various well-designed settings, including adjustable screen brightness, built-in lighting, high-resolution camera, photo and video storage and internet functions. These functions enable the smartphone to assist in eye examination. Thus, the aim of this thesis is to use a systematic review to explore how smartphones assist eyecare services.

Pubmed was used for searching. Keywords “smartphone” and its related terms “mobile phones” as well as “eyecare” and its related terms “optometry”, “ophthalmology” were used. Articles published in English studying how smartphones contribute in eyecare were included. The initial search yielded 192 studies for the initial title and abstract screening. Of the 61 articles eligible for full-text screening, 35 studies were selected and discussed them in details. The major findings of the reviewed research articles and their statistically significant value were presented. Then, the role of smartphone in eyecare according to its functions (including teleophthalmology, vision health screening and reminder systems) were evaluated. Next, further studies to enhance the use of smartphones in eyecare are recommended. This enables the improvement in eyecare delivery.

INTRODUCTION

Vision impairment is a major health issue among all ages. There is an association between academic performance and visual health. Children with poor academic performance had worse visual health than those with good academic performance (Alvarez-Peregrina et al., 2020). For children, early detection of amblyopia is important for effective treatment (Rashad et al., 2018). For cataract patients, early detection enhances the effectiveness of treatment (Khokhar et al., 2018). For chronic eye diseases, such as diabetic retinopathy, glaucoma, or age-related macular degeneration (ARMD), patients require lifelong monitoring and daily eye-drop administration to retard the disease progression (International Council of Ophthalmology, 2015; Korobelnik et al., 2020; Schmidt-Erfurth et al., 2014). Due to the aging population, the demand on eyecare is increasing.

However, the ophthalmic diagnostic tools, such as autrorefractor, fundus camera, visual field analyser, are costly and bulky. This is an obstacle to provide eyecare services in low- or middle-income countries, in rural areas, or in primary integrated healthcare clinic. Also, social factors (such as social events), environmental factors (such as a pandemic) and patient immobility may limit patients' accessibility to medical care. An alternative to conventional eye clinic setting should be considered.

On the other hand, a reminder system is useful to remind chronic glaucoma patients with chronic eye diseases for taking medication and attending medication consultations (Saeedi et al., 2014). Due to the high penetration rate of smartphones worldwide, a well-established internet service and advancements in smartphone technology, a smartphone is now considered a potential tool for assisting eyecare.

BACKGROUND

Vision is the most dominant of the five senses and plays a crucial role in every facet of our lives. Unfortunately, more than one billion people in the world have a vision impairment that could have been prevented or is still unaddressed (World Health Organization, 2021a). At least 800 million people suffer from distance or near vision impairment that could be addressed with an appropriate pair of spectacles, while an estimated 65 million people have moderate-to-severe distance vision impairment or blindness that could be corrected through access to cataract surgery. In addition, 16 million people have moderate or severe vision impairment or blindness due to glaucoma, corneal opacities, diabetic retinopathy and trachoma that could have been prevented through early detection and timely management. Due to ageing population, the number of people with the age-related eye condition glaucoma, for example, has been projected to increase by 1.3 times between 2020 (76 million) and 2030 (95.4 million), and the number of people with age-related macular degeneration by 1.2 times between 2020 (195.6 million) and 2030 (243.3 million).

Vision impairment not only affects people's quality of life, but also pose a heavy burden on the individual and society. It is well-documented that annual global productivity losses associated with vision impairment from uncorrected myopia and presbyopia alone are estimated to be US$ 244 billion (Congdon et al., 2019) and

US$ 25.4 billion (Frick et al., 2015), respectively. It is suggested that improving people's vision could contribute considerable economic benefits, especially in low- and middle-income regions (World Health Organization, 2012).

Meanwhile, there are some challenges for providing eyecare services. First, most ophthalmic instruments are expensive and bulky. The bulkiness and expensive cost of the visual field perimeter limits its usage in a clinical setting. In low-resource countries, i.e. low- or middle-income countries, those instruments are not affordable. Also, for rural areas, it is difficult to deliver the ophthalmic tools. Besides, a shortage of trained human resources in low- and middle-income countries is one of the greatest challenges to increasing the availability of eyecare services and reducing the prevalence of preventable or addressable vision impairment and blindness. All these are major barriers to establish outreach and/or community-based vision health screening programs.

In addition, new strategies are needed to meet the challenges related to the rapid emergence of non-communicable chronic eye conditions such as diabetic retinopathy, glaucoma, age-related macular degeneration, complications of high myopia and retinopathy of prematurity. These conditions require a comprehensive range of interventions for their management as well as long-term care, which will have a profound impact on the already strained health system and eyecare workforce. However, environmental factors, such as a pandemic, social events, affect eyecare services delivery. In view of a pandemic, various government policies, including social distance, quarantine and lockdown, disallow people attending eyecare services. In view of social events, community facilities may be damaged. This makes people inaccessible to eyecare services.

On the other hand, for people who have low mobility, such as the elderly, or those physically disabled, may have difficulty for accessing eyecare services. This lowers their appointment compliance. For people with cognitive impairment, they may find it difficult to undergo routine eyedrops instillation and attend frequent medical appointment. Such medication and appointment noncompliance reduces treatment effectiveness. For working people, they may find it too busy to attend regular eye check-up.

To face this challenge, there is a need to develop ophthalmic diagnostic tools which are portable and cost-effective. A smartphone is an option, because of its features. Firstly, it is light and portable. Secondly, when compared with current ophthalmic diagnostic tools, the cost of a smartphone is much lower and should be affordable in low-income countries. Thirdly, smartphones have screens to provide visual stimulus. Their ability of font size and contrast adjustments facilitates their development in ophthalmic tests. Next, smartphones can save images captured. They can be used for photodocumentation. As a smartphone can connect to internet, information can be sent worldwide through a well-established internet network. Lastly, nowadays, the high penetration rate of a smartphone and the high popularity of mobile app usage indicate the high acceptance of smartphone usage. In recent years, there has been increasing research on smartphone-based tools designed to provide eyecare services. However, there is lack of systemic review to summarise how a smartphone can be used in eyecare services.

OBJECTIVE OF STUDY

The goal this study is to investigate the role of smartphones in eyecare. I will conduct a systemic review of the published literatures to explore how clinicians use smartphones to assist their eyecare services.

MATERIAL

A literature search was conducted through PubMed using the term "smartphone" and/or "eyecare" in the title and/or abstract. As smartphones have become popular since late 2000s, the literature search was limited to articles published between January 1, 2010 and August 2021. Other inclusion criteria were empirical studies written in English. Exclusion criteria included systematic review or commentary/ explanatory papers, and conference papers. Non-English articles were also excluded.

The initial search yielded 186 articles from the selection criteria. Six additional articles (grey literatures) were identified through other sources to enhance the analysis. After removal of 2 duplicated articles, the first abstract scanning was performed in 190 articles to identify relevant terms. The 18 articles were excluded, based in the criteria of inclusion and exclusion. For the remaining 172 articles, second abstract scanning was conducted. A total of 117 articles were excluded because they are either (1) review publication and/ or (2) irrelevant in content. Next, the first full-text readings were done to the 61 articles to access the eligibility of articles. Twenty-six articles were excluded due to their irrelevance to address the issue of smartphone assisting in eyecare and/ or absence of full text availability. Lastly, the second full-text thorough reading was done in each of 35 articles to identify role of smartphone in eyecare (Figure 1).

RESULTS

Smartphone Applications on Optometric Examination

Entrance tests

Smartphone-based Visual Acuity (VA) Measurement: Smartphones have monitors which are capable to present visual stimulus. In this data source, there are 7 papers using 4 smartphone applications for VA measurement.

The Peek AcuityTM app from Portable Eye Examination Kit (Peek) was introduced by Bastawrous et al. (2015) for measuring distance VA. The design of optotype is based on ETDRS chart. It displays a 5x5 grid letter "E" in one of four orientations (90°, 180°, 270° and 0°). There are 3 studies to explore the ability of the Peek Acuity in VA measurement by comparing the performance of both the Peek Acuity test and the Snellen acuity chart (as clinically normal) with the ETDRS logMAR chart (as reference standard).

A study performed by Bastawrous et al. (2015) in 300 adults in rural central Kenya showed that the mean difference between the Peek Acuity in the clinic and EDTRS was 0.011 and 0.032 LogMAR for the right and left eye respectively. In addition, the mean difference between the Peek Acuity at home and EDTRS was 0.055 LogMAR and 0.072 LogMAR for the right and left eye, respectively. Later, a longitudinal study conducted by Brady et al. (2015) in 300 adults in Kenya demonstrated that the mean differences between the Peek Acuity and the ETDRS chart and the Peek Acuity and Snellen acuity data were 0.07 and 0.08 logMAR respectively. This indicates that the Peek Acuity agrees well with the Snellen and ETDRS charts. Besides, the Peek Acuity is a simple test, and it only requires minimal training. This test is easily be accepted by the local community healthcare workers. The results from these studies imply that the Peek Acuity can provide accurate acuity measurements under different environments.

Besides, Rono et al. (2018) investigated the effectiveness of the Peek Acuity test in schoolchildren. The sensitivity and specificity of the Peek Acuity test was 77% and 91% respectively. Meanwhile, the sensitivity and specificity of the Snellen Tumbling-E card was 75% and 97.4% respectively. The results indicate that the Peek Acuity test shows similar sensitivity but lower specificity when compared to Snellen Tumbling-E card.

Manus et al. (2021) used the Peek Acuity test for vision school screening program performed by 3 layman health workers in children aged between 4 to 9 years in South Africa. Among 4933 children participated vision screening, 179 children (3.6%) failed VA screening. Forty-five (25.1%) underwent further diagnostic vision tests, and 26 out of them (57.8%) were confirmed to have vision loss. This study implies that smartphones allow non-eyecare professionals using low-cost technology to identify school-aged children with vision loss in low-income communities.

On the other hand, there are 2 studies to understand how smartphones help in near VA measurement. Toy et al. (2016) compared patient self-administered near VA smartphone-assisted measurement using Paxos Scope telemedicine app with technician-administered Snellen VA measurement in 100 eyes of 50 adult diabetic patients. This study demonstrated that the best spectacle corrected VA (BSCVA) measured at near with the smartphone application was 69 ± 13 letters, while BSCVA measured at distance using Snellen was also 69 ± 13 letters. This implies that this app demonstrated good correlation with Snellen distance VA acquired in a standard clinical setting. However, a study conducted by Tofugh et al. (2015) in 100 adults aged from 18 - 89 years demonstrated that the EyeHandBook smartphone application for near vision overestimates the near VA compared with the conventional near vision card (LPO Rosenbaum pocket screener) in LogMAR format by an average of 0.11 LogMAR. Therefore, the accurate of using smartphone for near VA measurement is inconclusive.

Han et al. (2019) performed an empirical study in 3 study populations (elderly Chinese, adolescent Chinese, and Australian groups) to validate a smartphone-based VA test called Vision at home (V@home). They compared the results obtained from V@home to ETDRS charts tumbling E optotypes with measured monocularly at distant (2m) and binocularly at near (40 cm) respectively. The results demonstrated that the mean difference between V@home and ETDRS distance VA across all groups ranged from -0.010 to -0.100 logMAR. There was high agreement of V@home with near ETDRS VA across all groups, with a mean difference of -0.092 to -0.042 logMAR and a tolerant weighted kappa of 0.736 to 0.837. Most participants were satisfied with V@home. They concluded that the V@home system could potentially serve as a useful tool to improve eyecare.

Smartphone-based Colour Vision Test: Color vision refers to a person's ability to perceive differences between light composed of different wavelengths (Gegenfurtner & Kiper, 2003). A prospective case-control study of adults conducted by Ozgur et al. (2018) compared the correct number of plates obtained from the EyeHandBook Colour Vision Test application with that using standard Ishihara colour plates. The results revealed that there is an agreement between the results obtained in both tests for all participants (bias, 20.25), for the controls (bias, 20.01) and patients with ocular pathology (bias, 20.50). Besides, the sensitivity and specificity of the EyeHandBook was 0.92 and 1.00 respectively. In addition, the majority of study subjects preferred EHB. The results implied that there was an agreement of CVT results comparing EHB with ICP.

Refraction

Smartphone-based Refractor: Jeganathan et al. (2018) did a cross-sectional study to evaluate the accuracy and usability of a low-cost, portable, smartphone-based autorefractor called Netra. They compared the spherical equivalent (SE) by the Netra with that by manifest and cycloplegic subjective refraction for adults aged 20 - 90 years with best-corrected VA ≥ 20/40. Mean SE by the Netra and by manifest refraction were −2.76 diopters (D) and −2.49 D respectively. The mean relative difference in SE between methods was −0.27D (p= 0.001). Therefore, the Netra had small, but clinically significant differences from subjective refraction. However, a validated usability questionnaire revealed that in a 100-point scale, subjects reported average ease of use for the Netra was 75.4 ± 19.8. This indicates good overall patient acceptance.

Later, Tousignant et al. (2020) conducted a randomised, double-blind design to compare the results from unassisted Netra (participants alone) and refined Netra (sphere results refined by a practitioner), with professional subjective refraction. Among 36 eyes from adults aged 18 - 35 years, unassisted Netra yielded a median myopic overcorrection of 0.60D compared to professional subjective refraction. Median SE with unassisted Netra (−1.40 D) was significantly more myopic than refined Netra (−0.70 D) (p-values < 0.01) and subjective refraction (−0.80 D) (p < 0.01). Median VA with professional subjective refraction (−0.16) was superior to unassisted Netra (−0.08) (p < 0.01). Besides, most (72%) participants preferred professional subjective refraction, reporting higher visual comfort than with unassisted Netra (all p < 0.04). These 2 studies demonstrate that Netra showed overestimation in myopia while subject satisfaction is inconclusive.

Ocular Health Assessment

In the data source, most studies explore how smartphone assist ocular health assessment, including anterior ocular health, fundus imaging, perimetry and tonometry.

Smartphone-based Anterior Ocular Health Assessment: Anterior ocular health assessment refers to an examination of the anterior segment of the eye and adnexa including the eyelids, eyelashes, conjunctiva, tear layers, cornea, anterior chamber, iris, crystalline lens and anterior vitreous (Sakti, 2021). It is an essential test performed during proper eye examination and contact lens assessments.

Paxos Scope™ (previously known as EyeGo) was introduced by Ludwig et al. (2016) for both anterior and posterior ocular health assessment. For anterior ocular health assessment, an anterior adapter consisting of a macro lens and light emitting diode (LED) light attaches to the smartphone camera. They conducted a prospective cohort study in India to evaluate the ability of ancillary health staff to use Paxos Scope™ to capture images for excluding emergent eye findings. Among 54 eyes being studied, 96.3% of images taken with the Paxos adapter for anterior imaging and 96.3% of images taken with slit-lamp photography (using BX 900 slit-lamp with a Canon EOS 40D Digital Camera) were given a grade of ≥3/5 or, at least able to exclude all emergent findings. Also, a high positive agreement 92.6% was found between recording using this Paxos adapter and slit-lamp photography. This indicates the high diagnostic capability of this new device in emergency triage. Besides, both users and patients feel comfort for the device.

Besides, Bhatter et al. (2020) performed a study in 54 participants to investigate whether anterior segment images taken with the Easy Macro lens attached to a smartphone camera is superior to those obtained by using a smartphone camera alone. Images obtained from both methods were graded by two ophthalmologists. The results revealed that the smarphone alone was significantly superior in regard to in imaging of the lens and conjunctiva, while the Easy Macro lens attached to smartphone camera was superior in imaging of the anterior chamber, iris, and lens. Therefore, the imaging modality that best captures the pathology depends on the part of the anterior segment being examined.

Joshi et al. (2022) conducted a retrospective analysis of 344 images captured using a smartphone attached with GrabiTMLite to assess the utility of a universal smartphone attachment to capture anterior eye segment images. They identified factors affecting image quality, such as lack of perspective, lack of focus, improper illumination, and resolution. Among the 344 images captured using smartphone only, 7%, 60.8% and 32.2% of images rated as good, average and poor respectively. Also, 16% of images were deemed suitable for clinical decision-making, and 65.6% of images were adequate for risk stratification. However, among the 178 images captured using GrabiTMlite with imaging protocol, 57%, 32.6% and 19.6% of images rated as good, average and poor respectively ($p < .001$ using chi-square test). Also, 45% of images were deemed suitable for clinical decision-making, and 88.8% of images were adequate for risk stratification ($p < .001$ using chi-square test). The results indicate that smartphone-GrabiTMlite system significantly improved the quality of fundus imaging.

On the other hand, DryEyeRhythm is a free smartphone application for assessing dry eye disease (DED). Inomata et al. (2020) conducted a cross-sectional crowd sourced research using this app in 4454 people to assess the characteristics and risk factors associated with diagnosed and undiagnosed symptomatic dry eye. The results showed that the risk factors for symptomatic included younger age, female, hay fever, depression, mental illnesses other than depression or schizophrenia, current contact lens use, extended screen exposure, and smoking. On the other hand, the risk factors for undiagnosed dry eye included younger age, male, absence of collagen disease, mental illnesses other than depression or schizophrenia, ophthalmic surgery other than cataract surgery and laser-assisted in situ keratomileusis (LASIK) and experience of contact lens use. Later, this research group performed a prospective, cross-sectional, observational, single-center study to investigate the reliability, validity, and feasibility of the application for the diagnosis assistance of DED (Okumura et al., 2022). Among 82 adults aged over 20 years, 42 of them are suffered from DED. They found that the results obtained from app-based DED diagnosis (Ocular Surface Disease Index and maximum blink interval) were positively correlated with their clinical assessment results. The 2 studies indicate that the DryEyeRhythm is reliable, and valid for assessing DED.

Smartphone-based Fundus Imaging: Smartphones have good illumination and the built-in high-resolution cameras for imaging systems. By attaching proper ophthalmic lens to smartphone with or without using a tool called adaptor, or coupling special device with smartphone (digital ophthalmology), smartphones can assist in fundus imaging.

- Use of Smartphone Imaging Adaptor System for Fundus Imaging : Adam et al. (2015) did a prospective, cross-sectional study in 94 patients to examine the quality and diagnostic accuracy of images produced via smartphone ophthalmoscopy, which is non-stereoscopic, mydriatic, single-field indirect fundus video captured by a HTC Rezound smartphone coupled with a 28D lens. The results revealed that smartphone ophthalmology and mydriatic fundus camera photography (as reference standard) detected 74.3% and 77.1% of critical fundus findings respectively. Besides, other than anterior ocular health assessment, Ludwig et al. (2016) also used introduced Paxos Scope for fundus imaging. This device consists of macro lens and an indirect ophthalmoscopy lens coupled with an iPhone 5S. In the same study as mentioned, among 128 eyes being studied, 86.7% of those videos taken with the Paxos adapter and 97.7% of images taken with fundoscopic photography (using FF 450 plus Fundus Camera with VISUPACTM Digital Imaging System) were given a grade of ≥3/5 or, at least able to exclude all emergent findings. Also, a high positive agreement 84.4% was found between recording using the system and fundoscopic photography. Besides, both users and patients feel comfort for the device. These 2 studies indicate that smartphone ophthalmoscopy can capture fundus images with comparable diagnostic utility of mydriatic fundus camera photography.

However, when Ademola-Popoola and Olatunji (2017) explored the use of smartphone imaging adaptor system consisting of Blackberry Z-10 with non-contact +20D Volk lens for retinal imaging from dilated pupils in 12 patients with aged between 15 months and 61 years in Nigeria, they found that clear retinal images were obtained in different clinical conditions including branch retinal vein occlusion with fibrovascular proliferation, chorioretinal scarring from laser photocoagulation, presumed ocular toxoplasmosis, diabetic retinopathy, retinoblastoma, ocular albinism with fundus hypopigmentation. In cases of retinoblastoma with a reflective tumour mass and multiple vitreous seeds and mass, the images captured by the system were not as clear as that taken by traditional fundus photography. They commented that the use of smartphones as diagnostic tools for retinal abnormalities is not standardised.

- Use of Smartphone Fundus Imaging for Detection of Diabetic Retinopathy (DR). The following paragraphs described the ability of smartphone imaging adaptor system in detection of DR. Ryan et al. (2015) examined the ability of the smartphone imaging system to detect and grade DR. This system consists of a 20D condensing lens was held in the photographer's left hand and the iPhone 5 was held in the right hand. This group captured the images fundus using 3 imaging techniques in 300 diabetics patients in India. The 3 techniques are (1) nonmydriatic fundus photography using the Nidek Model AFC-230 from participants with physiologic mydriasis, (2) smartphone fundus photography and (3) 7-field mydriatic fundus photography performed by a trained optometrist using the Zeiss FF450 Plus (as reference standard). The results revealed that smartphone fundus photography and nonmydriatic fundus photography can detect both DR and STDR. However, the nonmydriatic fundus photography is more sensitive at detecting DR than the smartphone fundus photography (Table 1).

To extend the usage of fundus photography from imaging alone to diagnosis, the artificial intelligence (AI) is used. Rajalakshmi et al. (2018) assessed the role of AI-based automated software for detection of DR and STDR by fundus photography captured using Remidio 'Fundus on phone', which is a smartphone-based device. The retinal photographs were graded using a validated AI DR screening software (EyeArtTM) and by ophthalmologists (as reference standard). Among fundus imaging captured from 301 type 2 diabetic patients in India, high sensitivity and specificity of EyeArtTM or detecting any DR and STDR were found (Table 2). Also, there is a substantial agreement between the EyeArtTM and the ophthalmologists' grading for detection of DR (Kappa = 0.78) p < 0.001]) and STDR (Kappa= 0.75, [p < 0.001]).

Later, Sosale et al. (2020) used the Medios integrated AI-based software to detect DR in patients attending the outpatient services of tertiary center for diabetes care using. The retinal photographs were graded using the AI-based software and by vitreoretinal specialists (as reference standard). Similarly, there is a high sensitivity and specificity of AI software for detecting any DR and STDR (Table 2). These 2 studies implicate that integration with the smartphone imaging fundus system with image grading software is effective in detection of DR.

- Use of Smartphone Fundus Imaging for Detection of Retinopathy of prematurity (ROP). ROP is a potentially blinding disease in preterm babies (Blencowe et al., 2013). Other than indirect ophthalmoscopy, digital imaging with RetCam, an advanced wide field imaging system is more precise, but costly and not easily available. Smartphones are being explored as an alternate cost effective and accessible imaging tool.

Lekha et al. (2019) conducted a single-centre, retrospective observational study in preterm babies to illustrate the utility of Make In India (MII) RetCam assisted smartphone-based fundus imaging in the documentation and monitoring of ROP. They set up the imaging system by attaching iPhone 4S and + 20 D lens attached the MII RetCam device. The results revealed that good quality images of central and peripheral retina could be captured in 78.57% of babies with ROP. Later, Goyal et al. (2019) in India attached indirect non-contact condensing lenses of different powers (20D, 28D, or 40D lens, which give a field of view of 46°, 53°, and 90° respectively) and iPhone 5S to the MII RetCam device. Among 28 eyes out of 55 eyes having ROP, image quality of fundus photo captured by the imaging device was good in 89.28% eyes.

Wintergerst et al. (2019) used the smartphone-based fundus imaging device equipped with an iPod touch (sixth generation) and a Pan Retinal 2.2 for non-contact indirect smartphone-based fundus imaging in terms of feasibility for ROP screening and documentation in a total of 26 eyes from 14 infants who are eligible for ROP screening in Germany. Although smartphone-based fundus imaging demonstrated a smaller field-of-view and longer time of examination than conventional contact fundus imaging, both imaging techniques show equal level of detail. On the other hand, when compared with clinical evaluation by indirect funduscopy for assessment of plus disease and ROP stage, good agreements are observed for both smartphone-based fundus imaging (squared Cohen's kappa, 0.88 and 0.81, respectively) and conventional contact fundus imaging (squared Cohen's kappa, 0.86 and 0.93 respectively). In addition, the sensitivity and specificity of smartphone-based fundus imaging for detecting plus disease and ROP were high and comparable to that of contact fundus imaging (Table 3).

To conclude, smartphone-based fundus imaging potentially serves as an affordable , portable, use friendly, clinically competent, high-quality wide-field fundus imaging alternative to conventional contact fundus imaging for ROP screening and documentation

- Use of Smartphone Fundus Imaging for Optic Nerve Assessment. With fundus photography, the structure of the optic disc can be evaluated (Jonas & Papastathopoulos, 1995). In the data source, 2 publications studied how smartphone fundus imaging assess optic nerve heads. First, D-Eye invented by Russo et al. (2015) is an adapter consisting of a negative lens imprinted in a glass plate, a beam splitter, a mirror and polarized filters. It magnetically attaches to a smartphone. The lens of D-Eye shifts the focus capability of the smartphone. This enables the smartphone to be focused on the retina of eyes with refractive error between −12 and +6D. Wintergerst et al. (2018) compared the cup-disc ratio of images captured by the D-Eye in both undilated and dilated eyes with traditional fundus photography. Due to the inferior optical setup of the D-Eye, the image qualities of both dilated and undilated smartphone-based fundus photography are significantly lower than that of traditional fundus photography. On the other hand, in terms of cup-disc ratio evaluation, dilated eyes images correlates well with that on traditional fundus photography. However, undilated eyes image potentially underestimates the ratio, which leads to underestimate the patients' conditions.

Similarly, a study performed by Bastawrous et al. (2016) in 2920 dilated adult eyes in Kenya revealed that there is an excellent agreement in the vertical cup-to-disc-ratio grading between results of images captured by smartphone-based imaging adapter system with that taken by conventional digital fundus camera (as reference standard). for all participants (bias, 0.02), for the controls (bias, 20.01) and patients with ocular pathology (bias, 20.50). These findings indicate that optic nerve head evaluation is possible with this system in dilated eyes.

- Use of Smartphone as Digital Ophthalmoloscopy. Other than smartphone imaging adaptor system, smartphones can assist fundus imaging by being a part of ophthalmoscopes. Two studies demonstrated the role of smartphones in digital ophthalmoscopy.

oDocs nun is a digital ophthalmoscope which is compatible with any smartphone for smartphone retinal photography. Singh et al. (2020) recruited 28 general practitioners to determine the feasibility of the use of oDocs Nun ophthalmoscope in a primary care setting. The retinal photos taken by participants were graded by two ophthalmologists and two optometrists. The results revealed that 94.5% of the photographs have visible optic discs and 50.0% of the photographs have visible maculae adequate for detecting an abnormality.

Later, Wintergerst et al. (2020) used HEINE iC2 Funduscope, another digital ophthmoscope showing field of view up to 34°, to evaluate its ability in imaging retinal/vitreous pathologies. Among 47 eyes from 32 participants, when comparing image quality at the posterior pole, the mid periphery, and the far periphery, glare increased as images were obtained from a more peripheral retina. Also, reflex artifacts were more frequent in pseudophakic eyes. Image acquisition was also possible in children. In addition, image quality of conventional fundus imaging was superior to that of the digital ophthalmoscope, although this digital ophthalmoscope still achieved sufficient image quality for documenting different fundus pathologies. These 2 studies imply that smartphones contribute in fundus imaging by being a part of digital ophthalmoscopy.

- Modifications of Smartphone-based Pediatric Retina Fundus camera. To improve efficiency in image captures in children, Patel et al. (2019) introduced some modifications to the existing device for imaging the paediatric fundus. This includes a child-friendly 3D printed housing of animals, attention-grabbing targets, enhanced image stitching, and video-recording capabilities. The dilated retinal photographs captured in 43 children with mean aged 6.7 years were compared to masked retina-specialist graders' diagnosis. There was 96% agreement between image-based and specialist's diagnosis. The authors concluded that the modifications reduce technical barrier for image acquisition in children in order to rapidly complete wide-field fundus photography.

Smartphone-based Tonometry: Tonometry is a diagnostic test that determines intra-ocular pressure (IOP). The 4 types of contact tonometry are applanation tonometry, indentation tonometry, rebound tonometry and PASCAL tonometry (Aziz & Friedman, 2018). Use of local anesthetics and specialized training are required when performing contact tonometry, except rebound tonometry.

Mariakakis et al. (2016) integrated smartphone and applanation tonometer. This prototype emulates fixed-force tonometry by an adaptor, which is mechanically attached to the smartphone. This adaptor substitutes to the conventional applanator heads. The smartphone's camera records the applanation of the eye and captures as videos. The resulting videos are then processed in real-time to offer an absolute estimate of the patient's IOP. Later, Wu et al. (2020) compared the IOP measurements using this smartphone tonometer prototype and all 4 types of tonometry in glaucoma patients. They revealed that the smartphone tonometer results correlated best with Goldmann applanation tonometry. Also, this smartphone tonometer can be operated by minimally trained users.

Smartphone-based Visual Field Perimeter: Perimetry is the measurement of visual field function (Jampel et al., 2011). Computerized automated visual field perimetry is a gold standard. The bulkiness and expensive cost of visual field perimeter restricts its usage in a clinic setting. Since smartphone can provide the visual stimulus to visual field test, it serves as a part of portable visual field analyzer. Recently, Tsapakis et al. (2017) developed visual field test method using virtual reality glasses with a 6-inch smartphone. They found that there was a high correlation between the virtual reality visual field test and the Humphrey perimeter visual field. Similarly, Sircar et al. (2018) developed GearVision, which is a smartphone-based head mounted visual field analyzer. To improve test reliability, they designed optional rest intervals during the test according to patient's response. This can reduce errors due to patient fatigue.

Smartphone-based OCT: OCT is an ophthalmic test to evaluate the structure and to quantify the retinal thickness (Takada et al., 2016) . To enhance the flexibility of OCT usage, portable OCT system was developed (Kim et al., 2018). The system consists of a probe with on-probe display and control using a customized Liquid-Crystal Display (LCD) screen. Recently, smartphone was used to develop a wireless interactive control of an OCT, based on the concept of portable OCT system (Mehta et al., 2017). A web-based user interface (WebUI) for on-probe OCT display and control was designed.

This WebUI can be accessed from any available mobile device such as a smartphone, tablet, or laptop. Regarding to a hardware design, a handheld OCT system probe is attached to the smartphone, which display and control the system. The OCT images captured in smartphone can be sent to other devices, such as computes, tablets, across internet at remote area. This enables multiple users to visualize and control the same OCT imaging session.

Smartphone-based Contrast Sensitivity (CS) Test: CS is an essential visual function reflecting variations in everyday visual experience in different conditions (Habtamu et al., 2019). Paul et al. (2017) used a smartphone version of the Pellie-Robson chart, which is available in the EyeHandBook app, to assess CS in a sample of HIV positive Indian population. The chart was displayed full screen in a 7-inch smartphone with maximum background illumination. The results demonstrated that CS showed significant correlation with Retinal Nerve Fiber Layer Thickness (RNFLT) of the temporal quadrant only (r=0.37; p=0.02). Temporal RNFLT also showed statistical correlation with the Clusters of differentiation 4 (CD4) count (r=0.36; p=0.03). This indicates that CS may be correlated with CD4 count, though additional analysis should be performed.

<u>Smartphone-based Referral System</u>

Rono et al. (2018) compared the effectiveness of referral system using sight simulation referral cards with short message service (SMS) reminders and conventional written referral. The results revealed higher proportion of students identified as having visual impairment who attended their hospital referral in a smartphone-based referral system (54%) than in the standard group (22%). The Peek school eye health system increased adherence to hospital referral for visual impairment assessment compared with the standard approach among school children. This indicates the potential of this technology package to improve uptake of services and provide real-time visibility of health service delivery to help target resources.

<u>Smartphone-based Medication Reminder</u>

Recently, Aguilar-Rivera et al. (2020) innovated a smart electronic eye-drop bottle smart drop system for monitoring of glaucoma medication adherence. This device not only serve as a medication reminder, but also consists of a thin conductive pressure-sensitive electronic sensor, for bottle squeezing detection and an electronic circuit for signal processing and wireless transmission. After eye-drop delivery, the electronic eye-drop bottle transmits a signal via Bluetooth low energy to a mobile device, such as smartphone. The eye-drop instillation record from the mobile device is also connected to a cloud-hosted real-time database. This database is synchronized with any other connected app, which enables physicians, caregivers, or families understand patient's adherence. This database also allows the physicians or caregivers to remotely adjust medication reminders according to patient's conditions.

DISCUSSION

After analysing the literatures in the database, the role of smartphones in eyecare can be categorised into 3 areas. They are teleophthalomology, vision heatlh screening and promotion of patient adherence.

Teleophthalmology

According to the World Health Organization (2021b), telemedicine refers to "the provision of healthcare services at a distance with communication conducted between healthcare providers seeking clinical guidance and support from other healthcare providers (provider-to-provider telemedicine); or conducted between remote healthcare users seeking health services and healthcare providers (client-to-provider telemedicine)". Teleophthalmology is a branch of telemedicine that delivers eyecare through digital medical equipment and telecommunications technology. It enables health professionals to capture ocular images and attend to patients who have limited access to ocular health care (Chong et al., 2021). In this study, smartphones assist in eyecare via teleophthalmology. It can further be divided into remote patient monitoring (home monitoring) and remote consultation.

Remote patient monitoring (home monitoring)

Smartphone-based VA assessment, tonometry and visual field perimetry only require minimal technique. These tests can be performed anytime at home by patient themselves. When they notice a downtrend, they can seek for medical consultation earlier. Clinicians should be caution to the weakness of these smartphone-based diagnostic tests. For smartphone-based VA tests, in Peek Acutiy, only Tumbling E optotype is available. As this optotype is easier to be recognised, this test may not reflect patients' vision ability. To increase the difficulty of vision test, the use of different optotypes should be considered. Also, there is discrepancy in results obtained between smartphone-based VA assessment and conventional VA tests. The correlation between these tests should be determined.

On the other hand, during the smartphone-based tonometry, instillation of proparacaine hydrochloride ophthalmic solution for corneal anesthesia is required. Some rare but possible adverse reactions of the solution include severe immediate hyperallergic corneal reactions and allergic contact dermatitis. Therefore, management for any accidents during test should be considered. Instead, replacement of rebound tonometry with applanation tonometry can be considered, as rebound tonometry does not require local anesthetics.

Regarding visual field perimetry, other than glaucoma, this test can also be used for evaluation of neurological disorders. Smartphone-based perimeter can also be used in such area. Patient reliability is essential in helping clinicians interpret patients' visual field changes. To acquire reliable results, patients' understanding to the testing instructions, cooperation and concentration on the test are required (Phu et al., 2017). On the other hand, visual field sensitivity is age-dependent and gender-dependent (Tan et al., 2019). More smartphone-based visual field tests should be performed in different ages and genders to obtain a complete profile for analysis.

Remote Consultations

Remote consultation refers to medical consultation taking place via the phone, online or video link (European Observatory on Health et al., 2020). Smartphone-based remote consultation is found in various disciplines (Alam et al., 2019; Biswas et al., 2020; Hasselberg, et al., 2017; Parmanto et al., 2015; Wallis et al., 2016). In ophthalmology, smartphone-based remote consultation evolves in age-related macular degeneration (Kelly et al., 2011; Midena et al., 2020) and diabetic retinopathy (Fenner et al., 2018; Surendran & Raman, 2014). During the ophthalmic consultations, fundoscopy and/or OCT are required. Unlike perimetry and tonometry, specialized training is required for these tests.

Lee et al. (2014) did a questionnaire survey on 1,487 patients who attended at the outpatient glaucoma service in China to understand their perception towards telehealth. First, about 40% of participants spend more than 3 hours to travel from home to hospital, and nearly two-third of participants attended more than 4 follow-up visits in a year. Secondly, two-third of respondents was willing to participate in telehealth programs. Thirdly, the factors influencing their decisions included long travelling time from home to hospital, long waiting time during clinic visits and boring process. Lastly, the overall WeChat usage rate among participants was as high as 61.7%. The results indicate that there is potential in the development of telehealth because the reduction of time spending on clinic visits. Also, the high usage of smartphone app provides a foundation for telehealth development.

The advancement of optical quality of smartphone allows it becoming a supporting tool for fundus imaging and OCT. As the imaging information can be transferred from the smartphone to devices of their physician's clinic, such as computers, tablets, smartphone via internet, remote consultation can be developed. However, some technical issues of SBFP should be addressed. First, during glaucoma examination, stereoscopic assessment of the optic disc morphology is the preferred method for optic nerve grading (Stone et al., 2010). SBFP can only provide monoscopic images. This may lead to a potential misdiagnosis. Secondly, the adaptor of SBFP only allows the images to be captured from patients within a range of refractive error. The lens power of adaptor should be reviewed to extend the focusing ability of the system. Lastly, it is unknown whether SBFP can be performed in patients with either severe or irregular astigmatism. The image quality of these situations should be reviewed.

On the other hand, the innovation of smartphone-based OCT by modifying portable OCT with integrating a newly designed web interface allows chronic glaucoma patients to perform OCT in non-clinical setting. However, only technical references such as latency were determined. To have better understanding of the clinical use of smartphone-based OCT, the comparison between the smartphone-based OCT, and portable OCT, as well as traditional OCT should be performed in both normal and chronic glaucoma patients. Besides, the optimal conditions to capture the best OCT imaging quality should be determined.

More importantly, remote consultations cannot fully replace face-to-face medical consultations, which enable physicians to have a more accurate analysis and a better understanding of patients' health conditions. For patients with difficulty in travelling, it is suggested to partially replace face-to-face medical consultations to remote consultations.

Vision Health Screening

In the data source, there are many literatures utilize smartphones for vision health screening, including vision screening for children, diabetic retinopathy screening, ROP screening for pre-mature infants. Smartphone is beneficial for vision health screening can be explained in the following ways. First, smartphone and its accessories for performing diagnostic tests are portable so that there should be minimal logistic problem. Therefore, this facilitates the organization of outreach vision screening for children in rural areas. Secondly, smartphone-based fundus imaging system is much smaller in size when compared to conventional fundus photography. This system can be established in primary health setting or diabetic clinic setting. Also, there is referral function available in smartphone applications. This allows the healthcare providers to refer people for special eyecare services.

Reminder Systems

Forgetfulness is a common reason of medication non-adherence (Masoud et al., 2013; Wolfram et al., 2019; Wong et al., 2006). A cross-sectional survey conducted by Saeedi et al. (2014) found that many glaucoma or ocular hypertension patients agreed that reminders would help them remember medication administration.

For some chronic eye diseases, such as glaucoma, there are many medication options and/ or combinations for diseases, available of mobile medication reminder apps is convenient for such patients. The integration of eye-drop tracking device with reporting system allows their physicians and related healthcare providers to understand patients' the medication instillation status. Clinic staff can provide follow-up actions for patients with poor medication adherence. However, the app cannot monitor the proper use of eye-drop. For example, does the patient instil the eyedrops on the correct eye? Does the patient instil appropriate amount of eye-drops? Does the patient properly instil the eye-drops? The function of eye-drop instillation evaluation should be considered.

CONCLUDING REMARKS

In this review, smartphones assist in eyecare. In this session, some recommendations for future research are given.

First, contact lens assessment is an important optometric service. Although in this study, some publications explore how smartphone plays a role in anterior ocular health imaging, none of these investigate whether smartphone can assist contact lens consultation, such as dry eye assessment, contact lens fitting assessment. Also, whether smartphones can assist in corneal topography remains unclear. Further studies should explore the feasibility of smartphones in assisting corneal topography do that smartphones application in eyecare can extend assessment of special lens design, such as contact lenses for irregular corneas, keratoconus, and ortho keratology.

Secondly, in the data source, how smartphones assisting in fundus imaging focus on diabetic retinopathy, optic disc imaging and ROP. Some authors challenged the low sensitive and/ or specificity of smartphone fundus photography for detecting DR. This may be due to the quality of images captured from the system. Therefore, further studies should be performed to improve the imaging quality and techniques of the systems. Besides, future study should explore the ability of smartphone fundus imaging in assisting examination of other retinal diseases, such as ARMD, CSR, BRVO. On the other hand, risk assessment of stroke by assessing retinal vessels. The feasibility of using smartphones in this health assessment can be considered. This could extend its application in primary care setting, as general practitioners or other non-eyecare professionals can refer diabetic patients with diabetic retinopathy or patients under high risk of stroke to appropriate specialist care.

Thirdly, all publications in the data source only study 1 model of smartphone. To have a better understanding about the generalizability of the hypothesis, future studies should investigate 2 or more models. Also, to increase the popularity of smartphone application, the smartphone-based test app should be invented in both android system and iOS.

Lastly, as smartphones offer a wide range of functions in eyecare, these functions facilitate the development of a comprehensive mobile app for eyecare. The proposed mobile application consists of the following functions. First, it provides ophthalmic diagnostic tests (including VA measurement, refractor, color vision test, CS test, tonometry, perimetry, ocular health imaging and OCT). Some tests can be done by patients themselves and/ or their caregivers in order to achieve home monitoring. Besides, after proper training, non-eyecare professionals can perform the ophthalmic diagnostic tests at an acceptable level of accuracy in order to provide eye health screening. Secondly, with the availability of the test results, eyecare professionals, such as ophthalmologists, optometrists, can provide remote consultation to patients via the mobile applications. Thirdly, reminder systems with sharing function should be designed to remind the patients and their caregivers about medication administration. Meanwhile, the medication reminder containing an eye-drop tracking system, which reports the eye-drop administration record to the healthcare providers. Lastly, the app should provide up-to-date glaucoma education information to raise the public awareness to glaucoma. All these are essential functions to a comprehensive mobile app for glaucoma care.

CONCLUSION

In this study, many publications demonstrate that smartphones assist in ophthalmic diagnostic tests, including VA test, autorefractor, colour vision test, CS test, perimetry, tonometry, anterior and posterior ocular assessment and OCT. Also, the smartphone-based referral system allows healthcare providers to refer people for special eyecare. In addition, some literatures demonstrated how smartphone works as a medication and appointment reminder. The affordable and portable features of smartphones enable them to establish eyecare services in in low- or high-income countries.

The functions of smartphone in eyecare were discussed. First is teleophthalmology, which include remote patient monitoring and remote consultation. Patients can perform home monitoring by doing VA assessment, IOP measurements and perimetry at home. Also, healthcare workers can use smartphone to send their health assessment results to eyecare providers for remote consultation. This type of consultation is also applicable for people who are inaccessible to attend face-to-face consultations. Secondly, smartphone can plays a role in vision health screening programs. After proper training, non-eyecare professionals can perform smartphone-base ophthalmic tests. This allows them to organise screening program, such as vision screening for children, DR screening, ROP screening, to identify individuals who need further medical care, by using smartphone-based referral system. They can also perform fundus imaging for diabetic patients in primary care clinic. Lastly, smartphone can improve patient medication compliance and adherence by its reminder applications.

In future, addition studies should extend the application of smartphone to contact lens assessment, such as the development of smartphone-based corneal topography. Also, smartphone-based fundus imaging should extend to diagnosis of other retinal disease, such as ARMD, CSR. Next, future studies should investigate more the 1 brand of smartphone to have a better understanding of the generalizability of smartphones in certain functions. Besides, it is possible to develop a smartphone application to include ophthalmic diagnosis test, reminder systems and referral system. All these further increase the ability of smartphone in eyecare.

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