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General Research

Endockscope: Using Mobile Technology to Create Global Point of Service Endoscopy

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Abstract

Background and Purpose: Recent advances and the widespread availability of smartphones have ushered in a new wave of innovations in healthcare. We present our initial experience with Endockscope, a new docking system that optimizes the coupling of the iPhone 4S with modern endoscopes.

Materials and Methods: Using the United States Air Force resolution target, we compared the image resolution (line pairs/mm) of a flexible cystoscope coupled to the Endockscope + iPhone to the Storz high definition (HD) camera (H3-Z Versatile). We then used the Munsell ColorChecker chart to compare the color resolution with a 0° laparoscope. Furthermore, 12 expert endoscopists blindly compared and evaluated images from a porcine model using a cystoscope and ureteroscope for both systems. Finally, we also compared the cost (average of two company listed prices) and weight (lb) of the two systems.

Results: Overall, the image resolution allowed by the Endockscope was identical to the traditional HD camera (4.49 *vs* 4.49 lp/mm). Red ($\Delta E = 9.26$ *vs* 9.69) demonstrated better color resolution for iPhone, but green ($\Delta E = 7.76$ *vs* 10.95), and blue ($\Delta E = 12.35$ *vs* 14.66) revealed better color resolution with the Storz HD camera. Expert reviews of cystoscopic images acquired with the HD camera were superior in image, color, and overall quality ($P = 0.002$, 0.042, and 0.003). In contrast, the ureteroscopic reviews yielded no statistical difference in image, color, and overall ($P = 1$, 0.203, and 0.120) quality. The overall cost of the Endockscope + iPhone was $154 compared with $46,623 for a standard HD system. The weight of the mobile-coupled system was 0.47 lb and 1.01 lb for the Storz HD camera.

Conclusion: Endockscope demonstrated feasibility of coupling endoscopes to a smartphone. The lighter and inexpensive Endockscope acquired images of the same resolution and acceptable color resolution. When evaluated by expert endoscopists, the quality of the images overall were equivalent for flexible ureteroscopy and somewhat inferior, but still acceptable for flexible cystoscopy.

Introduction

Recent advances in mobile technology have ushered in a new wave of innovation and opened new avenues to deliver improved healthcare at less cost. The worldwide accessibility and ubiquity of smartphones makes the utility of this technology practical and promising in medicine.[1–4] There is a shift toward incorporating mobile technology into different facets of preventive, diagnostic, and personalized medicine.[5–8] This mobile technology continues to become ever more sophisticated and broad in its application even as its cost decreases.

Modern endoscopy has become a necessary diagnostic and therapeutic tool in many clinical specialties, such as pulmonary medicine, gastroenterology, colorectal surgery, and urology. Because of advances in flexible endoscopy that include smaller endoscopes light emitting diodes (LED) displays and camera miniaturization, these procedures have largely moved out of the hospital and into the office. While the product has been vastly improved, however, unlike other technologic advances devices (eg, laptop computers, tablets, smartphones), the cost of these endoscopes and their essential accessories (eg, high power light source, monitor, sophisticated camera technology, etc.) have only continued to escalate, thereby placing these important technologic advances out of reach of many/most developing nations and making them usually dedicated to a single office even if mounted on a mobile cart.

We describe the initial report of a specialized lens and docking system (Endockscope, Orange, CA) that transforms a smartphone into a completely mobile endoscopic viewing system.

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Materials and Methods

Design of Endockscope

Commercially available and custom machined components were assembled to relay the image produced by the cystoscope onto a smartphone, the Apple iPhone 4S™ (Apple Inc., Cupertino, CA) in camera mode. An off-the-shelf prescription lens system with a built in iPhone case was used to produce a combined effective focal length of 18 mm. A custom acetal coupling was machined and assembled to the prescription lens system using an interference fit (Fig. 1). The coupling was machined to within 0.010 inches of the outer diameter of the cystoscope eyepiece and fixed with a set-screw. This configuration provides a centered image on the iPhone camera with an 8X optical zoom with respect to the stock iPhone camera lens system. This eliminated the need to use digital zoom to fill the iPhone screen, providing for maximal image quality.

Incorporating wireless technology

In addition to the mobile phone display, the mobile platform allows users/physicians to use consumer mobile systems to relay a live image wirelessly, or wired to a secondary live display. The secondary display may be a larger screen in the endoscopy suite, or a secondary remote mobile phone/device for monitoring purposes. In our study, we used the Apple iPhone 4S and Apple TV™ to Airplay™ to wirelessly stream a mirrored display of the endoscopic image to a larger display (Fig. 2).

Image resolution

We compared the image resolution (line pairs/mm) of the Endockscope coupled mobile device to a high definition (HD) camera (Storz H3-Z Versatile High Definition Camera Head, Tuttlingen, Germany) by imaging a 1951 United States Air Force Contrast Resolution Chart Target (Edmund Industrial Optics,™ Barrington, NJ). The cystoscope was held 1 cm above the resolution target, and images were recorded for both Endockscope and Storz HD camera (Fig. 3). We used the standard high-powered xenon light source for both systems (Storz).

FIG. 1. Demonstrates the Endockscope coupling to the cystoscope with iPhone 4S.

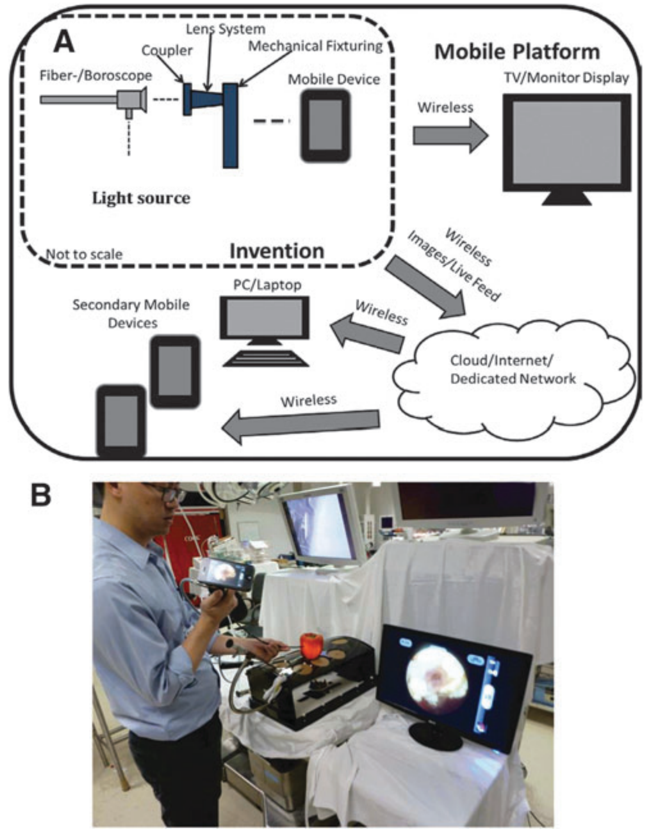

FIG. 2. (A) Schematic of incorporating wireless mobile display and cloud network. **(B)** Coupling of smartphone to flexible cystoscope. Image is transferred to larger display via Airplay (wireless mobile platform) using Apple TV.

Color resolution

The color resolution/quality was compared between the Endockscope and the Storz HD camera using the Munsell ColorChecker Chart. The colors compared between the two scopes included the following: Red, orange, yellow, green, blue, light purple, and purple. Still photographs were taken of each of these colors using the respective cameras and a rod lens laparoscope, while using the standard high-powered xenon light source for both systems. The standard Red Green Blue (sRGB) value was obtained using the eyedropper function in Pixelmator ver. 1.6 (Pixelmator Team Ltd., London,

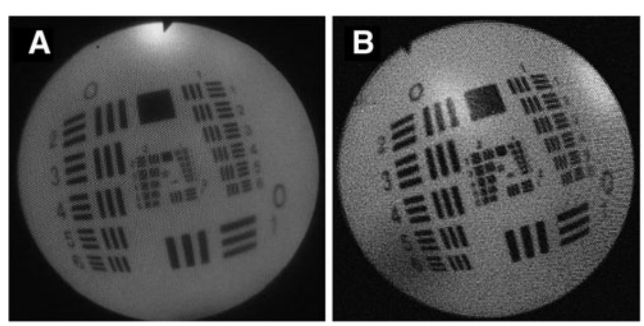

FIG. 3. Flexible cystoscope images of United States Air Force resolution target—Endockscope and iPhone in left **(A)** and Storz high definition camera on right **(B).**

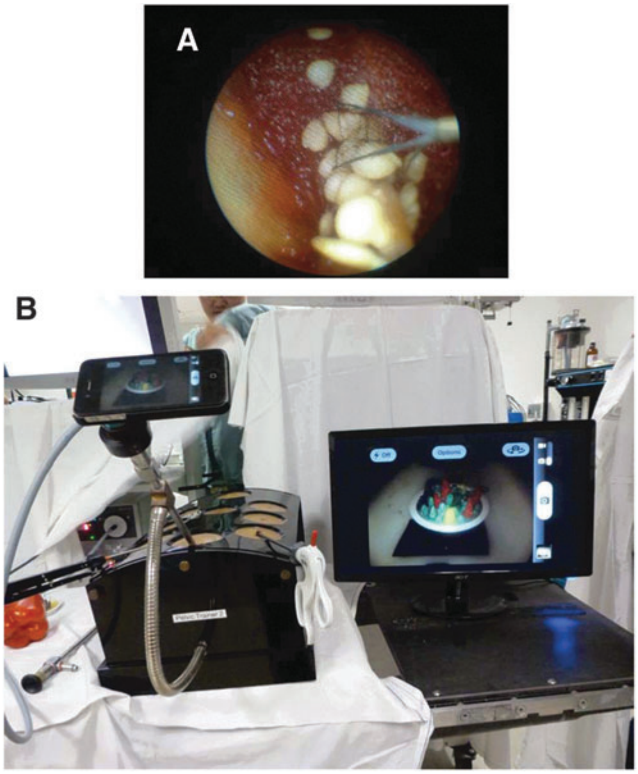

FIG. 4. (A) Image inside of bell pepper model with basketing of seeds (NCompass, Cook Medical) and **(B)** image of pelvic trainer set with smartphone coupling and wireless mobile platform.

UK). The sRGB value was taken from the average of 121 pixels approximately in the center of the color square. Assuming 2 degree viewer angle and fluorescent room lighting, the sRGB value was then converted to CIE L*a*b* color scale (International Commission on Illumination, $L^*=0$ yields black and $L^*=100$ indicates white, a^*=negative values indicate green while positive values indicate magenta, and b^*=negative values indicate blue and positive values indicate yellow).[9] The reference sRGB values were obtained from the Munsell ColorChecker Chart.[10] The color difference between the samples and the reference were then calculated using the CIEDE2000 color difference formula.[11] The output for this formula is ΔE, which is the difference in color from the reference, with higher numbers denoting a greater difference.

Cost comparison

The cost of the standard equipment used was an average of the listed product prices of two different companies. This was compared with the cost of the Endockscope using off-the-shelf materials.

Bell pepper, laparoscopic pelvic trainer and porcine model (expert reviews)

We performed fiberoptic flexible cystoscopy and fiberoptic flexible ureteroscopy in a bell pepper visualization model and also sought to entrap bell pepper seeds with a stone basket (Fig 4). A 30 kg, female Yorkshire porcine model underwent flexible cystoscopy and ureteroscopy with the two systems (Fig. 5). The images collected from each of the two aforementioned scenarios were reviewed and evaluated by 12 expert endocopists using a Lickert scale questionnaire to evaluate each pair of images. The 12 experts are all senior faculty: 6 endourologists, 2 colorectal surgeons, 2 gastroenterologists, 1 gynecologic oncologist, and 1 pulmonologist. The evaluators were asked to rate the resolution, brightness, color, and overall image quality from 1 (very poor) to 5 (very good) for set #1 (Endockscope + iPhone) with a standard light source and set #2 (Storz HD) with a standard light source; the evaluators were blinded as to which set was from either device. The evaluations were collected, and hypothesis testing for Lickert scale data was conducted in R using the Wilcoxon signed rank test for paired data.[12–14] Statistical significance level was set at $\alpha = 0.05$.

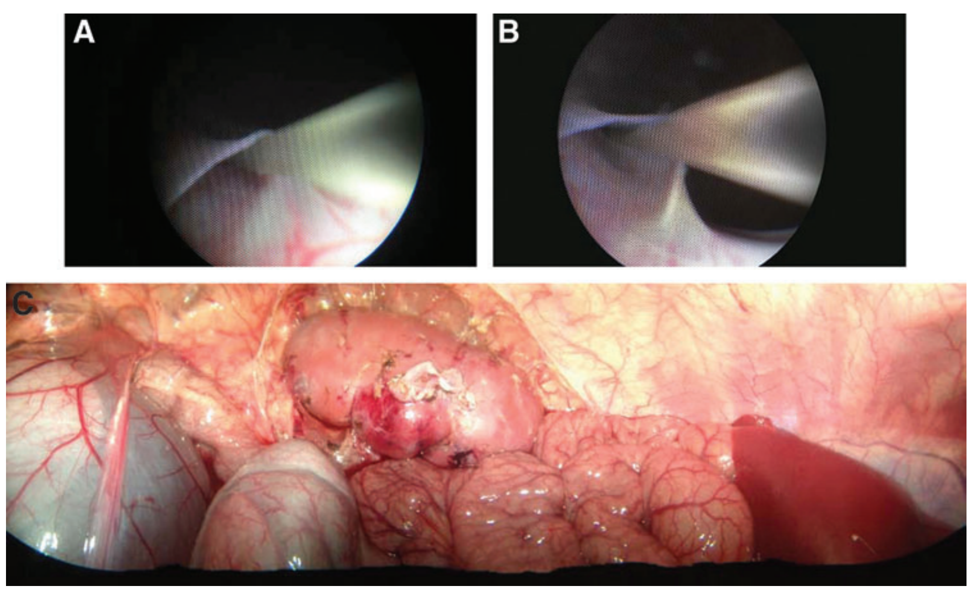

FIG. 5. Flexible cystoscope image of porcine ureteral orifice with nitinol guidewire in place with Endockscope **(A)** and Storz high definition **(B).** Panoramic image of the entire abdominal porcine cavity using the Endockscope system coupled to a laparoscope **(C).**

Results

Image resolution

The Endockscope system compared with a Storz HD system revealed no difference in the image resolution (line pairs/mm) (4.49 *vs* 4.49 lp/mm) (Fig. 3).

Color resolution

The color difference between the color samples and the reference (ΔE) demonstrated that the color resolution for red (ΔE = 9.26 *vs* 9.69) was similar for the two systems. There was better orange (ΔE = 18.13 *vs* 8.54) and yellow resolution (ΔE = 24.47 *vs* 20.51) for the Endockscope system; however, green (ΔE = 7.76 *vs* 10.95), blue (ΔE = 12.35 *vs* 14.66), and purple (ΔE = 11.55 *vs* 29.1) color resolution were better for the Storz HD system.

Weight comparison

The complete Endockscope system weighed (0.47 lb): Endockscope connector (0.16 lb) and the iPhone 4S (0.31 lb). In comparison, the Storz HD camera head weighed (1.01 lb). The standard light cable weighed (1.06 lb).

Cost comparison

The average of two standard HD endoscopic camera costs $15,589, and the video system/receiver costs $31,034. In comparison, the cost of manufacturing the Endockscope was $55 and the iPhone 4S was $99 with contract and $599 without contract (Table 1). The overall total cost was $46,623 for the standard HD system and $154 for the Endockscope plus iPhone 4S with a standard smartphone contract and $654 for the iPhone 4S noncontract purchase (Table 2). The total price difference is $46,469 between the standard and Endockscope system with carrier contract and $45,969 for the noncontract iPhone 4S. The Apple TV system costs $99, which can be used for Airplay display.

Porcine model–expert reviews (Table 3)

Cystoscope (flexible fiberoptic, 16F, Storz). Expert average scores of cystoscopic images for resolution, brightness, color, and overall image were 3.583, 3.667, 3.583, and 3.667, respectively, for the Storz system and 2.750, 3.167, 3.000, and 2.750, respectively, for the Endockscope system. Expert reviews of cystoscopic images acquired with the Storz HD camera were superior in image, color, and overall quality ($P = 0.002$, 0.042, and 0.003). The brightness in the cystoscopic images, however, was not statistically significant ($P = 0.12$); the standard high-powered xenon light source was used with both systems. When queried whether the images were acceptable for diagnostic procedures, experts noted they were acceptable.

Ureteroscope ([URS] flexible fiberoptic, 7F, Storz). Average scores of ureteroscopic images for resolution, brightness, color, and overall image from the experts yielded 2.667, 3.147, 2.833, and 2.833, respectively, for the Storz system and 2.667, 2.417, 2.5, and 2.417, respectively, for the Endockscope system. The expert scores revealed no statistical difference in image, color, and overall quality ($P = 1$, 0.203, and 0.120) between the two systems; of note, the experts rated the brightness with the standard system better ($P = 0.02$) than the Endockscope even though the same high-powered light source was used for both systems. When queried whether the images were acceptable for diagnostic procedures, experts noted they were acceptable.

Discussion

Since the initial description of urethroscopy in 1806 by Bozzini, the cystoscope has undergone multiple transformations over the ensuing 200 years. These advances include the advent of the rod-lens optical system, the high-powered xenon light source, fiberoptic light transmission bundle technology, digital images transmitted via proximally mounted, complementary metal-oxide–semiconductor image sensors, use of LED, and special video and display technology.[15,16] Each step forward has been laden with a marked increase in price and all too often a decrease in durability. This report describes a disruptive technology, which reverses the cost and sustainability trend using state of the art mobile technology to facilitate image display and transmission.

Table 2. Cost Analysis Between Standard High-Definition System and Endockscope

	Standard HD system cost (average of two companies)	*Endockscope cost*	*Difference*
Video system	$31,034	$55	$31,249
Camera	$15,589	$99 (contract) $599 (no contract)	$15,490 (contract) $14,990 (no contract)
Total	$46,623	$154 (contract) $654 (no contract)	$46,469 (contract) $45,969 (no contract)

HD = high definition.

Table 1. Itemized Cost of Endockscope*

Commercially available, focusable 8× macro lens and case for iPhone 4S	$25.00
Stock materials (aluminum, ABS plastic, etc.)	$20.00
Miscellaneous components (screws, switch, wire, etc.)	$10.00
Total	$55.00

*Manufacturing fee not included.

Table 3. Expert Review Analysis

	P *values from Wilcoxon Signed rank test*			
	Image quality	*Brightness*	*Color*	*Overall*
Cystoscope	0.0019	0.1198	0.0418	0.0027
Ureteroscope	1.0000	0.0197	0.2031	0.1198

Statistical significance $P < 0.05$. Shaded P values are not statistically significant.

In this study, cystoscopic image acquisition and resolution with the Endockscope system was equivalent to an existing high-definition surgical camera system; the expert reviewers found the overall image quality to be acceptable for diagnostic purposes. Ureteroscopic image resolution, color, and overall image were similar with the two systems; the brightness with the Endockscope system was judged inferior when coupled to the same high-powered light source. Beyond the current endoscope systems, the smartphone enabled Endockscope system provides additional fingertip functionality—simple and seamless one-touch recording, image sharing, real-time monitoring, and/or image transmission. Mobile technology provides accessibility because of minimal cost, portability, real-time sharing, efficient data collection, and global distribution.

The favorable aspects of this adaptation of off-the-shelf digital technology are myriad. First, a smartphone is accessible around the world. There are 1.03 billion smartphones in use in the world, and that number is expected to double by 2015.[17] Because of its low cost, the smartphone is also readily available in developing countries. In addition, the fast-moving pace of technology allows older versions of smartphones to be sold at a steeply discounted price. Currently, the iPhone 4 is free with a 2-yr mobile contract and $450 without a contract. The newer iPhone 4S is $99 with contract and $599 without contract, and the newest iPhone 5 is $199 and $699 with and without contract.[18,19] Eventually, these prices are likely to further decrease because a new model is being marketed every 6 months to a year by Apple Inc.. It is sobering to realize that more than 300 Endockscope systems could be purchased for the price of one standard HD system; in essence, this would be enough Endockscope systems to supply 40% of the urologic workforce of England![20]

Second, because a smartphone replaces the camera and video receiver box, no separate video receiver box is needed. The smartphone alone allows image acquisition, image capture, video capture, image projection over a wireless signal to an external monitor, and transmission of endoscopic images to remote devices; the last can be done with one hand while the device is attached to the endoscope during the actual cystoscopic or ureteroscopic procedure. The addition of a secondary display to use Airplay with Apple TV will only add minimal additional costs compared with the HD monitors that are sold with the standard system. The current monitors that are part of a standard tower range from $8,300 to $10,556, whereas a similar quality secondary display that is able to connect with the iPhone costs $475.[21]

In addition, a portable LED light source, such as the Vue-Light™ (Cook) and Brite Light™ (Storz) can be used to allow full portability and easy transfer from one location to another, especially in developing countries where there is poor infrastructure and transportation networks—indeed, by eliminating cables, light boxes, camera heads, and the camera box. All one needs is the endoscope, the Endockscope connector, a smartphone, and portable LED light source to deliver 21st century quality endoscopy to any hospital, clinic, office, or home worldwide.[22,23] In addition, the smartphone does not require a separate video receiver box with optical/hard drive, because the data are all stored within the device. It is, in essence, a portable computer that includes a high-quality camera.

The iPhone 4S has an 8 megapixel camera with autofocus, which allows for high dynamic range imaging, which may improve the quality of image acquisition. Once the endoscopic images are obtained, there are a number of image optimizing applications that may be applied to further enhance the image. Digital zoom can be used either intraoperatively or postoperatively to highlight a structure of interest. Finally, the iPhone camera also includes a panoramic function, which may allow for wide area image acquisition, a feature foreign to the standard endoscope systems. This feature could be very helpful in mapping patients with bladder cancer.

Our color resolution comparison using the sRGB data showed that there were differences noted in the resolution between the standard Storz HD *vs* the Endockscope system. Certain colors such as red, yellow, and orange yielded similar or better color resolution for the iPhone while green, blue, and purple demonstrated better resolution for the Storz HD. The Storz HD has three dedicated sensors for the individual RGB colors, but the iPhone system only has one sensor for all colors; we anticipate this may well change in future generations of smartphones. Be that as it may, it is of note that with a known reference for ΔE for each color, it is possible to use an imaging editing application to make standard color adjustments for an equivalent color resolution to the Storz HD system. This feature, however, was not tested in the current study.

Overall, the expert reviews of image resolution, brightness, color, and image quality for cystoscopy did yield superior images for the Storz HD compared with the Endockscope system. It is noteworthy, however, that the resolution with the cystoscope and the resolution, color, and overall image quality obtained with the URS were not statistically significantly different between the two systems. Likely, the relatively low resolution (small number of fibers, limited light collection) in the flexible fiberoptic URS was a major contributing factor to these favorable results. Preliminary work in our laboratory, using a rigid rod lens laparoscope, showed the Endockscope derived images to be markedly inferior to the images obtained with a standard laparoscopic setup.

Furthermore, we are currently incorporating a LED light system to the Endockscope that will make the entire system self-contained and fully mobile in the same carrying case as the endoscope. The current cost of portable light sources from Cook and Storz range from $700 to $737 (listed price), which are much cheaper than the high-powered xenon light source, which costs $7998 and the light cable cost of $329. Our goal, however, is to develop a self-contained system that is inexpensive with off-the shelf materials. This lightweight light source can be used with rechargeable batteries or AA batteries, so that the entire system can be operable in areas where even electricity is scarce; we have no doubt that solar cells built into the endoscope's carrying case can be used to recharge the batteries, allowing for extended work in the rural, impoverished areas.

Another added benefit is the ability to share videos and images in real-time over the Internet with available applications that complement the smartphone. This will promote telemedicine endoscopy, allowing information to be shared with experts, colleagues, and trainees for real-time consultation (even during the procedure itself), case presentation/discussion, and student education.[2,24] Indeed, this will allow for procedures to be performed in remote locations that lack basic amenities such as a reliable source of electricity (eg, third-world rural community) while simultaneously allowing immediate feedback from experts at an urban site.[25–27]

In addition, the Endockscope can also be used in the emergency department and hospital floor for general diagnostic procedures. Because the system is fully self-contained and portable, this will allow previous cumbersome procedures to be more efficient and cost-saving. Moreover, the data, when acquired from any location, can be tailored to patient-specific care tools with event logs, patient electronic profiles, and recording of the entire endoscopic procedure for later editing.[5] Finally, smartphones continue to gain new features and improvements with each iteration. Rather than relying on the medical device company to update the software and hardware, there will be new consumer driven device options that will further impact on the features and user friendly nature of the smartphone that can then be immediately applied to endoscopy.

There has always been interest in the dissemination of advanced technology to underserved regions and third- world countries to improve global healthcare. With the active promotion of current, inexpensive digital technology we are further empowered to close the healthcare disparity gap. Talukdar and Reddy[23] realized this gap in the accessibility of advanced endoscopy in the rural regions of India and developed a hospital bus with up-to-date diagnostic and therapeutic endoscopic instrumentation. The basic endoscopy unit was set up to match a simple modern endoscopy room with standard equipment. All data collected were transferred (at 512 kbps) back to the telemedicine unit in the parent hospital. Their vision was to improve rural health conditions by providing free clinical, diagnostic, and therapeutic services. Over a 5-year period, the ambulatory endoscopy unit that was contained on a hospital bus had been used to perform 32,756 upper gastrointestinal endoscopic procedures, and the unit visited more than 4837 villages, with a target population of 10 million people.[23]

After the success of this healthcare initiative in India, a Chinese group transformed a train into a mobile hospital to provide advanced technologic healthcare for the rural population.[22] Both groups, however, mention that some isolated areas of India or China could not be reached either by bus or train because of nonexistent roads or tracks for the vehicles; thus, it was difficult and sometimes impossible to mobilize the equipment. This is not the situation with the Endockscope system; this empowers a physician on a motorcycle, bicycle, or hiking trail to bring 21st century endoscopy to the bedside of any patient, in any location worldwide!

One limitation of this study is the lack of human endoscopic images for comparison. We are presently working to further develop this technology for use in human studies: This entails both improved image acquisition and the development of proper encryption to ensure patient information security. In addition, once we incorporate the LED light source to the Endockscope, we will compare the image and color resolution of the flexible cystoscope and URS to the standard high-powered light source.

Furthermore, we are currently developing a sterilizable Endockscope system and also a screen cover system to keep the smartphone sterile throughout the procedure. Moreover, another limitation of the Endockscope is that it only couples with a fiberoptic endoscope and not the latest digital endoscopes. The digital endoscopes, however, are already self-contained units that have a camera and light source incorporated into the system, with no eyepiece onto which to affix the Endockscope system. Finally, we will also proceed to couple the Endockscope to Android™ and Windows™ operating system-based smartphones to study the image and color resolution and increase the accessibility of the Endockscope to all smartphone consumers.

Conclusion

The novel docking system we have developed is successful in the seamless coupling of current mobile technology to urologic flexible endoscopes. This amalgamation of evolving consumer mobile technology with flexible fiberoptic endoscopes may prove to be a critical step in providing the benefits of endoscopically driven healthcare to persons in all communities across the globe. "Have scope, will travel."

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Disclosure Statement

Drs. William Sohn, Samir Shreim, and Hak J. Lee are inventors of the Endockscope. None of the authors have any direct or indirect commercial financial incentive associated with publishing this article. All authors have read and approved the final submitted manuscript.

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Abbreviations Used

HD = high definition
LED = light-emitting diode
sRBG = standard red blue green
URS = ureteroscope