Ophthalmol Ther (2023) 12:2281–2293
https://doi.org/10.1007/s40123-023-00764-3

REVIEW

# Telemedicine for Cornea and External Disease: A Scoping Review of Imaging Devices

Binh Cao · Chi H. V. Vu · Jeremy D. Keenan

Received: May 9, 2023 / Accepted: June 23, 2023 / Published online: July 17, 2023


## ABSTRACT

***Objective***: The objective of this scoping review is to understand the extent and type of evidence in relation to telemedicine imaging devices for cornea and external segment conditions.
***Introduction***: The coronavirus pandemic has emphasized the benefits of telemedicine in diagnosing and managing ocular diseases. With the rapid advancement of technology in slit lamp biomicroscopes, smartphones and other ocular surface imaging modalities, telemedicine applications for cornea and external diseases have become an active area of research.
***Inclusion Criteria***: For studies to be included, they had to discuss the concept of imaging devices for cornea and external diseases in the context of telemedicine. There was no restriction on the studied population or participants.
***Methods***: A scoping review was conducted according to an a priori protocol. Documents written in English were identified from the PubMed and Embase databases and searches. Anterior segment imaging devices were then classified into different categories.
***Results***: Anterior segment imaging devices identified in this review included 19 slit lamp-based devices, 17 smartphone-based devices and 15 other devices. These tools can detect a wide variety of cornea and external diseases (e.g., pterygium, conjunctivitis, corneal opacity, corneal ulcer, and blepharitis). Fewer than half of the devices (24/51) were assessed for diagnostic performance. Their diagnostic accuracy varied greatly from condition to condition and from device to device. The inter-rater reliability of different photo-graders assessing images was assessed in only a few studies.
***Conclusions***: Anterior segment imaging devices are promising tools for remote diagnosis and management of patients with cornea and external disease. However, there are significant gaps in the literature regarding the diagnostic accuracy and inter-rater reliability of several devices. Future research with rigorous methods is required to validate the use of these devices in telemedicine settings.

**Keywords:** Cornea and external diseases; Imaging; Scoping review; Telemedicine

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s40123-023-00764-3.

B. Cao · J. D. Keenan (✉)
Francis I. Proctor Foundation, University of California, 490 Illinois St, San Francisco, CA 94158, USA
e-mail: Jeremy.Keenan@ucsf.edu

C. H. V. Vu
Vietnam National Eye Hospital, Hanoi, Vietnam

J. D. Keenan
Department of Ophthalmology, University of California, San Francisco, USA

**Key Summary Points**

Technological advances and the recent coronavirus pandemic have spurred greater interest in telemedicine applications for cornea and external diseases.

Given the rapid emergence of telemedicine imaging devices for cornea and external diseases, we conducted this scoping review to map the scope of literature for this topic.

Anterior segment imaging devices for cornea and external diseases vary from complicated slit lamp cameras to simple smartphones, and have a wide range of diagnostic accuracy.

These devices are promising tools for telemedicine in different use case scenarios, including triaging and training at tertiary health care facilities, diagnosis and management of eye diseases in community-based and primary care clinics, and epidemiologic studies.

Current gaps in the literature with regards to cornea and external segment imaging devices include a lack of rigorous studies assessing diagnostic accuracy, inter-photo-grader repeatability, and inter-device-operator repeatability.

## INTRODUCTION

Interest in the use of telemedicine for diagnosing and managing ocular pathologies has been increasing rapidly over the past several decades, driven in large part by innovations in ocular imaging. The benefits of tele-ophthalmology became apparent to many clinicians during the coronavirus pandemic, spurring even greater awareness of the potential for the use of technologies outside of the hospital to improve health. Advances in tele-ophthalmology have been most notable for posterior segment diseases, with established remote screening programs for diabetic retinopathy and retinopathy of prematurity [1, 2]. Telemedicine applications for cornea and external disease conditions, while not widespread, are an active area of research. The technology required to image the ocular surface is typically simpler and less expensive than that for posterior segment imaging, increasing the range of settings where such telemedicine imaging could take place.

Telemedicine visits in ophthalmology can be either synchronous (real time) or asynchronous (store and forward). Synchronous telemedicine visits require instantaneous transmission of audio and video signals between patients and providers, allowing providers to examine patients and make clinical decisions in real time. In contrast, asynchronous telemedicine visits involve collecting patients' clinical information, including photographs and videos, followed by the forwarding of those data to physicians or reading centers for reviewing before communicating results to patients. Anterior segment imaging can be used both for synchronous and asynchronous telemedicine purposes.

The objective of this paper was to conduct a scoping review to identify the extent of research that has been performed on telemedicine imaging devices for cornea and external segment conditions. Our goal was to highlight the uses of the imaging devices and identify gaps in the evidence base in order to spur more rigorous assessments of these devices going forward.

## METHODS

This study is a scoping review of telemedicine imaging devices for cornea and external disease. Scoping reviews are a relatively new approach that focus on mapping the scope or coverage of a body of literature on a given topic [3]. They are especially useful when a new topic is emerging and it is still unclear what specific questions can be asked. Given the rapid emergence of telemedicine imaging devices for cornea and external disease, a scoping review for this topic is justified. This scoping review was conducted and reported in accordance with the Joanna Briggs Institute (JBI) methodology for scoping reviews and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR) guidelines (Supplementary Material) [4, 5]. A scoping review protocol was developed in advance (Supplementary Material). This review is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

### Data Sources and Search Strategy

The primary sources used were PubMed and Embase. The search term used for this scoping review was (cornea OR "external disease" OR conjunctiva OR "ocular surface" OR "anterior segment") AND (device OR tool OR smartphone OR diagnosis OR imaging OR photography) AND (telemedicine OR tele-medicine OR tele-ophthalmology OR teleophthalmology OR teleconsultation). Additional relevant papers were considered by reviewing the references listed in the included studies and obtaining expert opinion. The search was first performed on 14 January 2023 and again on 14 March 2023 to update new publications.

### Study Selection

To be eligible for inclusion, the article had to discuss imaging devices for cornea and external diseases that were intended for telemedicine applications. There was no restriction on the studied population or date of publication. Titles and abstracts that did not meet the eligibility criteria were excluded. Studies without English text were also excluded. Full-text articles were retrieved for those that met the criteria.

### Data Extraction

Data from full articles, or from abstracts if full texts were not available, were extracted and recorded onto a standardized electronic data collection form. One reviewer (BC) was responsible for extracting data from each study identified in the review, and these were verified by a co-reviewer (JK). Discrepancies were resolved by discussion until a consensus was reached. The following data were recorded if available: description of device, cornea and external segment conditions studied, whether validity was assessed, study setting, sample size, sensitivity, specificity, positive predictive value, negative predictive value, intergrader/interoperator reproducibility, cost, financial interest, and other relevant findings.

### Collating, Summarizing and Reporting Findings

Anterior segment imaging devices were classified into different categories. Categories were discussed by the authors and presented in narrative sections describing the studied conditions, diagnostic accuracy, interoperator/intergrader reproducibility and other relevant information.

## RESULTS

### Study Inclusion

The search identified 123 articles on PubMed and 198 on Embase. After removing overlapping articles between the two databases and duplicate articles within the same database, we identified 218 unique papers. Six additional articles were identified through reviewing bibliographies and expert opinion. Titles and abstracts of 224 studies were screened for inclusion in the review. Based on the information provided in the titles and abstracts, 127 (57%) articles did not meet the inclusion criteria and were excluded. Among the remaining articles, 7 were conference abstracts and 90 were full-text articles. Full-text articles were assessed for eligibility, and 35/90 (39%) were excluded for reasons listed in Fig. 1. In total, 62 articles, including 7 abstracts, were included in this study.

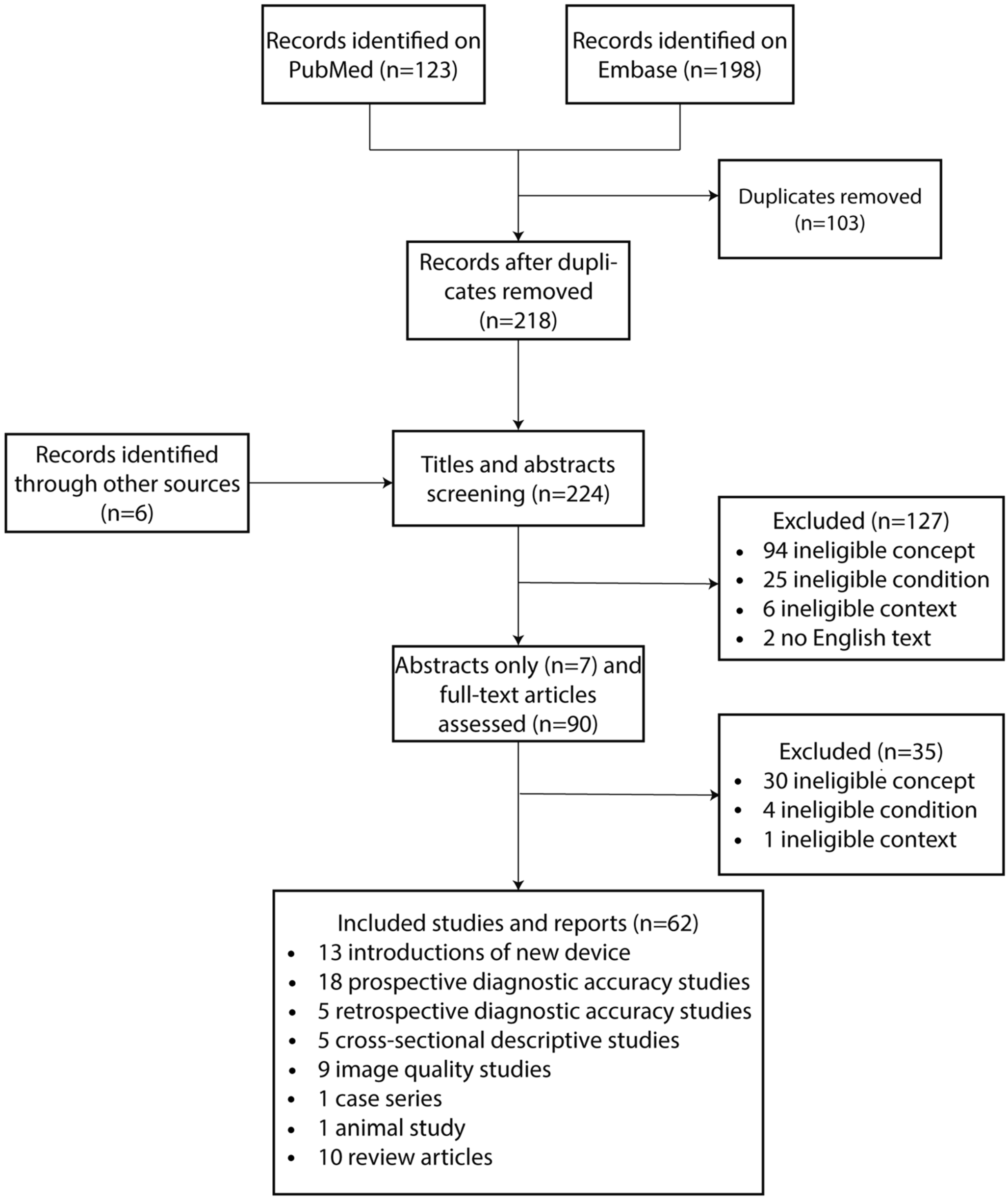


**Fig. 1** Flow diagram

### General Characteristics of Included Studies

The included studies and reports were published between 1998 and 2023 and consisted of introductions of a new device/technique ($n$ = 13) [6–18], prospective diagnostic accuracy studies ($n$ = 18) [19–36], retrospective diagnostic accuracy studies ($n$ = 5) [37–41], cross-sectional descriptive studies ($n$ = 5) [42–46], image quality studies ($n$ = 9) [47–55], a case series ($n$ = 1) [56], an animal study ($n$ = 1) [57], and reviews ($n$ = 10) [58–67]. After excluding the review articles, the largest number of studies were conducted in the United States ($n$ = 13) and India ($n$ = 13) (Fig. 2). The 52 non-review articles discussed a total of 52 devices, which we classified into three categories: slit-lamp-based devices ($n$ = 19), smartphone-based devices ($n$ = 18), and other devices ($n$ = 15). A formal

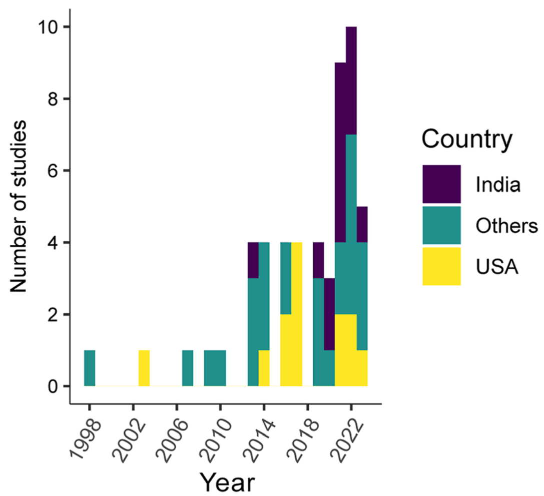


**Fig. 2** Non-review studies about anterior segment imaging devices over time. The plot shows the number of non-review studies published on Pubmed and Embase per year with the search terms (cornea OR "external disease" OR conjunctiva OR "ocular surface" OR "anterior segment") AND (device OR tool OR smartphone OR diagnosis OR imaging OR photography) AND (telemedicine OR tele-medicine OR tele-ophthalmology OR teleophthalmology OR teleconsultation)

assessment of diagnostic accuracy was performed in 23 articles for a total of 25 devices. Of 23 diagnostic accuracy studies, 20 employed photo-graders to interpret the images or video recordings and 3 used artificial intelligence algorithms. The inter-rater reliability of different graders assessing images from a given device was reported in 10 of 20 (50%) diagnostic accuracy studies that used photo-graders, 2 of 9 (22%) image quality studies, and 1 of 5 (20%) descriptive studies. Only the animal study assessed the reproducibility of different photographers for capturing images.

## Slit-Lamp-Based Devices

Nineteen different tools were discussed in 19 papers (Table S1, Supplementary Material). Among these tools, nine were dedicated slit lamp cameras, four were slit lamps equipped with a digital camera (i.e., digital camera assisted), and six were slit lamps equipped with a smartphone or tablet (i.e., smartphone assisted). Most of the devices were studied in hospital settings, except for three studies that were conducted at primary eye care centers.

*Slit lamp cameras*. Of the nine slit lamp camera-based systems, five were studied in real-time telemedicine settings, one of which allowed the remote examiner to take full control of the slit lamp biomicroscope while viewing the images on an LCD screen. The slit lamp cameras could detect a wide variety of cornea and external findings during the eye examination, including epithelial defects, corneal edema, corneal opacification and haze, corneal vascularization, conjunctival injection, pterygium, pinguecula, and blepharitis [15, 19, 21, 24, 27, 33]. The diagnostic accuracy of slit lamp cameras in reference to an in-person slit lamp examination was assessed in four studies. One study found that the traditional (Zeiss) slit lamp camera had moderate to high sensitivity for more obvious findings such as corneal grafts (81%), contact lens (100%), corneal vascularization (79%), corneal edema (67%) and pterygium (70%), but low sensitivity for small and subtle signs such as keratic precipitates (0%), epitheliopathy (0%), conjunctivitis (19%) and blepharitis (31%) [24]. Similarly, other studies from cornea clinics found that slit lamp cameras had high sensitivity (up to 100%) and specificity (up to 100%) for corneal opacity, vascularization, corneal ulcer and pterygium [8, 11]. In pediatric patients, slit lamp cameras generally had higher sensitivity and specificity for corneal diseases than for conjunctival and external diseases [27]. Slit lamp cameras were also used to follow up post-keratoplasty or post-trabeculectomy patients [46, 52]. One study showed that a real-time, remote slit lamp examination provided similar performance to a conventional slit lamp examination in assessing bleb morphology (height, wall thickness, vascularity, horizontal and meridian extent)—kappa ranged from 0.71 to 0.94 depending on the specific bleb characteristic—and was superior to two-dimensional images taken with diffuse illumination [52]. A study that assessed inter-rater reliability found good agreement between two image-graders for abnormalities of the eyelids/eyelashes (76%), conjunctiva/sclera (88%), and cornea (84%) [27]. Despite their generally high diagnostic performance, slit lamp cameras have certain limitations, such as a high cost, limited portability and the need for specialized personnel.

*Conventional slit lamps equipped with a digital camera*. Digital cameras can be attached to the oculars of a conventional slit lamp through an adapter. Such devices were mainly studied to identify corneal disorders such as infectious keratitis and corneal scar. The sensitivity and specificity of these devices have not been reported, although one study reported good agreement between digital-camera-assisted slit lamp photography and in-person slit lamp examination for correctly classifying the ocular surface findings into infectious or inflammatory keratitis/ulcer, corneal scar, corneal/conjunctival neoplasm, trauma or surgical complication (kappas for each of three photo-graders ranged from 0.67 to 1.00) and fair inter-rater reliability (kappas between pairs of photo-graders ranged from 0.53 to 0.83) [28]. A study found that the ease of use and quality of images differed depending on the type of camera installed on the slit lamp [57]. In another study, a vision center in rural South India implemented real-time teleconsultation with ophthalmologists located at the tertiary eye hospital using images taken from digital cameras attached to the slit lamps at the vision centers [43]. A paper reported a device in which the slit lamp was equipped with digital cameras and the slit lamp operator and a remote viewer wore virtual reality headsets, allowing the remote viewer a stereoscopic view of the examination [18].

*Slit lamps equipped with a smartphone*. Adapters have also been developed to attach a smartphone to a slit lamp. Devices have been studied for the diagnosis of a wide variety of pathologies of the eyelid and ocular surface, with one study even reporting the use of a smartphone to assess corneal endothelium density [16]. These devices have mainly been studied in asynchronous telemedicine settings. The diagnostic accuracy of these tools has not been validated, with most reports consisting of descriptions of new instruments with a focus on image quality. In one comparative study, investigators attached a smartphone to a slit lamp biomicroscope via a device known as the anterior imaging module, and reported taking high-quality images with this system just as frequently as a high-end slit lamp camera [48].

### Smartphone-Based Devices

Eighteen different tools were discussed in 26 studies (Table S2, Supplementary Material). Among these tools, four consisted of smartphones without adapters/attachments and the remainder consisted of smartphones with external attachments. The attachments ranged from simple additions such as a headrest or lens attachment to more complex devices incorporating lenses, blue-light and red-free filters, and slit beams. All of the tools were studied in store-and-forward telemedicine settings. Diagnostic accuracy was assessed for nine devices, most often for corneal disorders against in-person slit lamp examination or slit lamp photography. Inter-rater reliability was reported in seven studies. The majority of these studies enrolled patients in hospital-based settings, except for three community-based studies. All devices were intended for use in community or resource-limited settings.

*Smartphones without attachments*. A study assessing the diagnostic accuracy of smartphone photography for trichiasis found that smartphone photography had poor intergrader reproducibility (kappa between two ophthalmologist photo-graders was 0.36 for photographs taken by the study ophthalmologist and 0.21 for photographs taken by the patient's companion) and low sensitivity relative to slit lamp examination (40–51%, depending on the photo-grader) [22]. Smartphone photographs were found to provide accurate diagnosis of pterygium when analyzed by a deep learning model [38]. One study reported that an Apple iTouch had high sensitivity for the detection of corneal ulcers (mean of three photo-graders: 88%) and pterygium (mean 93%) but lower sensitivity for corneal abrasions (mean 74%) and corneal scars (mean 42%) [36].

*Smartphones with attachments*. Several attachments have been invented to enhance the diagnostic accuracy of smartphone photography for eye disorders. Grabi Lite is a universal smartphone attachment with a headrest that allows patients to capture higher-quality images of their own corneas by setting an optimal working distance [49]. Attachments with a cobalt-blue filter have been developed to obtain images of fluorescent-stained corneas [7, 56]. Several attachments have incorporated external macro lenses to improve the magnification of smartphone images. One study reported that the use of smartphones with external lens attachments helped identify an “ocular urgency” in the emergency department with a 93% sensitivity and 82% specificity relative to an ophthalmologist examination [29]. One study compared smartphone photography of the anterior segment with and without an external macro lens attachment in a community setting, and found that the addition of a $5 + 40D macro lens did not improve smartphone photographs of the eyelids, conjunctiva, or cornea [47]. Another small study ($N = 5$ participants) reported that using a low-cost clip-on 10 × macro lens and external illumination with a penlight improved the quality of bleb images relative to the absence of these modifications and provided similar assessments of bleb morphology and area compared with slit lamp photographs [51]. One study reported the design of a smartphone attachment incorporating an external biconvex lens as well as cobalt blue and red-free optical filters [8]. The Smart Eye Camera (SEC), a 3D-printed smartphone attachment with an external convex 20 × lens and a blue light filter for corneal fluorescein staining, has been reported to have a sensitivity of 96% and specificity of 90% for the diagnosis of dry eye disease relative to slit lamp examination when image capture and interpretation was performed by ophthalmologists, and a sensitivity of 78% and specificity of 86% when processed by a deep learning algorithm [40, 41]. SEC images interpreted for conjunctival hyperemia have also been reported to have high correlation with slit lamp examination [55]. The Cornea CellScope, a 3D-printed smartphone attachment with an external + 25D lens and light-emitting diode (LED) light sources, has been reported to provide good inter-rater reliability and acceptable diagnostic accuracy compared with slit lamp examination both for corneal opacities (e.g., a sensitivity of 68% and specificity of 97% using the default smartphone camera settings) and for corneal abrasions (e.g., a sensitivity of 89% and a specificity of 91% when using a blue light filter on a fluorescein-stained eye) [23, 25]. The CellScope device has also been used to photograph the everted superior tarsal conjunctiva for community trachoma surveillance [32]. More advanced optical systems have been developed for smartphone attachments designed to be used as handheld slit lamp cameras [9]. One such attachment allows patients to take slit lamp videos of their own eyes; this device was reported to correctly identify the presence or absence of corneal pathology in 74% of eyes relative to a slit lamp examination [17, 34].

### Other Devices

*Handheld fundus cameras*. Several commercially available handheld fundus cameras have attachments for anterior segment photography (Table S3, Supplementary Material). The Volk Pictor (Volk Optical Inc., Mentor, OH, USA), a handheld anterior segment and non-mydriatic fundus camera, was reported to detect “critical anterior segment exam findings” in the emergency setting with a sensitivity of 89% relative to slit lamp examination [31]. The Pictor Plus was reported to detect the presence of “anterior segment pathology” in the emergency and inpatient setting with a sensitivity of 71% and specificity of 81% relative to the medical record [35]. Similar estimates of sensitivity were reported for the Nidek Versacam relative to slit lamp examination for corneal abrasions (mean of three photo-graders: 82%), corneal ulcers (mean 92%), and pterygium (mean 97%), although sensitivity was lower for corneal scars (mean 50%) [36]. Other investigators have found lower sensitivity, including a study of the Canon CR-2 Plus AF (Tokyo, Japan) that reported a 13% sensitivity for corneal findings and 31% sensitivity for pterygium [30].

*Single lens reflex (SLR) cameras*. A digital SLR camera can be equipped with a macro lens to take photographs of the cornea and ocular surface. An SLR camera was reported to have a sensitivity of 59% and specificity of 97% for corneal opacity, with high inter-rater agreement (intraclass coefficient [ICC] = 0.94) and intra-rater agreement (ICC = 0.98) [23]. When graded by a deep learning algorithm (ResNet), photographs from handheld digital cameras have been reported to detect bacterial and fungal keratitis with a sensitivity of 70% and 80%, respectively [39].

*Portable slit lamp cameras*. Several devices allow a portable slit lamp to capture images or videos. Videos taken with the Microclear digital hand-held slit lamp (Suzhou, China) were reported to have low sensitivity relative to slit lamp examination for corneal abnormalities (15%), pinguecula (21%), pterygium (38%) and conjunctival abnormalities (14%) [30]. A study of a custom-made portable slit-lamp video camera with a fixed-width slit beam reported low sensitivity relative to a slit lamp examination for subtle corneal, conjunctival and lid abnormalities, but higher sensitivity for more obvious corneal findings such as corneal edema (67%) and corneal vascularity (69%)—similar to results observed for the traditional (Zeiss) slit lamp camera [24].

*Wearable headset cameras*. One paper described a prototype in which autofocus sensors and external cameras were attached to an augmented reality headset. Video recordings from this system generally had poor sensitivity for correctly identifying anterior segment pathologies relative to a medical record review [20].

*Topography*. One study reported that a tabletop topographer allowed a remote assessment of the progression of keratoconus with a sensitivity of 69% and a specificity of 96% relative to a clinical exam [37].

## DISCUSSION

This scoping review aimed to examine the extent of research on imaging devices used to screen or diagnose cornea and external diseases in telemedicine settings. Imaging devices identified for this review included dedicated slit lamp cameras, camera attachments for slit lamps, smartphone-based devices, anterior segment modules for handheld retinal cameras, and a handful of other devices. Reports included the use of both synchronous and asynchronous telemedicine applications. Most studies did not report diagnostic accuracy. Many of the studies that did assess diagnostic accuracy reported the diagnostic accuracy in terms of a correct diagnosis of any eye pathology as opposed to a specific disease. A smaller number of studies reported the diagnostic accuracy for specific cornea and external disease conditions. Relatively few studies examined the intra- or inter-rater reliability of the graders assessing the images. Only one study assessed the reproducibility of imaging results when performed by different photographers.

Several use cases for an imaging device of the cornea and external segment were identified in this review. In the context of the hospital, the main functions of a device would likely be for triaging and training. For example, non-ophthalmologists could use a device to capture images of a red eye and send them to an ophthalmologist for triage advice. Ophthalmology residents could use a device to communicate findings with attending physicians on call or to document findings for presentations. In the community context, imaging devices could be used for individual patient care and also for public health activities. For example, patients could image their own eyes, facilitating remote diagnosis and management—a capability that could prove useful in the case of another pandemic. Non-ophthalmic providers at primary care clinics or vision centers could use a device in a synchronous telemedicine program to help diagnose and manage corneal ulcers and other ocular surface conditions. Devices could also be used for epidemiologic studies assessing the prevalence of important causes of blindness such as corneal opacity and trachoma.

Each of the imaging devices has advantages and disadvantages. Dedicated slit lamp cameras are able to capture a wide variety of pathologies at all levels of the anterior segment, and allow multiple forms of illumination (e.g., diffuse direct illumination, fine slit beam illumination, retro-illumination, sclerotic scatter), but are relatively complicated to operate and require an experienced and technical photographer. Attaching a camera to the oculars of a slit lamp is slightly less technical, although it requires a user familiar with operating a slit lamp. Any imaging modality based on a traditional slit lamp will be expensive and not portable. However, slit lamps are often already present in emergency departments, and eye hospitals, especially in South Asia, often have outreach centers staffed by non-ophthalmologist personnel that are equipped with slit lamps. Slit-lamp-based imaging would be viable in such settings. Smartphone-based devices are much less expensive, more portable, and simpler to operate. However, there is variability in the quality of native smartphone cameras. A wide variety of external smartphone attachments have been developed to improve smartphone images of the anterior segment, including external macro lenses, blue light filters, and external light sources. These smartphone attachments offer often inexpensive upgrades to the images capable of being captured with a smartphone. In addition, smartphone camera technologies are constantly evolving and improving. Some newer smartphones have native macro lenses, which may increase the quality of images of the cornea and external segment. The ease of use and low cost of smartphone-based devices make them promising candidates for tele-ophthalmology in community-based and resource-limited settings.

This review identified some gaps in the current literature on cornea and external disease imaging for telemedicine. Many of the devices (21 of 52) have not been compared to a reference standard test, making it difficult to judge their utility. Of those studies that have assessed diagnostic performance, 87% (20 of 23) reported sensitivity and/or specificity and the others reported a single estimate of diagnostic accuracy (e.g., percentage of cases classified as a true positive or true negative; Cohen's kappa comparing the index test and reference standard). The sensitivity and specificity would provide more useful information. None of the articles mentioned the Standards for Reporting Diagnostic Accuracy (STARD) statement, a guideline for reporting studies of diagnostic accuracy [68]. More than a third of the diagnostic accuracy studies that employed photo-graders (8 of 20) did not mention if photo-graders were masked to the results of the reference standard test, raising the possibility of biased assessments of diagnostic accuracy. Few studies reported the inter-rater reliability of different photo-graders, and only one study reported the inter-rater reliability of different photographers. Although the majority of these devices were intended for use in community-based, rural, or limited-resource settings, studies were mostly conducted in hospital-based settings. Whether the findings from the hospital-based studies can be applied or extrapolated to the communities remains to be seen. Very few studies compared different imaging devices head-to-head, making it difficult to determine if a particular device is superior to another. Finally, very few studies included the actual costs of the devices. Some studies described costs qualitatively (i.e., high costs vs. low costs), but such descriptions can have different meanings in different settings.

This review has limitations. The literature search was primarily done on the general databases PubMed and Embase, which may not include all available relevant literature, especially those in the engineering field. We only selected articles that emphasized the telemedicine applications of the studied imaging devices, and thus may have omitted papers in which the device's telemedicine function was not expressly highlighted in the text. As this is a scoping review, we did not formally assess the quality or bias of published studies. However, we speculate that the reported results for device performance may be optimistic since poorly performing devices were probably less likely to be reported and the authors of several studies had a financial interest in the devices. The focus of the review was limited to devices for cornea and external disease. The literature search identified papers that used anterior segment imaging for the detection of narrow angles and cataract, but these were considered outside the scope of the present review. For similar reasons, the review did not specifically focus on the use of artificial intelligence for image grading. Most of the studies included in this review reported the diagnostic accuracy based on human assessment of the images/videos, although we anticipate that artificial intelligence algorithms will be an increasingly important part of telemedicine in the future.

## CONCLUSIONS

In conclusion, anterior segment imaging devices are promising tools for remote diagnosis and management of patients with cornea and external diseases. A wide variety of devices are available, allowing imaging from a slit lamp, a handheld device, or a headset. Many of the devices can be used for either synchronous or asynchronous telemedicine applications. Further research with rigorous methods would be helpful to determine valid estimates of diagnostic accuracy for specific ocular diseases, to determine the inter-rater reliability when used by different people, and to determine the feasibility and accuracy of devices when used in the community.

## ACKNOWLEDGEMENTS

The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or University of California Global Health Institute.

***Funding.*** This project was conducted during the fellowship time of the author Binh Cao, who was supported by the Fogarty International Center of the National Institutes of Health (award number D43TW009343) and the University of California Global Health Institute. The work was also supported by the All May See Foundation, Research to Prevent Blindness, Harold Varmus, MD Endowed Fund for Global Health Scholars, and UCSF School of Medicine Yearlong Research Fellowship. No funding or sponsorship was received for the publication of this article.

***Author Contributions.*** Jeremy Keenan had the idea for the article. Jeremy Keenan and Binh Cao performed the literature search and data analysis. Binh Cao drafted the manuscript. Jeremy Keenan and Chi Hoang Viet Vu critically revised the work.

***Disclosure.*** Binh Cao, Chi Hoang Viet Vu and Jeremy Keenan declare no conflicts of interest.

***Compliance with Ethics Guidelines.*** This review is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

***Data Availability.*** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.



## REFERENCES

1. Brady CJ, D'Amico S, Campbell JP. Telemedicine for retinopathy of prematurity. Telemed e-Health. 2020;26:556–64.

2. Horton MB, et al. Practice guidelines for ocular telehealth-diabetic retinopathy, third edition. Telemed e-Health. 2020;26:495–543.

3. Munn Z, et al. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol. 2018;18:143.

4. Peters MDJ, et al. Best practice guidance and reporting items for the development of scoping review protocols. JBI Evid Synthesis. 2022;20: 953–68.

5. Tricco AC, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med. 2018;169:467–73.

6. Barsam A, Bhogal M, Morris S, Little B. Anterior segment slitlamp photography using the iPhone. J Cataract Refract Surg. 2010;36:1240–1.

7. Chandrakanth P, et al. Smartphone co-aided cobalt blue anterior segment with intraocular lens photography. Indian J Ophthalmol. 2023;71:290–3.

8. Chiong HS, Fang JLL, Wilson G. Tele-manufactured affordable smartphone anterior segment microscope. Clin Exp Optom. 2016;99:580–2.

9. Dutt S, et al. Design and performance characterization of a novel, smartphone-based, portable digital slit lamp for anterior segment screening using telemedicine. Transl Vis Sci Technol. 2021;10:29.

10. Ifantides C, Naids S. New lens converts smartphone into portable slit lamp. Invest Ophthalmol Vis Sci. 2016;57:1683.

11. Loomba A, et al. Use of a tablet attachment in teleophthalmology for real-time video transmission from rural vision centers in a three-tier eye care network in India: EyeSmart cyclops. Int J Telemed Appl. 2019. https://doi.org/10.1155/2019/5683085

12. Mohammadpour M, Mohammadpour L, Hassanzad M. Smartphone assisted slit lamp free anterior segment imaging: a novel technique in teleophthalmology. Cont Lens Anterior Eye. 2016;39:80–1.

13. Myung D, Jais A, He L, Chang RT. Simple, low-cost smartphone adapter for rapid, high quality ocular anterior segment imaging: a photo diary. JournalMTM. 2014;3:2–8.

14. Puthalath AS, Gupta N. An innovative filter for smartphones in tele-ophthalmology. Indian J Med Res. 2020;152:22–3.

15. Shimmura S, Shinozaki N, Fukagawa K, Shimazaki J, Tsubota K. Real-time telemedicine in the clinical assessment of the ocular surface. Am J Ophthalmol. 1998;125:388–90.

16. Toslak D, Thapa D, Erol MK, Chen Y, Yao X. Smartphone-based imaging of the corneal endothelium at sub-cellular resolution. J Mod Opt. 2017;64:1229–32.

17. Truong P, et al. A smartphone attachment for remote ophthalmic slit lamp examinations. Microsyst Technol. 2020;26:3403–7.

18. Vora P, Bader J, Higgins E, De Carvalho AB. Novel camera device for enhanced stereoscopic ophthalmology exams and teaching. Invest Ophthalmol Vis Sci. 2022;63:4456-F0135.

19. Bar-Sela SM, Glovinsky Y. A feasibility study of an Internet-based telemedicine system for consultation in an ophthalmic emergency room. J Telemed Telecare. 2007;13:119–24.

20. Diego A, Abou Shousha M. Portable anterior eye segment imaging system for teleophthalmology. Transl Vis Sci Technol. 2023;12:11.

21. Gupta SC, Sinha SK, Dagar AB. Evaluation of the effectiveness of diagnostic & management decision by teleophthalmology using indigenous equipment in comparison with in-clinic assessment of patients. Indian J Med Res. 2013;138:531–5.

22. Kamano G, Bellote FL, de Oliveira PRR, Schellini SA. Telemedicine as an auxiliary tool in trichiasis treatment follow-up. Arq Bras Oftalmol. 2022;85: 427–8.

23. Kumar A, et al. Smartphone-based anterior segment imaging: a comparative diagnostic accuracy study of a potential tool for blindness prevalence surveys. Ophthalmic Epidemiol. 2022;29:491–8.

24. Kumar S, Yogesan K, Constable IJ. Telemedical diagnosis of anterior segment eye diseases: validation of digital slit-lamp still images. Eye (Lond). 2009;23:652–60.

25. Maamari R, et al. A novel telemedicine device for diagnosis of corneal abrasions and ulcers in resource-poor settings. JAMA Ophthalmol. 2014;132:894.

26. Mamtora S, et al. A smartphone lens attachment improves the quality of referrals to eye casualty. Eye (Lond). 2022. https://doi.org/10.1038/s41433-022-02233-w.

27. Mulchandani D, et al. Evaluation of digital slit-lamp videos for paediatric anterior segment telemedicine consultations. J Telemed Telecare. 2021. https://doi.org/10.1177/1357633X21990991.

28. Peeler CE, et al. Telemedicine for corneal disease in rural Nepal. J Telemed Telecare. 2014;20:263–6.

29. Ribeiro AG, Rodrigues RAM, Guerreiro AM, Regatieri CVS. A teleophthalmology system for the

diagnosis of ocular urgency in remote areas of Brazil. Arq Bras Oftalmol. 2014;77(4):214–8.

30. Schott B, Zhu A, Szirth B, Habiel M. Validation of portable slit lamp videos and anterior segment photographs as telemedicine modalities. Invest Ophthalmol Vis Sci. 2022;63:4100-F0064.

31. Sieber M, Shahlaee A, Adam MK, Cohen M, Federman JL. Quality and utility of a portable anterior segment and non-mydriatic fundus camera linked to a smartphone-based virtual consultation platform. Invest Ophthalmol Vis Sci. 2017;58(8):4840.

32. Snyder BM, et al. Smartphone photography as a possible method of post-validation trachoma surveillance in resource-limited settings. Int Health. 2019;11:613–5.

33. Tan JCH, Poh EWT, Srinivasan S, Lim TH. A pilot trial of tele-ophthalmology for diagnosis of chronic blurred vision. J Telemed Telecare. 2013;19:65–9.

34. van der Star L, et al. First clinical experience with ophthalmic e-device for unaided patient self-examination during COVID-19 lockdown. Cornea. 2022;41:353–8.

35. Woodward MA, et al. Telemedicine for ophthalmic consultation services: use of a portable device and layering information for graders. J Telemed Telecare. 2017;23:365–70.

36. Woodward MA, et al. Teleophthalmic approach for detection of corneal diseases: accuracy and reliability. Cornea. 2017;36:1159–65.

37. Barequet D, et al. Evaluation of a telemedicine model for following keratoconus patients in the era of COVID-19 pandemic. Telemed J E Health. 2022;28:1023–7.

38. Liu Y, et al. Accurate detection and grading of pterygium through smartphone by a fusion training model. Br J Ophthalmol. 2023. https://doi.org/10.1136/bjo-2022-322552.

39. Redd TK, et al. Automated differentiation of bacterial from fungal keratitis using deep learning. Invest Ophthalmol Vis Sci. 2021;62(8):2161.

40. Shimizu E, et al. Artificial intelligence to estimate the tear film breakup time and diagnose dry eye disease. Sci Rep. 2023;13:5822.

41. Shimizu E, et al. Smart eye camera: a validation study for evaluating the tear film breakup time in human subjects. Trans Vis Sci Tech. 2021;10:28.

42. De Andrade Coelho M, et al. TelemeDicine as a useful tool for referrals to eye care services in a remote city of the Brazilian Amazon. Invest Ophthalmol Vis Sci. 2014;55:5882.

43. Komal S, Radhakrishnan N, Vardhan SA, Prajna NV. Effectiveness of a tele-ophthalmology vision center in treating corneal disorders and its associated economic benefits. Cornea. 2022;41:688–91.

44. Misra N, et al. Role of teleophthalmology to manage anterior segment conditions in vision centres of south India: EyeSmart study-I. Indian J Ophthalmol. 2020;68:362–7.

45. Nesemann JM, et al. Telemedicine for screening eye disease in the remote Peruvian Amazon: proof-of-concept. Trans R Soc Trop Med Hyg. 2022;116:589–91.

46. Siregar SR, Ardiani LS, Chua A, Chong BYQ, Tan DTH. Establishing a virtual corneal clinic: a real-time teleophthalmology approach. Cornea. 2023;42:376–82.

47. Bhatter P, et al. Using a macro lens for anterior segment imaging in rural Panama. Telemedicine e-Health. 2020;26(11):1414–8.

48. Dutt S, et al. A novel approach to anterior segment imaging with smartphones in the COVID-19 era. Indian J Ophthalmol. 2021;69:1257–62.

49. Joshi VP, Jain A, Thyagrajan R, Vaddavalli PK. Anterior segment imaging using a simple universal smartphone attachment for patients. Semin Ophthalmol. 2022;37:232–40.

50. Kalra G, et al. A pilot study for smartphone photography to assess bleb morphology and vasculature post-trabeculectomy. Int Ophthalmol. 2021;41:483–90.

51. Kalra G, Ichhpujani P, Thakur S, Sharma U. Ideal illumination for smartphone-based trabeculectomy bleb photography. J Ophthalmic Vis Res. 2021;16:357–66.

52. Kashiwagi K, et al. Comparison of a remote operating slit-lamp microscope system with a conventional slit-lamp microscope system for examination of trabeculectomy eyes. J Glaucoma. 2013;22:278–83.

53. Otero C, García-Porta N, Tabernero J, Pardhan S. Comparison of different smartphone cameras to evaluate conjunctival hyperaemia in normal subjects. Sci Rep. 2019;9:1339.

54. Xia T, Szirth B, Khouri AS. Anterior segment smartphone imaging quality in telemedicine. Invest Ophthalmol Vis Sci. 2016;57:5930.

55. Yazu H, et al. Clinical observation of allergic conjunctival diseases with portable and recordable slit-lamp device. Diagnostics. 2021;11:535.

56. Puthalath AS, et al. Cobalt blue light unit filter—a smartphone attachment for blue light photography. Indian J Ophthalmol. 2021;69:2841–3.

57. Simon DP, Thach AB, Bower KS. Teleophthalmology in the evaluation of ocular trauma. Mil Med. 2003;168:205–11.

58. Alawa KA, Sales CS. Alleviating an increasingly burdened healthcare system with telemedicine: anterior segment. Ophthalmol Ther. 2021;10: 225–9.

59. Alexopoulos P, Madu C, Wollstein G, Schuman JS. The development and clinical application of innovative optical ophthalmic imaging techniques. Front Med. 2022;9.

60. Armstrong GW, Kalra G, De Arrigunaga S, Friedman DS, Lorch AC. Anterior segment imaging devices in ophthalmic telemedicine. Semin Ophthalmol. 2021;36:149–56.

61. Bolster NM, Giardini ME, Livingstone IA, Bastawrous A. How the smartphone is driving the eye-health imaging revolution. Expert Rev Ophthalmol. 2014;9:475–85.

62. Cui T, Yun D, Wu X, Lin H. Anterior segment and others in teleophthalmology: past, present, and future. Asia Pac J Ophthalmol (Phila). 2021;10: 234–43.

63. Giardini ME, Livingstone IAT. Extending the reach and task-shifting ophthalmology diagnostics through remote visualisation. Adv Exp Med Biol. 2020;1260:161–74.

64. Hu WF, Lorch AC. Teleophthalmology for anterior segment disease. Int Ophthalmol Clin. 2019;59: 55–67.

65. Sommer AC, Blumenthal EZ. Telemedicine in ophthalmology in view of the emerging COVID-19 outbreak. Graefes Arch Clin Exp Ophthalmol. 2020;258:2341–52.

66. Tang RA, Morales M, Ricur G, Schiffman JS. Telemedicine for eye care. J Telemed Telecare. 2005;11: 391–6.

67. Yuen J, Pike S, Khachikyan S, Nallasamy S. Telehealth in ophthalmology. In: Linwood SL, editor. Digital health. Brisbane: Exon Publications; 2022.

68. Cohen JF, et al. STARD 2015 guidelines for reporting diagnostic accuracy studies: explanation and elaboration. BMJ Open. 2016;6: e012799.