

Design and Performance Characterization of a Novel, Smartphone-Based, Portable Digital Slit Lamp for Anterior Segment Screening Using Telemedicine

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Purpose: Telemedicine-enabled, portable digital slit lamps can help to decentralize screening to close-to-patient contexts. We report a novel design for a portable, digital slit lamp using a smartphone. It works on an advanced optical design and has the capability of instantaneous, objective photodocumentation to capture anterior segment images and is telemedicine-enabled.

Methods: The device is constructed keeping its usability and the importance of design ergonomics for nonspecialized field personnel in mind. The optical design is described, and the resolution and magnification are compared with traditional desktop-based slit lamps. A Health Insurance Portability and Accountability Act (HIPAA)-compliant, patient management software is integrated to synchronize the captured images with a secure cloud server along with a sharpness algorithm to extract the best focused frames of the cornea, iris, and lens, from videos. We demonstrate its photodocumentation ability and teleophthalmology feasibility by capturing images in a pilot study from nine subjects.

Results: Images were obtained in various illumination, magnification, and filter settings. Synchronous and asynchronous teleophthalmology consults were conducted. The performance of the device was shown to be limited by the smartphone sensor resolution and not the optical design, because the Air Force target resolution was found to be the same on smartphone-mounted traditional slit lamps despite a lower magnification.

Conclusions: The novel, portable, digital slit lamp with advanced optical design using smartphones has the ability to screen for anterior segment pathologies using telemedicine.

Translational Relevance: A portable, telemedicine-friendly, ergonomically designed, slit lamp used by nonspecialist personnel allows for both synchronous and asynchronous modes of consultation at remote locations, facilitating mass screening programs.

Introduction

Slit-lamp biomicroscopy is the gold standard for examining anterior segment pathologies.^{1,2} Slit lamps can provide a range of thin slit beams that can be used to focus specifically on optical sections like those in the cornea and lens, to understand pathologies and screen patients better.³ However, owing to their

bulky design, high cost of ownership, and complexity of use, professional slit lamp cameras are limited to be used in specialized clinics and hospitals. Their fixed installations conventionally require patients to visit the clinic and adjust themselves on slit-lamp chin rests for examinations. This process presents a problem in monitoring the eye health of populations in remote regions as well those with limited mobility, such as those with disability and in emergency wards.

From a public health perspective, 32 million people suffer from total blindness or severe visual impairment owing to anterior segment diseases globally, such as cataract, refractive errors, corneal opacities, and infectious diseases.^{4–9} Telemedicine-enabled portable digital slit lamps can help to decentralize screening to close-to-patient contexts such as public health centers, primary care centers, pharmacies, and even in the convenience of a patient's home, as may be warranted during the case of the current coronavirus disease 2019 (COVID-19) pandemic. Simpler, cost-effective, and ergonomically designed portable digital slit lamps can thus help to decentralize the screening and management of anterior segment diseases.

The operational simplicity of smartphones, with consistent advances in camera technology and image processing, make them suitable for imaging in ophthalmology for screening as well as for certain diagnostic imaging. Another key feature of smartphones is that their seamless integration with cloud connectivity facilitates scalable telehealth opportunities. This feature includes remote synchronous and asynchronous teleconsultations for regular eye care, postsurgical monitoring as well as in emergency care contexts.^{4,6–9}

In this study, we report a novel design for a portable digital slit lamp (PSL D20) that works on an advanced optical design and documents images instantly with the help of a smartphone. We have focused specifically on design ergonomics to make it usable by nonspecialized health care workers, with minimum training. The key challenge in anterior segment imaging using a slit lamp has often been the small depth of focus between the planes of the iris, lens, and the cornea. This feature makes it very difficult to use such devices in a handheld mode. The Remidio PSL D20 device uses an on-phone image processing algorithm that automatically extracts frames with peak sharpness from videos to produce the best possible images where the lens, iris and cornea may be independently in focus. This effectively decreases or, in many cases, eliminates defocused images. We have compared the performance of the PSL D20 device with that of traditional digital slit lamps, from a resolution perspective. The device comes with a built-in, HIPAA compliant patient management software that synchronizes the images with a secure cloud server. It is telemedicine friendly, allowing for even a synchronous use with screen mirroring over third-party video applications like Zoom, Google Meet, and Webex and can be used effectively to bridge the existing screening gaps in delivery of quality health care, especially in the COVID-19 era.

Methods

Optical Design and Hardware

We designed the portable, digital slit lamp, consisting of an optomechanical module swiveling on a guide-way, constituting the illumination system and a linear imaging module developed on a smartphone-based design (Fig. 1). It has separate paths for illumination and imaging to get clear images of the anterior segment, devoid of artefacts. Light from the multicolor LED source passes through the condenser lens as a single convergent beam and then through the illumination lens. It is then reflected via an anti-reflection-coated right-angled prism to illuminate the eye. The entire illumination set-up is mounted on a slit swiveling system that can be rotated to 45° on both sides, depending on the physician's requirement. The reflected ray then passes along the imaging plane, crossing two sets of imaging lenses, to be captured by the smartphone, post an optical magnification. The slit width can be controlled between 0 and 12 mm. The length of the slit is fixed at 12 mm. Instant photodocumentation is done on a smartphone (we tested the device on both iPhone 7 and iPhone SE 2020 because they have nearly similar features in terms of the camera resolution) (Apple Inc., Cupertino, CA). Both phones use the Sony Exmor RS sensors (Sony Corporation or Sonī kabushiki kaisha, Tokyo, Japan). The PSL D20 captures images at a resolution of 4032 × 3024 pixels (approximately 12 megapixels), uses a sensor with a pixel size of 1.22 μm and a contrast ratio of 1400:1. The resulting image is viewed on the phone screen with a resolution of 750 × 1334 pixels and a pixel density of approximately 326 ppi, and can also be screen mirrored via an Apple TV.

We focused on a user research-based approach for designing the PSL D20, with the aim to make it as ergonomic as possible. Initial prototypes were tested for ergonomic handling and ease of use among health workers, paramedics in the field and optometrists and ophthalmologists in hospitals (Fig. 2A). Because a good grip determines the ease of use of the device, we prototyped several handle designs inspired from common everyday objects with proven designs, such as handheld tape dispensers. Once we narrowed on two options, a 3-dimensional (3D) printed version was given to a set of people with varying hand sizes. Given that the average hand length (perpendicular to the wrist) was measured to be 170 mm (for adult women) and 180 mm (for adult men),^{10,11} a pilot set of 12 volunteers were chosen with hand measurements ranging from 160 to 190 mm (Fig. 3) to express their views

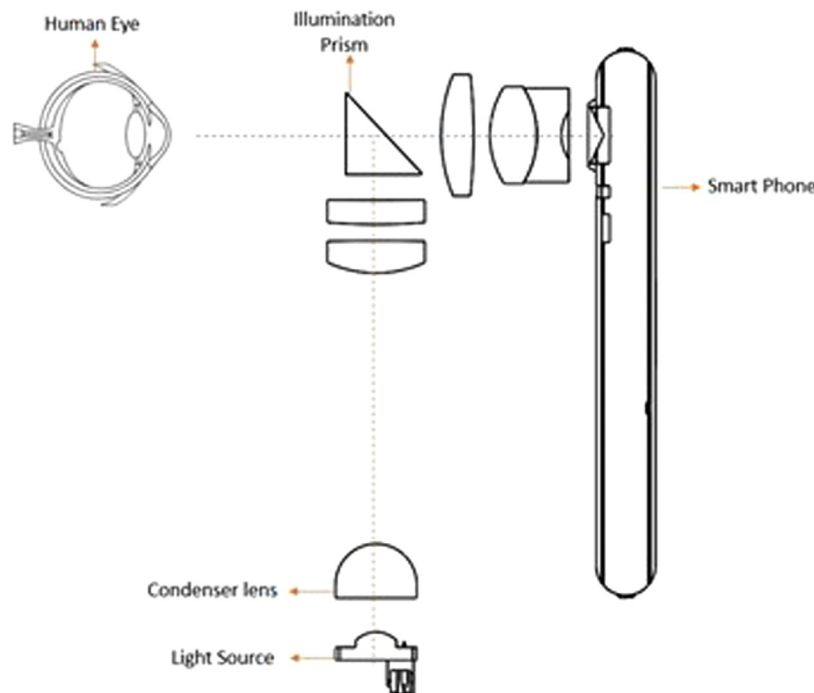


Figure 1. Optical design of the digital Portable Slit lamp Remidio PSL D20.

on the ease of handling and the grip while using the device in the field. Keeping their responses in mind, we decided the final dimensions of the handle and design of the grip. This user-based approach helped us to design a compact, portable, easy-to-use, and light-weight device without compromising on its image quality.

The device dimensions are $201 \times 157 \times 245$ mm and it weighs in just under 500 g. The battery, electronic components, and the illumination optics have been arranged in a compact, linear design to fit within the handle of the device. The handle diameter comes comfortably within the grip of a single hand (Figs. 4 and 5). This feature, makes it much smaller than the available, high-end portable slit lamps. The device has an adjustable headrest for convenience of (manual) focusing, with a $4\times$ optical magnification. This feature makes the object of focus visible clearly on the phone screen, contributing to the stability of the device and allowing easy capture of images just by looking at the phone screen instead of a binocular in most high-end portable slit lamps, (Fig. 6). The background light has three variants—white LED, blue, and green—to suit specific examination techniques. One can effectively operate the PSL D20 using four controls: a button to toggle between background illumination lights, a button to capture the image, and a knob to adjust the slit beam intensity; the three fall comfortably within

the grasp of the thumb (Fig. 5). A knob to adjust the variable slit width is located on the swiveling optomechanical unit, underneath the prism. The controls make it convenient for the user to adjust to the ambient light conditions when imaging a patient's eye. The optomechanical illumination unit is supported by a pair of ball spring plungers to provide the necessary friction and prevent variation of angles when a patient is being examined. The design ergonomics make PSL D20 stand out among other portable slit lamps. When not in use, the device is mounted on a docking station (Fig. 4).

The PSL D20 houses a rechargeable lithium ion battery with a customized circuit board having a microcontroller, a Bluetooth module (Nordic semiconductors, Trondheim, Oslo, Norway), a pair of current-controlled LED drivers, battery management controller, power supply, and indicator LEDs. External, multicolor LED light sources, compliant to ISO 15004–1 and –2 standards for light hazard protection were used for the PSL D20. Using external light sources helped in varying the intensity of the slit beam, implementing diffuse illumination on the same device, maneuvering of the slit angle between 0° and 45° on each side, thus allowing for different illumination techniques, and achieving an overall bright illumination system, mimicking the mode of action of standard slit lamps. The PSL D20 is rechargeable,



Figure 2. (A) The initial prototypes for the PSL D20 designed based on ease of handling. From a design that required both hands for operation, we deduced a design which was suitable for one-handed use. (B) A line of handles prototyped for ease of use for the PSL.

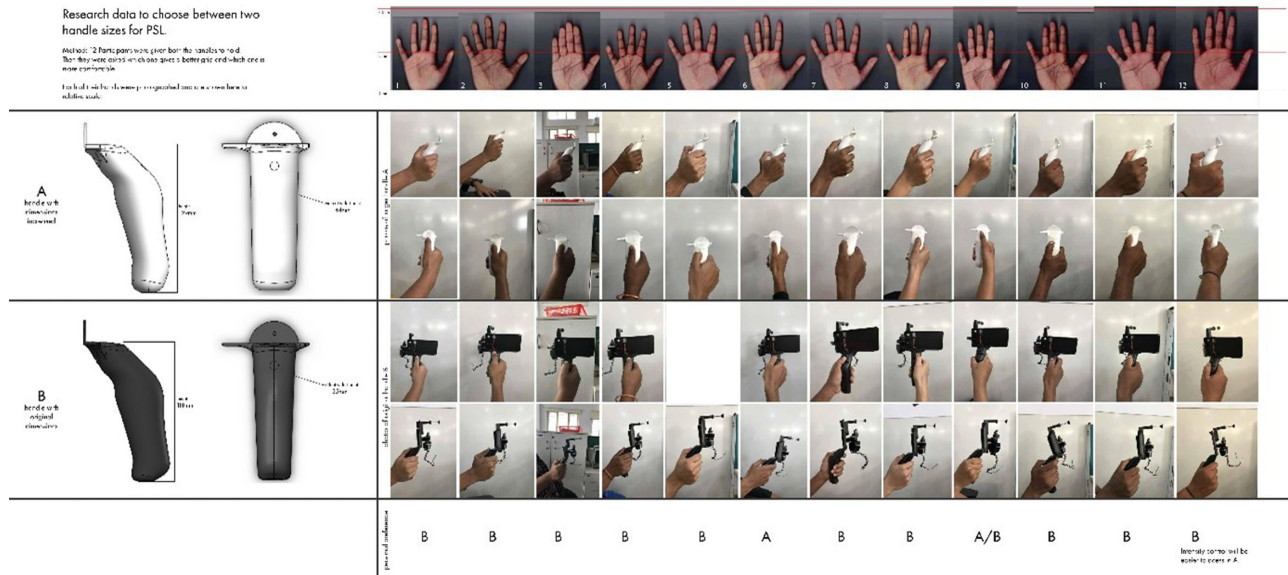


Figure 3. The PSL D20 was designed keeping ease of handling and operational simplicity in mind. A pilot set of volunteers were surveyed with differing hand grip measurements before the arriving at an ergonomic design.

with a charging time of 3 hours and a battery life of minimum 5 hours (assuming continuous use of the device). To ensure optimum in-field battery use, the device automatically switches to a sleep mode after 5 minutes of inactivity.

The PSL D20 works on an intelligent acquisition software. It allows users to manually focus on the desired part of the eye and capture images instantly, depending on the distance of the imaging lens from the part of the eye of interest, similar in optical design to a

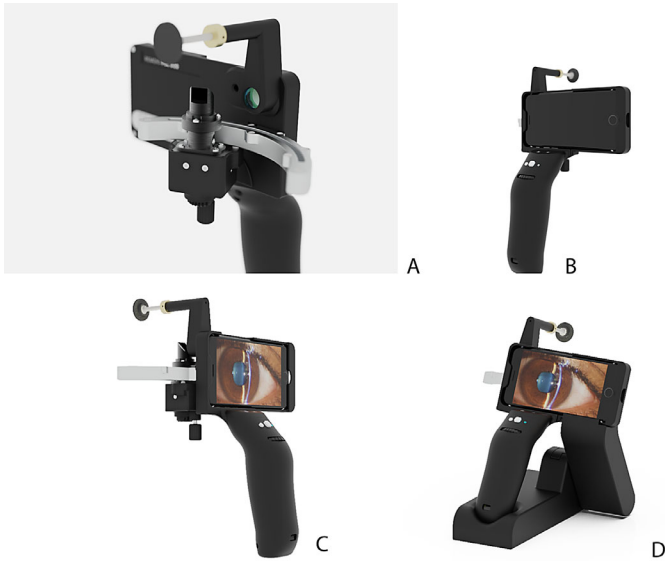


Figure 4. PSL D20 hardware design with a swiveling illumination system.



Figure 5. PSL D20, with an ergonomic design can be operated with one hand with minimum hassles.

traditional fixed focus desktop slit lamp. The focus on the phone is thus driven by the focus of the portable digital slit lamp without further adjustments. This ensures that the physician sees and captures exactly what one chooses to focus on, be it the lens, iris, or the cornea, ensuring imaging objectivity. The working distance (between the patient's eye and the objective lens) is 61 mm (Fig. 5). The smartphone-based display also ensures that the physician can remain physically distanced during the COVID-19 pandemic with a minimum distance of 0.6 m from the patient. The aperture of $f/1.8$ along with a minimum angle of resolution of 45° and a depth of focus of 0.0574 mm (57.4 μm) allows for distinguishing between different planes of the anterior segment, antero-posteriorly, with a minimum distance of 57.4 μm between them.^{12–15}

An Air Force (AF) resolution test card (U. S. Air Force 1951, Edmund Optics, Inc, Barrington, NJ) was used to test the spatial resolution in specific magnification on the PSL D20 and compared the same to the resolution of two standard slit lamps (Labomed America Inc., Feasterville, PA, and Inami & Co. Ltd., Tokyo, Japan) using an anterior imaging and photodocumentation device, the Anterior Imaging Module (AIM) attached to the desktop slit lamp (Remidio Innovative Solutions Pvt. Ltd., Bangalore). Figures 7 to 9 show the test results (captured on iPhone 7 and SE 2020 screens) with a magnification of $4\times$. Furthermore, we also compared the magnification of the PSL D20 with a standard slit lamp (Labomed America Inc.) to compare the field of view achieved in both devices (Figs. 10 and 11).

Software

The PSL D20 application allows the user to get optimal lighting for imaging, by adjusting the shutter speed, ISO settings, and mode of illumination and ambient light settings (Fig. 12). The software is programmed to allow an additional digital zoom of $2.25\times$ on the phone (the effective magnification and variation of resolution with magnification are shown in Figs. 10 and 11). The built-in patient management software offers the convenience of instantaneous capture and storage of patient data securely on a HIPAA-compliant cloud server powered by Google Cloud Platform (Google LLC, Menlo Park, CA) after a secure login process. A customized desktop-based interface can be provided additionally to support a DICOM-based transfer for institutes with a centralized EMR/PACS system. The PSL D20 software is teleophthalmology enabled and allows seamless data transfer and generation of immediate reports. The application can also be integrated with third-party video conferencing software for live consultation through the screen-sharing facility.

To improve ease of use, an image processing algorithm was developed that operates offline on the smartphone, which extracts frames with peak sharpness in a video taken by the PSL D20. This feature allows the user to capture a continuous video instead of pressing the image capture trigger when correct focus is achieved, eliminating motion blurred images. For each frame, we extract the area of interest by binary thresholding, apply a Difference of Gaussians (DoG) filter, and compute the variance of the filter output on the thresholded area. This value is interpreted as a sharpness metric. We then assess how the value evolves along the frames of the video and detect peaks. Figure 13 shows the variation of our sharpness metric along



Figure 6. Conventional portable slit lamps are heavier and nondigital.

a sample video. [Figure 14](#) shows the corresponding extracted frames. [Figure 15](#) shows sample out of focus frames.

Compliance Standards

The PSL D20 was tested for compliance with ISO 15004-1,2, ISO 10939:2017, ISO 14971:2012, ISO 10993-1:2009, and IEC 60601-1:2005 + AMD1: 2012, ANSI+Z80.36-2016, EN 60601-1-2:2007+AC: 2010, EN 60601-1:2006/A1:2013, EN 60601-1-6:2010, and EN 62366:2007+A1:2014 standards.

Pilot Study to Demonstrate Photodocumentation

We demonstrated the photodocumentation capability and feasibility of teleophthalmology of the device in a pilot study on nine subjects who were more than 18 years of age, with prior informed consent. This study was approved by an Institutional Ethics Committee at a tertiary eye care center in Bangalore, India, and was performed as per the tenets of the declaration of Helsinki. Of these nine subjects, we imaged five subjects to demonstrate the photodocumentation capability. Images were captured in various illumination, magnification, and filter settings. On the remaining four subjects, we demonstrated the feasibility of teleophthalmology. The optometrist captured one diffuse image at 10 \times magnification and one slit image with an optical section across the lens with the slit beam at an angle of 45 $^\circ$, at magnifications of 16 \times . The ISO and shutter speed settings were prefixed at 22 and 1/100 for diffuse illumination and 150 and 1/30 for slit illumination, respectively. These images were transmitted to an ophthalmologist through the cloud platform. All data were stored on an MS Excel

spreadsheet (Microsoft Corporation, Redmond, WA) and analyzed.

Results

The mean age of the five subjects chosen for showing photodocumentation capability was 36.6 \pm 12.9 years. Slit and diffuse illumination images techniques used on all subjects are shown in [Figure 16](#). Optical sections across the lens ([Figs. 16A, E, F](#)) and retroillumination ([Fig. 16H](#)) allow for objective grading of cataracts (graded here as per the Lens Opacities Classification System (LOCS) III scale). Evaluation of the disc is highlighted in [Figure 16I](#) using a 90-diopter lens. The green filter allows for better delineation of conjunctival blood vessels ([Fig. 16D](#)). Fluorescent dye is administered and viewed with blue filter to evaluate the tear film break-up time (TBUT) in [Figure 17](#).

The mean age of the four subjects chosen for demonstrating feasibility of teleophthalmology in this study was 50 \pm 8.16 years. Synchronous teleconsultation was applied for two subjects and asynchronous teleconsultation was performed for the other two. Zoom (Zoom Video Communications, San Jose, CA) was used for synchronous teleconsultation (representative image shown in [Fig. 18](#)). The average time to capture images was 45.00 \pm 7.07 seconds. The time for uploading images was 5 seconds on both cases of asynchronous consult. The average time to make a diagnosis on the synchronous consultation was 4.5 \pm 0.7 minutes and that during asynchronous consultation was 5.5 \pm 0.7 minutes.

From the AF target analysis, the resolution of the device was found to be 57 line pairs/mm. Additionally, by comparing the performance of the PSL D20

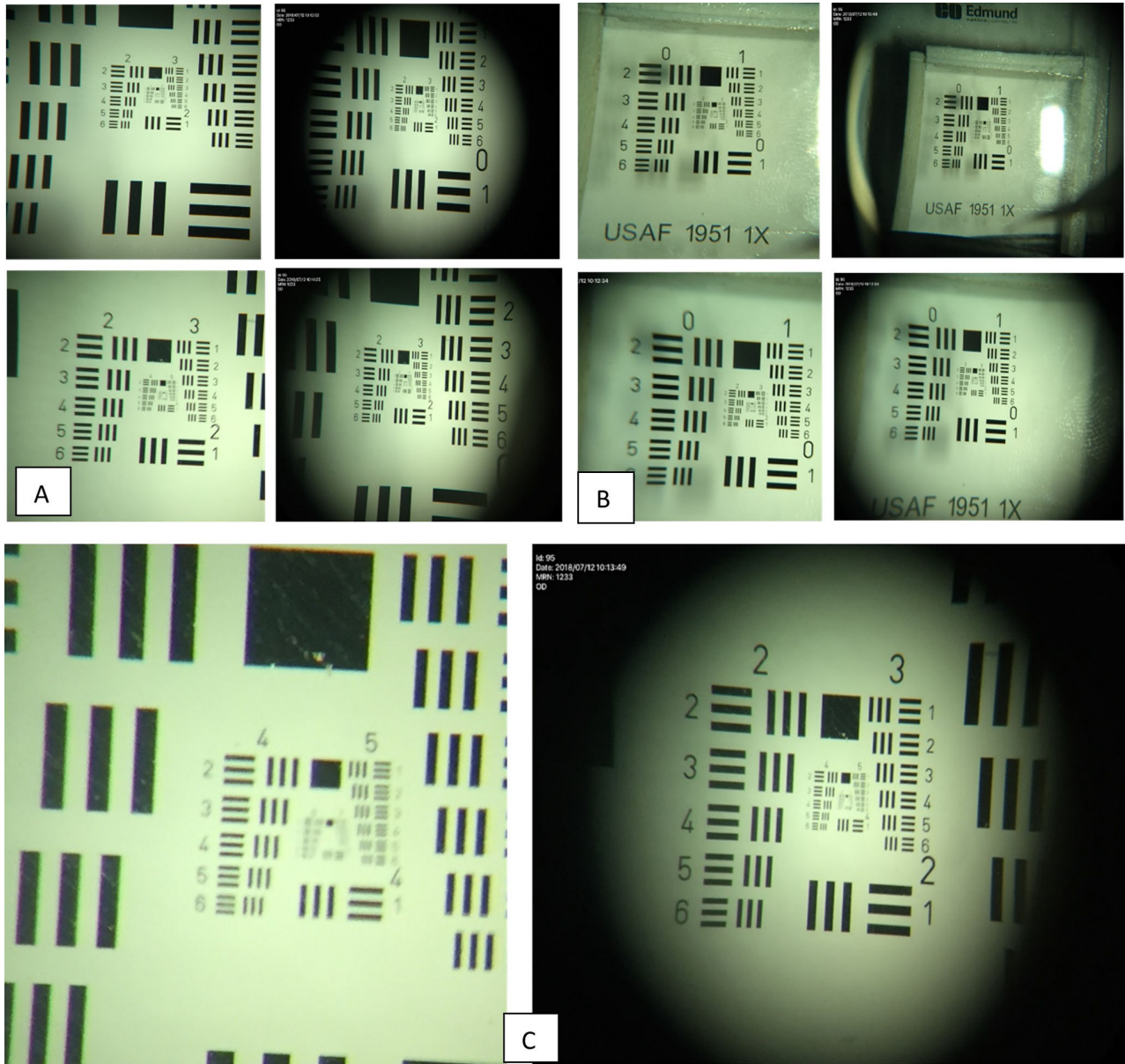


Figure 7. AF Resolution Test for Labomed eV 350 Slit lamp, at (A) 6.5× (Row 1) and 10× magnification (Row 2), (B) 16× (Row 1) and 25× magnification (Row 2), and (C) 40× magnification. All images as seen on iPhone 7. The resolution thus measured has been shown in Table 1.

with that of the smartphone-mounted traditional slit lamps, it was seen that the resolution obtained was not optically limited, as the AF target resolution was found to be the same on both systems despite the lower magnification. The results from the AF target resolution tests on standard slit lamps and that on the PSL D20 have been shown in detail in Tables 1, 2 and 3 respectively. This finding showed that the performance of the device is limited by the smartphone sensor resolution and not the optical design. The sharpness detection algorithm enabled the user to

automatically produce frames from a video grab of the eye, wherein the iris, cornea, and lens are separately in focus.

Discussion

We have designed a portable, digital, teleophthalmology-enabled slit lamp with an ergonomic design for objective, instantaneous image

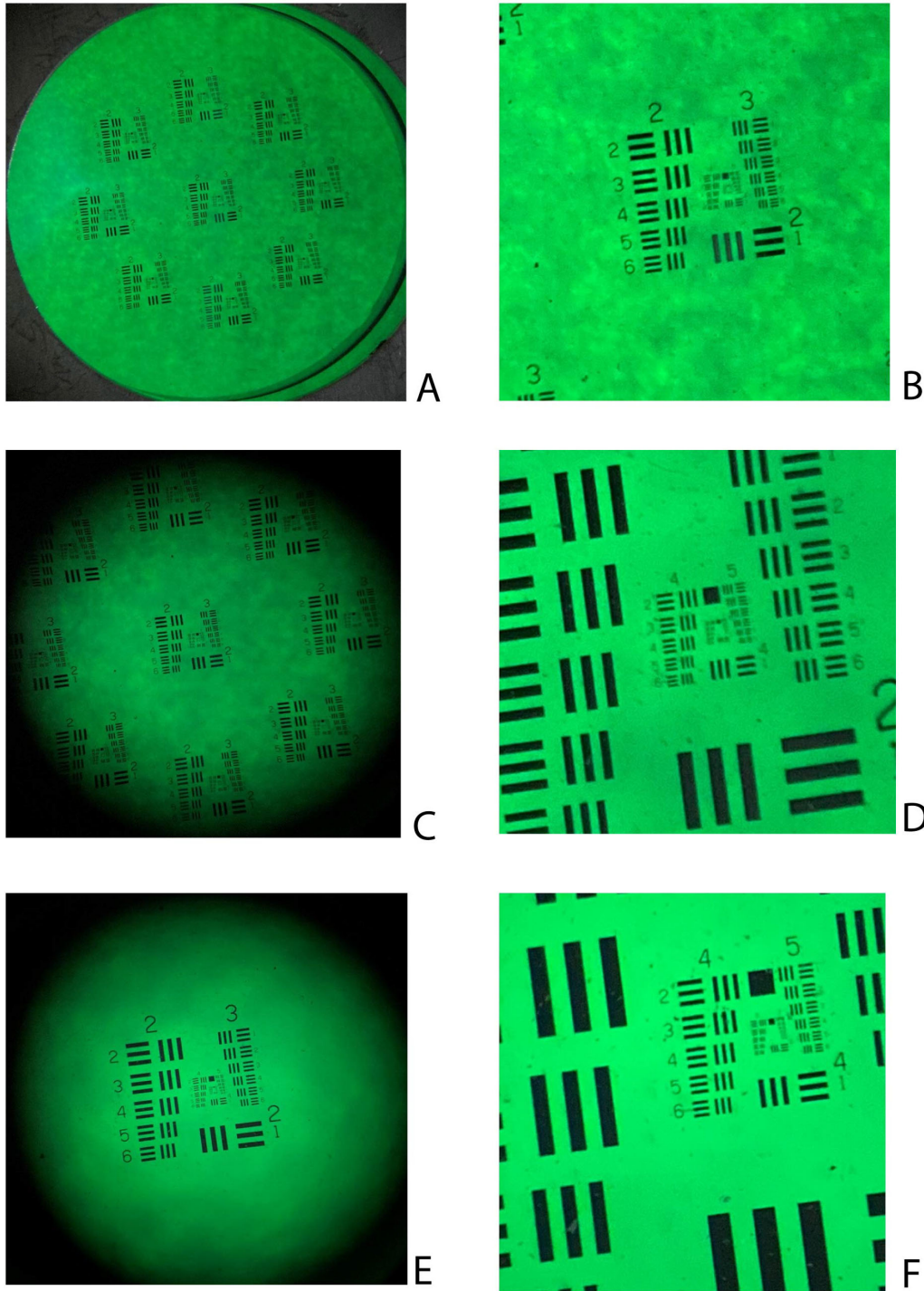


Figure 8. AF Resolution Test for a 2-step Inami Slit Lamp at (A, B) 10× magnification, (C, D) 16× and (E, F) 25× magnification. All images captured on iPhone SE 2020. The resolution thus measured have been shown in [Table 2](#).

documentation of anterior segment pathologies. The performance of the portable, digital slit lamp was determined to be sensor resolution and performance oriented, instead of the optical design. This was justified when we compared the resolution of the PSL D20 to standard, desktop-based slit lamps using an AF

target, giving similar resolutions at lower magnifications. Additionally, to obtain traceability on image quality with standard slit lamps, we also compared the PSL D20 in terms of magnification. PSL D20 comes with all key features of a conventional slit lamp, in terms of modes of illumination and background

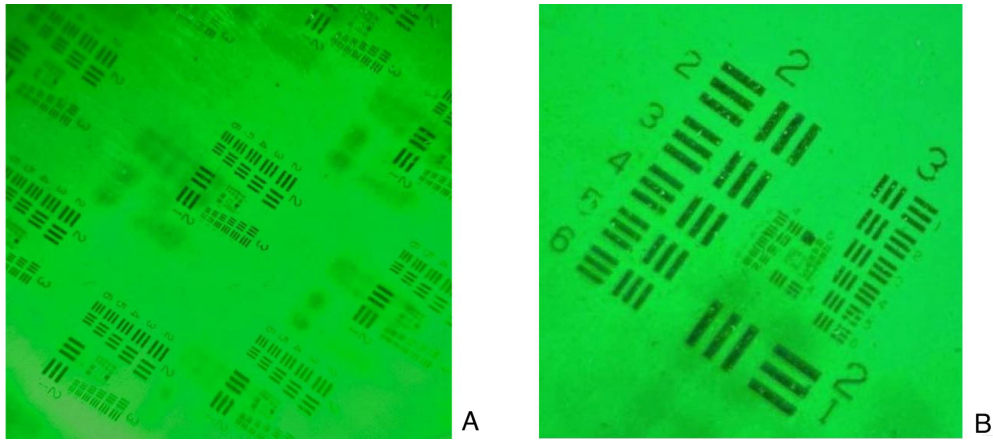


Figure 9. (A) & (B) AF resolution test for PSL D20 at 4× optical magnification (along with maximum digital magnification); image captured on iPhone 7 (image quality on phone sensors differs from camera sensors in desktop-based slit lamps). The resolution thus measured has been shown in [Table 3](#).

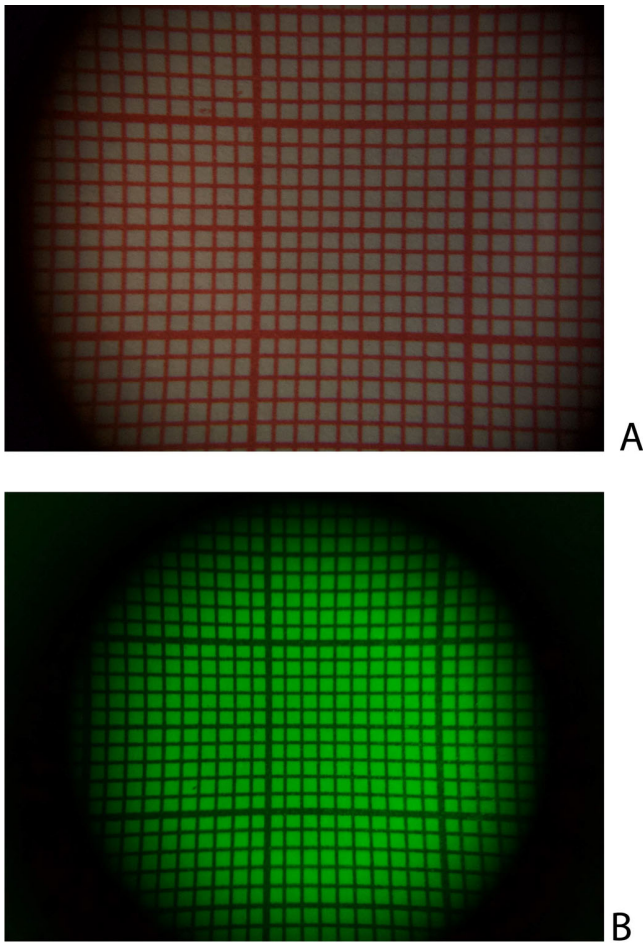


Figure 10. A comparison of the magnification of (A) a standard Labomed slit lamp (10×) with (B) the PSL D20 (4×). The field of view (FOV) was equal in both cases (2.5 cm). This implies that the image seen with 10× in a standard slit lamp is equal to the image seen with 4× on PSL D20.

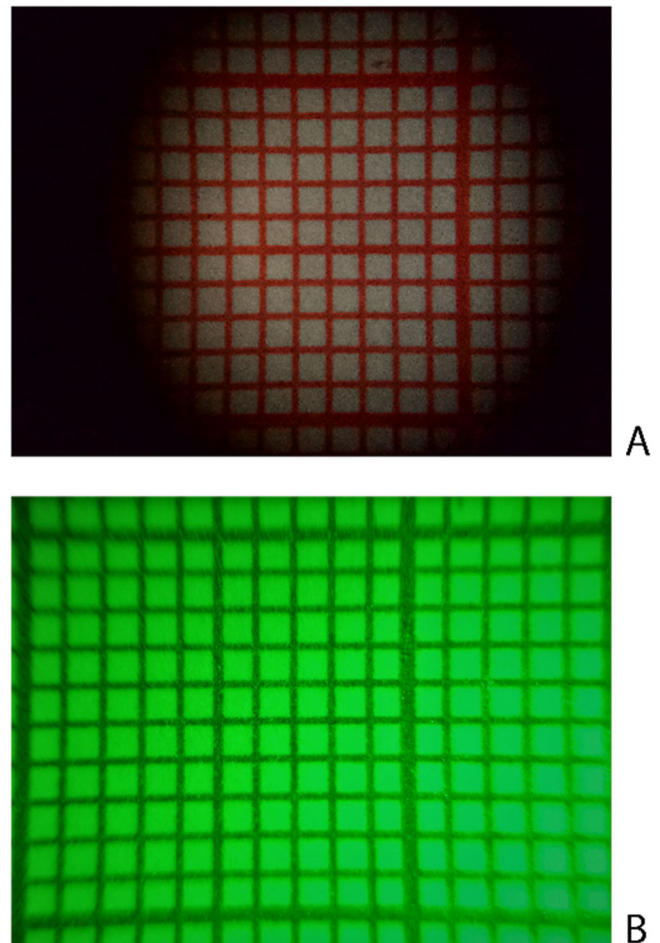


Figure 11. A comparison of the magnification of (A) a standard Labomed Slit lamp (16×) with (B) an equivalent FOV on the PSL D20 (with an additional 2.25× digital zoom). The FOV in both are 1.5 cm. This implies that the image obtained on a 16× magnification on a slit lamp was equivalent to that obtained on the PSL with an additional digital zoom of 2.25×.

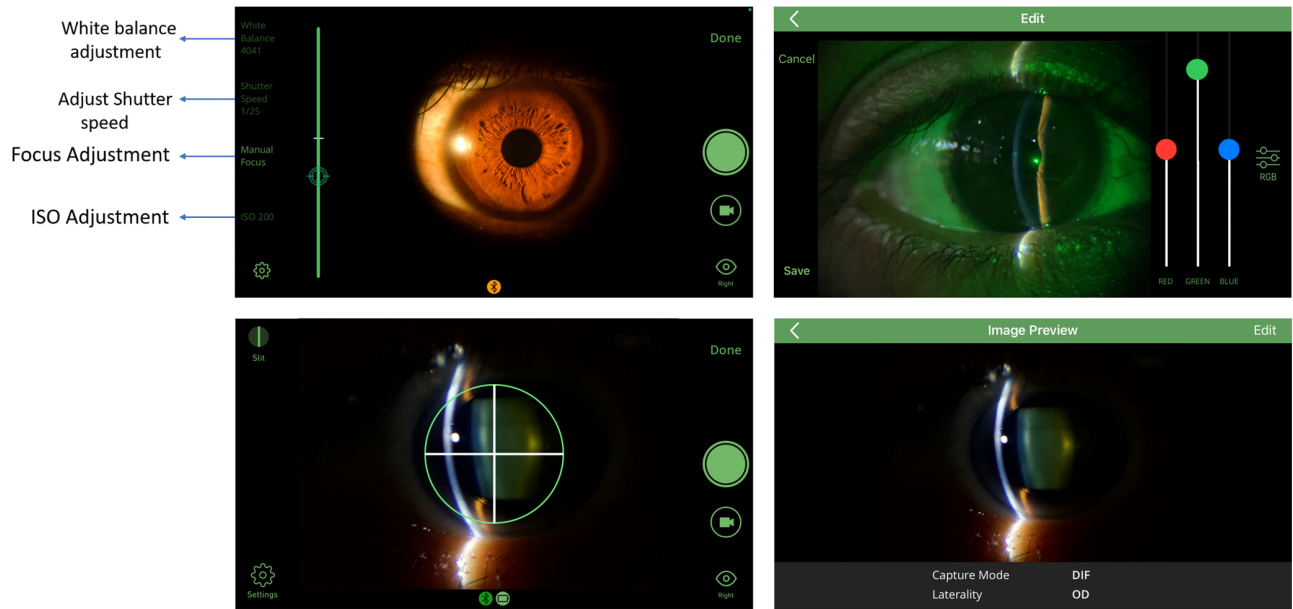


Figure 12. Screenshots showing the different settings and pre and post capture previews on the PSL D20 application. The software allows for manual adjustment of light settings, color corrections depending on the operator’s convenience and ambient light conditions before capturing the final image.

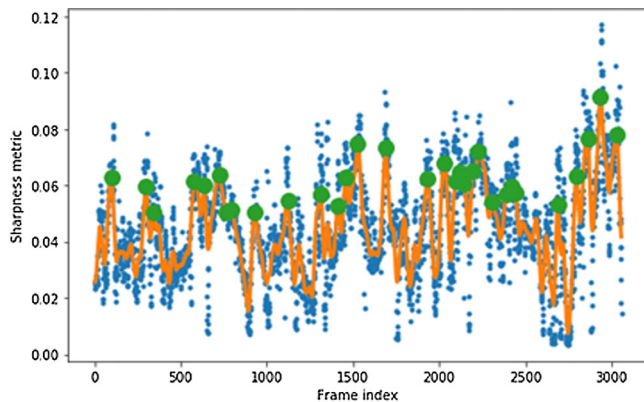


Figure 13. Variation of our sharpness metric along the frames of a sample video. Raw values as blue dots, median filtered values as orange curve, and detected peaks along the curve as green dots.

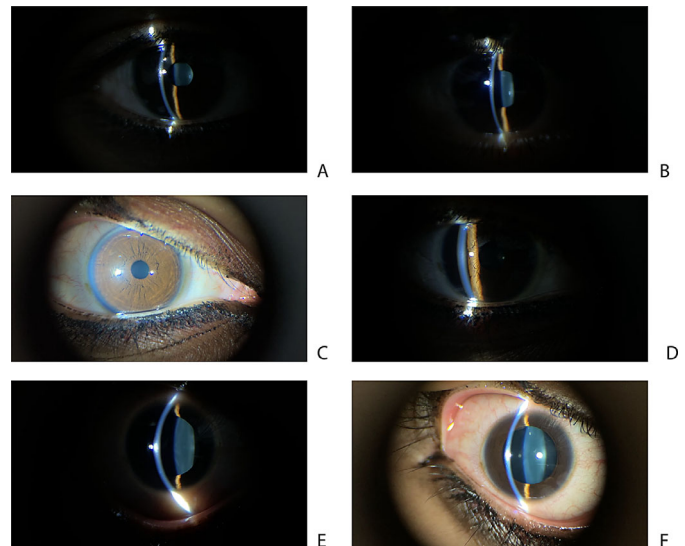


Figure 14. Frames corresponding to the peaks illustrated as green dots in Figure 13, with a focus on the cornea (A, B), iris (C, D), and lens (E, F) in diffuse and slit illumination respectively on the PSL D20.

light, and with a simpler mode of operation, based on a smartphone. We used both the iPhone 7 and the iPhone SE 2020 owing to similar camera sensors and an affordable pricing. We adopted a user-based approach to ease on the usability and enhance its operational simplicity. The slit intensity and width can be controlled, and the background illumination can be changed with minimum hassles, without hampering the focus. A 4× optical magnification on the PSL D20 was shown to be equivalent to a 10× magnification on standard slit lamps. An offline image processing algorithm was developed to extract frames with peak sharpness in a video taken by the

PSL D20, thereby decreasing a technician’s effort to correctly focus on the iris, lens, or the cornea each time during image capture. The focus of the phone is driven by the manual focus of the physician, and hence what is seen on the phone is what one gets. A holistic patient management software ensures that all images captured are stored securely in a HIPAA-compliant cloud server powered by Google Cloud Platform. Our pilot telemedicine feasibility study

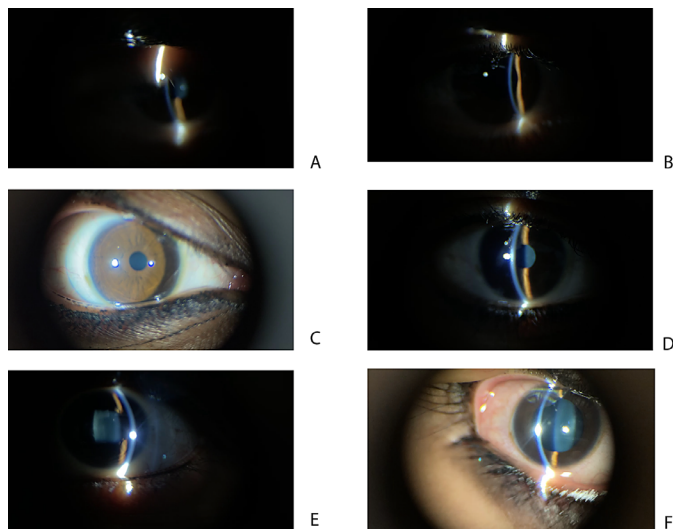


Figure 15. Sample out of focus frames in the video used in Figures 13 and 14.

showed that the attending technician could integrate the PSL D20 application with any third-party video conferencing applications (such as Zoom, Google Meet, or Webex) and share screen with a specialist, to get an opinion on the spot within a maximum span of five minutes. Alternatively, the images could be stored on the secure cloud server and accessed by a specialist, remotely, as per convenience. This feature made the setup cater to both synchronous and asynchronous modes of teleophthalmology. The use of screen mirroring with Apple TV (Apple Inc.) allows for the images to also be seen with minimal lag, wirelessly, on smart TVs for educating patients and training residents.

We constructed the PSL D20 keeping in mind three major constraints faced in present times: fewer portable devices for screening the anterior segment, travelling constraints in remote areas, operational complexities of available portable slit lamps, higher costs, and a lack of objective, instantaneous photodocumentation. The devices reported in literature in the past have focused on ideas to improve screening methods using portable slit lamps. Kumar et al.² used the Lion's Eye Institute Portable Slit lamp camera, with a fixed slit beam. Image documentation was done by freezing a video frame, captured on a video camera fixed as a part of the device and compared with those on a standard Zeiss (Carl Zeiss, Jena, Germany) 40SL/P slit lamp camera in terms of image quality. It showed that pathologies like cataracts and corneal grafts and opacities were equally well detected in both devices.² This trial was key in proving that digital images on the portable slit lamp were of equal diagnostic quality in comparison to

traditional slit lamps in case of gross corneal pathologies. Posterior subcapsular opacities, lid pathologies, and a few in the iris could not be well-detected in this case. A major drawback here was the fixed slit thickness. Other factors hampering the quality of images in this study were lack of maneuvering capacity for the operators, leading to limited focusing, and a shallow depth of focus. Multiple studies have shown acceptable image quality using adaptors with smartphones, to mimic portable screening systems.^{16–18} However, few have focused on the criticality of slit thickness when it comes to anterior segment imaging. Specialists in ophthalmology imaging need a narrow slit light that is thinner than the pupil width of 2 to 8 mm to ensure that the slit light reaches the crystalline lens.¹⁹ Recently, Hu et al.²⁰ reported another smartphone-based adaptor to screen for cataracts—but this was not a full-fledged portable slit lamp. The device was effective in focusing on the anterior capsule, cortex, and posterior capsule of the lens of the eye. A drawback in this case was adjusting the light intensity. Moving the patient to a dimly lit room or making them wear a dark chamber would also hamper the focus of the device. There was no mention of any light filter that could be used to suit specific illumination needs, like tracing inflamed blood vessels, viewing hemorrhages, examining the tear film, or viewing damaged corneal epithellia.²⁰ A study by Yazu et al.¹⁶ demonstrated a portable smartphone-based screening device to screen and grade nuclear cataracts. Their design, called the Smart Eye Camera, is based on a 3D printed adapter that could be attached to a smartphone camera used for capturing and grading nuclear cataracts in human eyes.^{16,21} However, it was only reported to have been used for grading nuclear cataracts. Moreover, there was no traceability in terms of image resolution and magnification for this device against standard slit lamps.¹⁶ A commercially available portable slit lamp, S150 (MediWorks, Shanghai, China) can attach a smartphone to its magnetic pad to digitize the device. A drawback here is the lack of a proper casing or holding pad for the smartphone that may alter the focus. There is no headrest to support or stabilize the focus of the device and no mention of a red-free filter as well.²² A list of features distinguishing PSL D20 from other commercially available portable slit lamps is presented in Table 4.

The PSL D20 overcomes the aforementioned drawbacks with a higher resolution (approximately 12 megapixels), adjustable slit beam, with the ability to focus on all parts of the anterior segment uniformly—be it the eyelids, lens, cornea, or the iris. It allows for maneuvering the angles of illumination, intensity, and the background light—LED, blue, and red free—all controls falling within the grasp of the

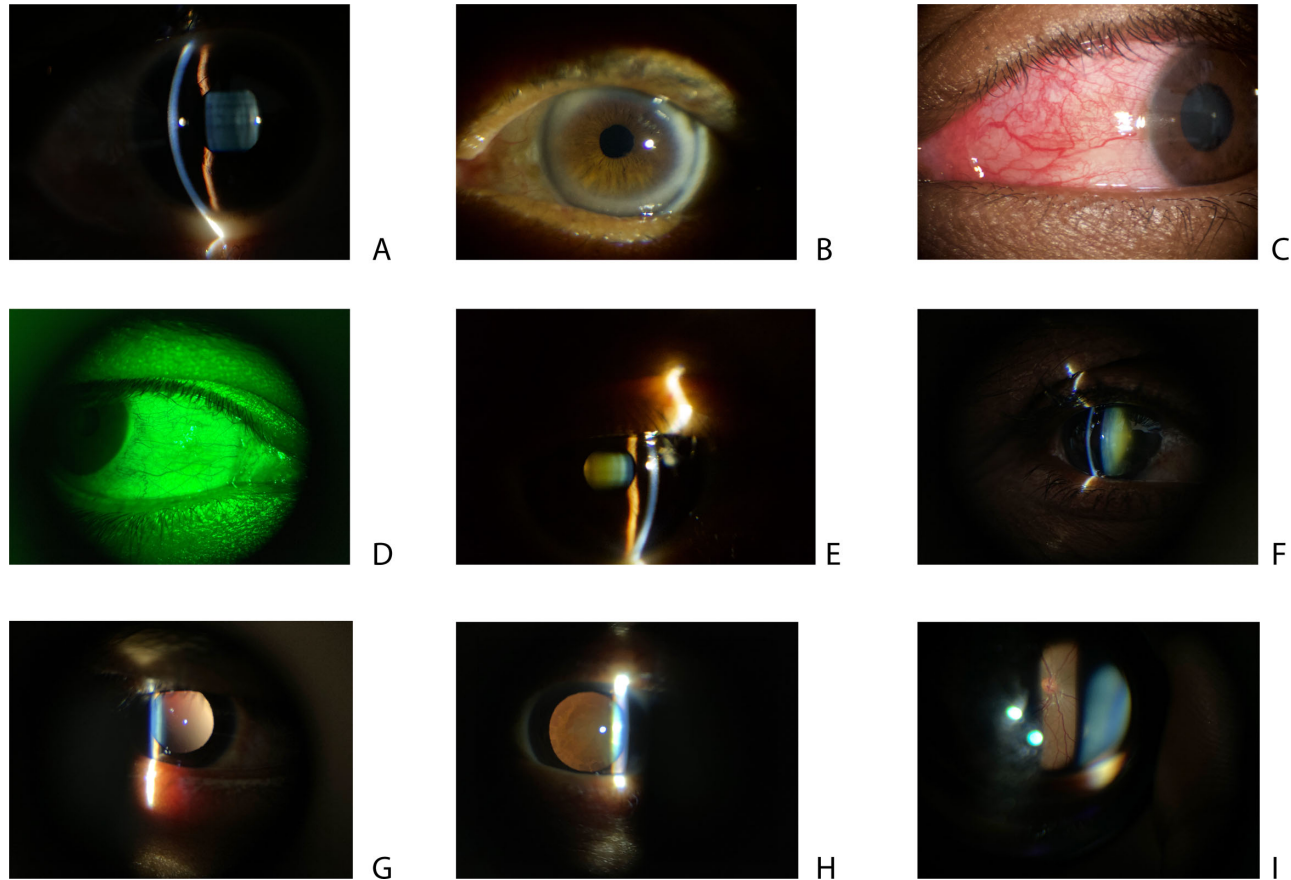


Figure 16. (A) A narrow slit beam is projected at an angle of 45°. It cuts an optical section through the lens which appears clear; captured at a magnification equivalent of 16× on standard microscopes. (B) Diffuse illumination provides evenly balanced lighting. This image shows a dense arcus senilis in a pseudophakic eye captured at a magnification equivalent of 10× on standard microscopes. (C) Diffuse illumination showing a diffuse conjunctival hyperemia captured at a magnification equivalent of 10× on standard slit lamps. (D) Conjunctival vessels better appreciated in green filter captured at a magnification equivalent of 10× on standard slit lamps. (E) A narrow slit beam cuts an optical section through the lens with a nuclear cataract (Lens Opacities Classification System (LOCS) III grade NO 4 and NC 4) captured at a magnification equivalent of 16× on standard slit lamps. (F) A narrow slit beam cuts an optical section through the lens with a nuclear cataract (LOCS III grade NO 3 and NC 3) captured at a magnification equivalent of 10× on standard slit lamps. (G) Retroillumination technique showing a good fundal glow with no peripheral cortical or posterior subcapsular opacities, captured at a magnification equivalent of 10× on standard slit lamps. (H) Retroillumination imaging showing posterior subcapsular cataract (LOCS grade P5) captured at a magnification equivalent to 10×. (I) PSL biomicroscopy with a 90-diopter lens shows a clear media with a normal optic disc in view captured at a magnification equivalent of 10× on standard slit lamps.

thumb while operating it single handedly. The PSL D20 caters to both synchronous and asynchronous modes of telemedicine, making it ideal for access across remote or rural areas. In addition to screening camps and clinics, the PSL D20 can also be used to conduct bedside examination for patients needing emergency care, wheelchair-bound patients, and critical care patients alike, where imaging can be undertaken at the point-of-care. Studies have shown the use of portable, nondigital, slit lamps in ventilated patients in Intensive Care Units (ICUs) wherein doctors and staff have used the devices to screen for ocular surface disorders like exposure keratopathy, conjunctival and corneal infections.²³ Another benefit

of using teleophthalmology-based systems in the current pandemic-struck environment is the practice of examining from a safe distance. Studies have shown a statistically significant and relevant increase in ophthalmic examination distance between doctors and patients using telemedicine-based devices. Traditional slit lamp-based examination distance increased from 27 to 67 cm and portable slit lamp examination distance increased from 18 to 55 cm in these cases.²⁴ In our case, this distance was a minimum of 600 cm, making it even more relevant for use in the COVID-19 era. Using an iPhone 7 or SE 2020 decreased the cost significantly, allowing for a competitive pricing for the device.

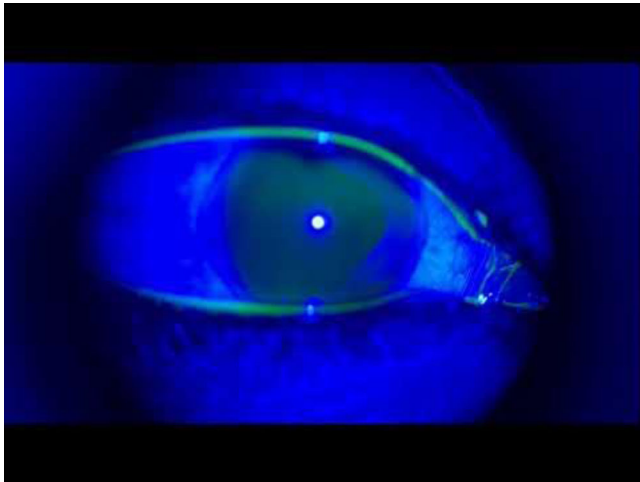


Figure 17. Video showing abnormal tear film break-up time (TBUT) (<10 seconds) captured at a magnification equivalent of 10× on the PSL D20.



A



B

Figure 18. Synchronous tele-consultation conducted using PSL D20, where (A) an ophthalmologist or specialist connects to the patient being screened via screen sharing, using third-party video conferencing applications. (B) A technician images the eye of a patient, live on the same application.

A few limitations faced while using the PSL D20 include use of concomitant gonioscopic lenses and applanation tonometry that is possible in the case of conventional, desktop-based slit lamps. However, these techniques are more relevant in a specialist context and

Table 1. AF Resolution Details of Labomed eV350 Slit Lamp

Magnification	Group	Element	Lp/mm
6.5×	3	1	8.00
10×	3	6	14.25
16×	4	3	20.16
25×	5	1	32.00
40×	5	6	57.00

Table 2. AF Resolution Details of a Two-Step Inami Slit Lamp

Magnification	Group	Element	Lp/mm
10×	4	1	16.00
16×	5	2	35.90
25×	5	6	57.00

Table 3. AF Resolution Test Details of PSL D20

Magnification	Group	Element	Lp/mm
4×	5	6	57.00

not in screening. Using a 90-diopter lens to capture fundus photographs is possible, albeit tedious, with the PSL D20 because it would require the simultaneous use of both hands, one to hold the lens steady and the other to capture images with the device (Fig. 16I). We also explored the possibility of retroillumination (Fig. 16H) with the device as well, something that was missing in literature among the available portable, digital slit lamps. By placing the slit illumination beam nearly coaxial to the imaging lens, with a slight 5° off center, capturing retroillumination images is possible. However, this maneuver will require a certain level of expertise on the technician's part. The corneal endothelium with a monolayer of cells is required to be viewed by specular reflection illumination using a slit lamp biomicroscope at 40× magnification. The current version of PSL D20 can only view objects with a minimum size of 57 μm. Similarly, detection of flare and occasional cells in the anterior chamber as a marker of early signs of inflammation is a limitation of the current version of the PSL D20 given a higher magnification requirement. We plan to address this limitation in the next version of the device by using lenses with a higher magnification. In the context of screening, the utility of many of these techniques is far from essential, requires the presence of an ophthalmologist and can be deferred to be conducted after referral.

Table 4. A Comparison of Key Features of Major Commercially Available Portable Slit Lamps

Features	Shin-Nippon XL 1	Remidio PSL D20	Keeler	Haag-Streit BA-904	Ezer US Ophthalmic	MediaWorks S150
Photodocumentation	Not possible	Possible	Possible	Not possible	Not possible	Possible
Slit width	0–11 mm	0–12 mm	0.15, 0.5, 0.8, 1.6, 12 mm	0–12 mm	0–12 mm	0–12 mm
Slit length	11 mm	14 mm	12 mm	12 mm	0–12 mm	12 mm
Magnification	10× and 16×	10× and 16×	10× and 16×	10× and 16×	10× and 15×	6×
Working distance	80 mm	61 mm	16 mm	53 mm	60 mm	53 mm
Filters	Green and blue	Green and blue	Green, blue, neutral density 0.8	Green, blue, neutral density 0.8	Green and blue	Blue
Maximum angle of illumination system	30°	45°	60°	90°	30°	–
Diopter adjustment	+7 to –7	–	–	+8 to –8	+8 to –8	–
Light source	LED	LED	LED	LED	LED	LED
Battery backup	2 hours	5–6 hours	50 minutes	2–3 hours	2.5 hours	6 hours
Weight	700 g	450 g	900 g	1200 g	900 g	240 g
Screen mirroring/broadcasting	No	Yes	Yes	No	No	Yes
Patient management system	No	Yes	No	No	No	No
Cloud storage	No	Yes	No	No	No	No

Conclusions

Telemedicine-enabled portable digital slit lamps are the need of the hour as they can help to decentralize screening to close-to-patients and point-of-care contexts. Advancement of technology has made it possible to use smartphones as reliable devices for anterior segment ophthalmic imaging. A portable digital slit lamp like the PSL D20 stands out in the smartphone-based anterior segment screening space owing to its simple and ergonomically sound design with key features comparable with conventional slit lamps, as well as its ability to focus distinctively on different layers of the anterior segment using a thin slit beam to capture instant images, and even produce the sharpest frames from any video captured. Its holistic design as a screening solution includes a patient management software for secure data storage and teleconsultation. The feasibility of both synchronous and asynchronous teleophthalmology consultation can thus be impactful during the COVID-19 era. Our next focus would be to conduct clinical trials on patients to and compare the image quality against standard high-end, portable slit lamps. In a nutshell, the PSL D20 takes the revolutionary, teleophthalmology-based screening system, one step ahead in the digital health care space.

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