Smart Ophthalmics©: the future in Tele-Ophthalmology has arrived

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ABSTRACT

Smart Ophthalmics© extends ophthalmic healthcare to people who operate/live in austere environments (e.g., military, third world, natural disaster), or are geographically dispersed (e.g., rural populations), where time, cost, and the possibility of travel/transportation make access to even adequate medical care difficult, if at all possible. Operators attach optical devices that act as ophthalmic examination extensions to smartphones and run custom apps to perform examinations of specific areas of the eye. The smartphone apps submit over wireless networks the collected examination data to a smart remote expert system, which provides in-depth medical analyses that are sent back in near real-time to the operators for subsequent triage.

Keywords: Smartphone-based ophthalmic examination devices, smart remote expert system for data analysis, ophthalmic examinations in relevant operational environments, Mobile-Health, Tele-Health, Tele-Ophthalmology, quality healthcare in austere environments, military health systems

1. INTRODUCTION

1.1 Prime Motivation: Smart Service Platforms in Healthcare

Quality health care no longer requires a health care provider and patient to be in the same room at the same time. With the advancement of mobile health, patients can receive high-quality health care remotely through telemedicine. In fact, telemedicine is rapidly becoming a viable solution to meeting the health care needs of patients in rural and other underserved areas. Telemedicine also brings additional benefits, such as reduced patient costs for travel, reduced absences from work to go to medical appointments, health system efficiencies and potential cost savings from improved care management and coordination, and local economic gains as residents remain in the community for care.

Even today, people all around the world—particularly those living in rural or remote areas—are found to have severely limited access to timely medical treatment. Many regions are characterized by densely populated communities spread over vast distances. In addition, there is in general a lack of qualified personnel in many sectors of health care.

Mobile health and telemedicine have been developed to serve not only rural populations, but any people who are geographically dispersed, where time and the cost of travel make access to even adequate medical care difficult.

The major drivers in the adoption of mobile health services include:

- Seasonal or catastrophic isolation of some tracts of land, e.g., due to floods, snow, earthquakes, tsunamis, and hurricanes.
- Hazardous environments not conducive to in-resident medical professionals, e.g., military theatres, submarines, International Space Station, and long-duration spaceflight.
- Economically disadvantaged areas that do not attract highly paid medical professionals.
- Topological constraints, such as vast land areas with difficult or inaccessible terrain.
- Lack of traditional telecommunication infrastructures.

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- Large indigenous populations with inequitable distribution of resources.
- Countries in which the majority of the population lives in rural areas while the majority of the qualified medical consultants practice in urban areas.

Telemedicine can improve the health of populations living in rural and medically underserved communities by providing in situ access to quality health care and facilitating coordinated care for complex conditions. Telemedicine is used to screen, diagnose, treat, and monitor a wide range of health conditions from common illnesses, such as strep throat and asthma, to conditions requiring specialty care in such fields as dermatology, endocrinology, emergency and critical care, neurology, gastroenterology, radiology, pathology, oral health, and ophthalmology. Telemedicine and Mobile-Health applications help patients manage their own health, reducing the need for more complex and costly (post) hospital visits and health treatments. Telemedicine can also promote health care efficiency by improving screening and triage processes (e.g., especially in military settings) and helping to ensure that patients see an appropriate provider when needed and avoid unnecessary visits.

The term telemedicine includes, but is not limited to, the Internet, computers, hardware, software applications, telecommunications technology, advanced media technology, and hand-held devices. It also includes other technologies utilized for telemedicine, Tele-Health, and Mobile-Health applications, such as remote monitoring devices, electronic clinical equipment, and other emerging technologies used to improve the health of individuals.

Mobile Health (M-Health) is the intersection of mobile technology and healthcare. M-Health and Tele-Health are deeply intertwined and share the possibility of reshaping how and where healthcare is delivered. M-Health is an emerging field characterized by the use of portable, mobile devices capable of collecting, storing, retrieving, and transmitting data over wireless networks in real time for the purpose of improving safety and quality of care. Moreover, M-Health and Tele-Health harbor the potential of significant savings in healthcare costs to patients, health insurers, and economies at large.

The paradigm of *Smart Ophthalmics*© introduced here (Fig. 1 below) will not only augment the existing telemedicine and mobile health archetypes, such as clinic-centric ophthalmic examination infrastructure, but will add *a fully automated pre-diagnostic capability in lieu of the absence of qualified medical personnel*, e.g., in disaster-stricken areas. In this regard, automated telediagnosis offers the potential of concatenating mobile health and telemedicine to provide both rapidity of evaluation and increased coverage.

Figure 1. Schematic overview (extracted from [5, 6]) of *Smart Ophthalmics*©: a smart service platform in ophthalmology.

According to a recent BCC Research report "GLOBAL MARKETS FOR TELEMEDICINE TECHNOLOGIES",[1] the global telemedicine market is expected to grow from $9.8 billion in 2010 to $27.3 billion in 2016, at a compound annual growth rate (CAGR) of 18.6% over the next five years. The telemedicine market is segmented into telehospital/clinic and telehome markets. The telehospital/clinic market segment worth was $6.9 billion in 2010, while the telehome market was valued at nearly $2.9 billion. However, the telehome segment is growing faster than the telehospital/clinic segment (i.e., at a projected CAGR of 22.5% vs. 16.8%, respectively), and as a result is expected to increase its market share of the market from 29.4% of the market in 2010 to 35.6% by 2016.

1.2 Prime Application: Ophthalmic Examination

Vision is the primary sense used by civilians and warfighters in daily life, and visual information is essential. In civilian life there are many conditions that, if undetected or detected too late, may lead to visual impairment, irreversible visual field loss, and eventually to blindness, such as glaucoma and macular degeneration – the two leading causes of permanent blindness. Military environments have many significant effects on the visual and ocular system that can adversely affect warfighter performance, and may lead to long-term health consequences.

The Army SBIR Call Topic Number A12-117: "Adapting SmartPhones for Ocular Diagnosis" of Fall 2012 states very fittingly: *"Ocular injuries currently account for approximately 13-22% of all combat casualties and up to 32% in disaster scenarios,*[2,3] *while untold others experience other less devastating eye issues while deployed. Because the diagnosis and treatment of ocular trauma and disease are daunting to most non-ophthalmic providers, most opt to refer ocular patients to theater ophthalmologists or optometrists for evaluation of all but the most routine conditions; most often, however, those assets are very limited or non-existent in military operations so that transferring even relatively simple ocular conditions entails significant risk, or may not be possible at all (e.g., ships afloat or humanitarian missions). In this regard, telediagnosis should offer both rapidity of evaluation and increased security; evacuation of the patient can then be more judiciously advised or avoided based on evaluation of the tele-information. Because Ophthalmology is so heavily reliant on visual information, high-quality photographic attachments are very helpful to the teleconsultants.*[4] *Limitations to current photodocumentation are the 2-dimensional nature of standard photographs, the inability to selectively focus standard cameras on the microscopic structures of the ocular anatomy on which diagnoses can hinge, and overall resolution. Because of their size, weight, cost, fragility, and training requirements, conventional and portable slitlamps are not typically deployed in all forward clinical settings such as ships' sick bays, Forward Operating Bases (FOBs), Battalion Aid Stations (BAS), disaster areas, or humanitarian missions, and when available are not equipped with photo capability (a technique that requires considerable skill in itself). Smartphone technology has recently put high quality photography, advanced processing capability, and robust connectivity into the hands of technically untrained populations. Still photos or video can be captured and quickly edited for rapid dispatch via the internet in near real-time, or can be stored for later transmission. Continual advances in smartphone hardware have increased photographic resolution while decreasing the size of the cameras, and have even broached into 3-D applications. Such handheld capability is of significant interest to military Ophthalmology. Inherent portability, connectivity, and affordability would allow use by minimally trained personnel and deployment to areas heretofore considered inaccessible or impractical. However, mere adaptation of existing smartphones may not answer all of the specialty's needs. For example, a key aspect would be the capability to do high-resolution stereo photography of ocular structures that vary in scale from a few centimeters (external macro photography), to millimeters (microphotography of the surface of the eye), to sub-millimeter or microns (e.g., internal structures such as the anterior chamber, lens and fundus). Additionally, selective illumination by slit beams of light cast at oblique angles allows greater precision in diagnosis unavailable in current smartphone technology. Software applications should facilitate ophthalmic telediagnosis, to include collection of patient ocular exam data as well as enhanced photography/ videography and bundling for teleconsultation. Capacity should include both real-time and store-and-forward teleconsultation."*

The real-time and store-and-forward teleconsultation capabilities will be critically augmented by utilizing powerful server-backend processing to render analysis and diagnosis of the collected data in near real time, with transmission back to the originating smartphone. As such, the use of a server-side application will turn, for the first time, a smartphone into a smart service platform capable of developing differential diagnoses (i.e., medical information collected on individuals seen in context as opposed to in isolation). While image capture can be performed in isolation, e.g., on a smartphone, image interpretation and the development of an expert system for smart image classification mandate an active server back end having access to essential medical context, thereby delivering a rapid, "in-situ" informed analysis. The result of this novel development will change the very economy of extending smart healthcare to those most in need.

2. SMARTPHONE-BASED OPHTHALMIC EXAMINATION DEVICES

To establish a smart service platform in ophthalmology, we have developed a server-based telediagnostic analysis capability (Section 3 below). Embedded within this capability are currently available and anticipated smartphone-based ophthalmic examination devices to be developed. These handheld devices will enable field-conducted examinations (e.g., in forward operating bases during military deployment) that are otherwise restricted to clinical settings (e.g., medical offices and clinics). Compared to state-of-the-art ophthalmic equipment, these devices are miniaturized, portable, and usable even by non-specialists with minimal training outside of clinical settings.

Companies have been developing adapter-based optics for digital cameras (including smartphone cameras) to turn them into ophthalmic examination devices, such as ophthalmic microscopes (Fig. 2, left) to image ocular surfaces, ophthalmic slitlamps (Fig. 2, middle) to image internal ocular structures, and ophthalmoscopes/fundoscopes (Fig. 2, right) for fundus imaging. Our team in particular has developed a smartphone-based binocular pupillometer (Fig. 3).[5-7]

Figure 2. Examples of smartphone-based ophthalmic examination devices: ophthalmic microscope (left); ophthalmic slitlamp by *Eidolon* (middle); and ophthalmoscope/fundoscope by *Welch Allyn* (right).

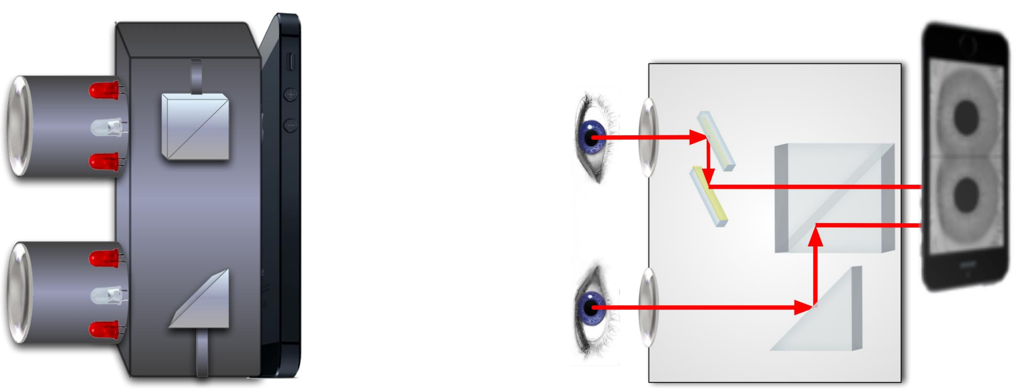

Figure 3. *Left:* Schematic drawing of binocular pupillometer prototype that can be attached to a smartphone. *Right:* Sketch of optical pathway (not to scale) within the binocular pupillometer.[5-7]

The concept of smartphone-based ophthalmic examination devices is extensible to numerous ophthalmic and non-ophthalmic applications. This will be made possible by a plug-and-play architecture (via customized lens adapters on the smartphone casing) that allows rapid and easy selection of various ophthalmic and non-ophthalmic examination modalities.

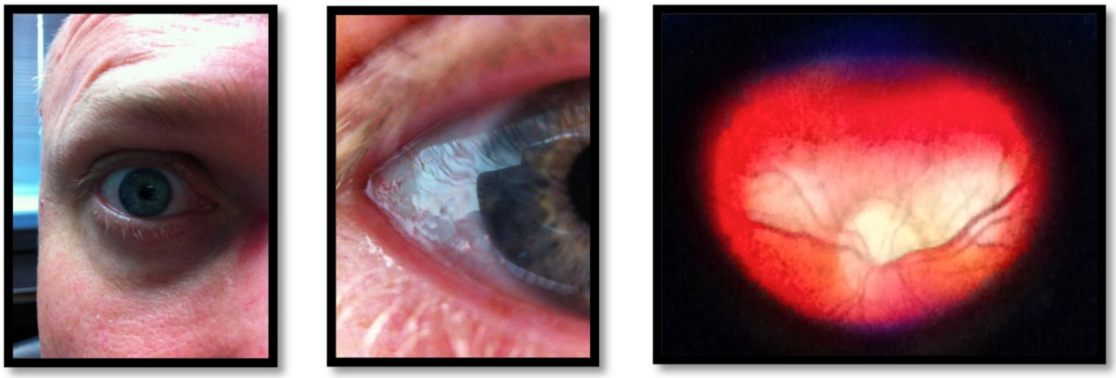

Figure 4. Preliminary examination results: raw iPhone camera image of an eye (left); using 4X lens (middle); and fundus image using ophthalmoscope/fundoscope optical extension in front of iPhone camera (right).

Preliminary research has indicated suitability of the proposed smartphone-based handheld ophthalmic examination device concept. Figure 4 shows (1) an example of a raw image taken with a default iPhone camera (Fig. 4, left), (2) a 4X magnified image of the temporal sclera and parts of the iris (Fig. 4, middle) of the same eye using a 4X magnification lens in front of the iPhone camera, and (3) an image of the fundus (Fig. 4, right) of the same eye using a handheld ophthalmoscope/fundoscope optic in front of the iPhone camera.

3. SERVER-BASED TELEDIAGNOSTIC ANALYSIS CAPABILITY

What is currently lacking in modern telemedicine is the capability of in-situ, near real-time analysis and diagnosis of the image data obtained with such smartphone-based ophthalmic examination devices. As a leading example for other medical applications, we have created a server-based telediagnostic analysis capability (Fig. 1) for currently available and future smartphone-based ophthalmic examination devices (Section 2 above). This capability would allow examination data gathered with such devices to be sent wirelessly to a server for automated analysis, the results of which would be sent back to the originating smartphone. This server-based telediagnostic analysis capability allows for either tele-expert or automated machine-based in-depth evaluation and diagnosis of the submitted image data. This is made possible because smartphones are ubiquitous and Internet-connected. This capability enables both real-time and store-and-forward teleconsultation and communication to other health professionals for a full diagnosis later in time when convenient or possible. Such a server-based telediagnostic analysis capability requires a “Smartphone-to-Server Backend Interaction for Bidirectional Data Transfer.”

Built atop the bidirectional communication framework, this application merges off-the-shelf and the proposed optical extensions to couple with the smartphone’s built-in camera. This arrangement allows imaging of segments within the eye, including the cornea, anterior chamber, vitreous cavity, and fundus.

As a prime example of an automated and diagnostically useful analysis, we have been focusing on the early detection of glaucoma, the leading incurable blinding disease, by calculating the cup-to-disc ratio (Fig. 5) via image processing (Fig. 6). The cup-to-disc ratio is a measurement used in ophthalmology to assess the progression of glaucoma. The optic disc is the anatomical location of the eye’s “blind spot”, the area where the optic nerve and blood vessels enter the retina. The optic disc can be flat or it can have a certain amount of normal cupping (Fig. 5). But glaucoma, which is due to an increase in intra-ocular pressure, produces additional pathological cupping of the optic disc. As glaucoma advances, the cup enlarges until it occupies most of the disc area. A normal cup-to-disc ratio is ~0.3. A large cup-to-disc ratio (> 0.5) may imply the onset of glaucoma. As such, the cup-to-disc ratio may be used for early detection of glaucoma.

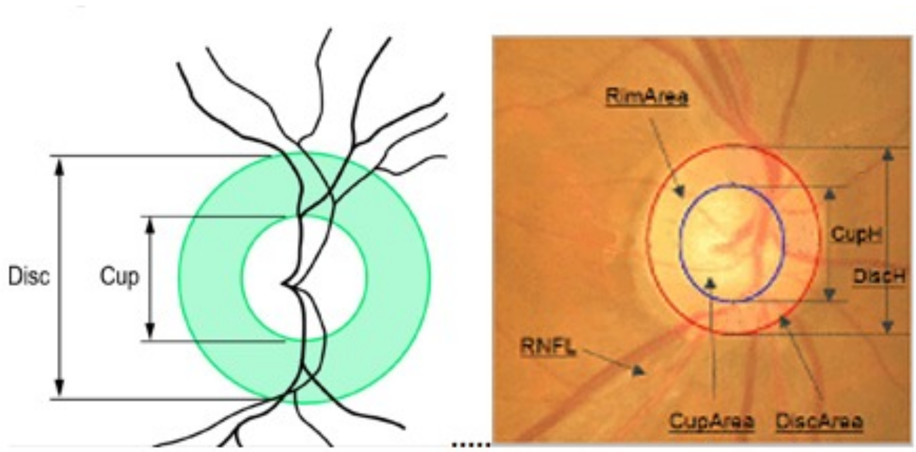

Figure 5. Schematic definition of the cup-to-disc ratio for the early detection of glaucoma (image courtesy: http://www.fiteyes.com/home/understanding-your-test-results).

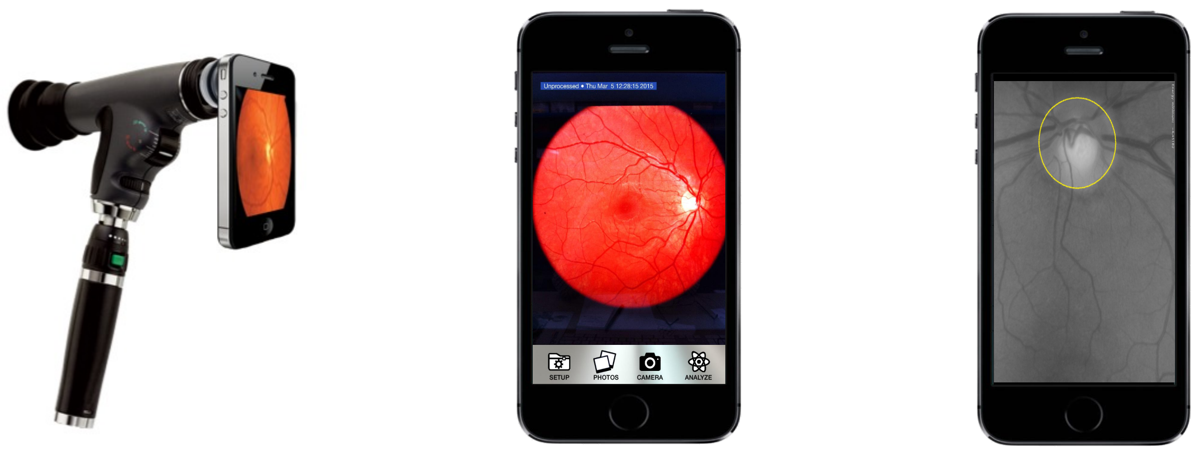

Figure 6. Image processing cascade for calculating the cup-to-disc ratio to assist the early detection of glaucoma. *Left:* ophthalmoscope/fundoscope attachment to a smartphone. *Middle:* fundus image captured on smartphone app. *Right:* optic disc perimeter as determined by the server-based ophthalmic imaging analysis (yellow line).

Moreover, we have developed a data-fusion and analysis framework[8] to normalize features extracted from a variety of image modalities, cluster them into meaningful groups in a unified feature space, and identify anomalies within. The data fusion framework enables comparisons and correlations between data collected using different modalities and different functional tests over time. The framework has been proven on a variety of tasks, including space-based imagery analysis and visual field analysis.[8]

4. SUMMARY & OUTLOOK

Smartphone-based mobile ophthalmic examination devices combined with server-based smart telediagnosis capabilities pave the way towards *Smart Ophthalmics*©, i.e., smart tele-ophthalmology. This paradigm may greatly improve remote patient screening and triage. It may help ensure that patients with undiagnosed eye diseases are detected early and treated in time to prevent permanent vision impairment. Establishing this paradigm has the potential to change the very economy of extending quality healthcare to many while reducing cost both for health insurances and the insured.

Smartphone-based ophthalmic examination devices with telediagnostic capabilities will benefit from the rapid growth of telemedicine in clinical medicine, i.e., the use of telecommunications technology to deliver medical information or services to patients or other users at a distance from the provider, e.g., outside the hospital setting. An entire ocular diagnosis and monitoring segment of M-Health can be established with such smart ophthalmics, in sync with a national and international focus and thrust in this area. This may lead to the eventual integration of the introduced smart service platform (Fig. 1) and its associated devices into established ophthalmic clinical practice.

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6. AUTHOR DISCLOSURE STATEMENT

Authors WF and MAT may have financial interest in the technology presented here as they are named as inventors on several issued Caltech patents and pending University of Arizona patents on the underlying technologies. Author KG has no financial interest in the technology presented.

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