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Optimizing and validating the technical infrastructure of a novel tele-cystoscopy system

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Abstract

Introduction: Bladder cancer is the most costly malignancy to manage per capita due to the technical nature and intensity of follow-up. There are few urologists in rural areas, often necessitating that patients travel hours to receive follow-up care multiple times per year. We plan to train registered nurses and allied health professionals to perform cystoscopies which are monitored and interpreted in real-time by board-certified urologists. The key is to ensure optimal picture resolution to guarantee this technology is not inferior to traditional cystoscopy. Our objective was to develop the technical infrastructure needed for a tele-cystoscopy system through assessment of the transmitted video quality using expert reviewers and crowd-sourcing.

Methods: All combinations of the tele-cystoscopy system were systematically tested using a single Thiel cadaver. The videos were reviewed by expert urologists and general reviewers using a crowd-sourcing website. The video quality responses were assessed to determine concordance between each set of reviewers, and to determine the optimal equipment that should be selected for the tele-cystoscopy system.

Results: Of eight equipment combinations, only two were of high enough quality to be appropriate for medical use. We found there to be strong concordance of responses between the expert and crowd-sourced responses. The trade-offs between cost and tele-cystoscopy system component quality were compared with efficiency frontiers to elucidate the optimal system.

Discussion: We created and tested the feasibility of a tele-cystoscopy system that was deemed suitable for medical diagnosis by a group of experts. We further validated tele-cystoscopy video quality using both experts and recently validated crowd-sourcing.

Keywords

Cost benefits; crowd-sourcing; tele-oncology; telesurgery

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Declaration of Conflicting Interests

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Introduction

Bladder cancer is the most costly malignancy to manage per capita due to the intensity of treatment and technical nature of the follow-up.¹ Bladder cancer is classified into non-muscle invasive disease and muscle invasive disease. Survivors of non-muscle invasive bladder cancer (NMIBC) require frequent surveillance cystoscopy. For high risk NMIBC, European guidelines (European Association of Urology (EUA) and the National Institute for Health and Care Excellence (NICE)) are in accord with the American Urological Association (AUA) recommendations of frequent cystoscopies: at three-month intervals for the first two years, semi-annually for the next three years, and annually thereafter for life. The AUA differs from the EUA guidelines in that the EUA advocates urinary markers rather than cystoscopy to limit the number of unnecessary procedures.^{2,3} The University of Virginia (UVA) serves patients from rural Appalachia ranging from Southwest Virginia, Kentucky, Tennessee, and West Virginia. In these medically underserved areas, there are high rates of smoking, a shortage of providers, and large numbers of uninsured patients necessitating patients to travel hundreds of miles to receive safety net care. Urologists are in abundance in urban areas, but they are in short supply in rural areas. Indeed, this phenomenon has been described worldwide, such as in sub-Saharan Africa.⁴ To increase access to surveillance cystoscopies, we are developing a tele-cystoscopy system. We plan to train registered nurses (RNs) to perform cystoscopies monitored and interpreted in real-time by board-certified urologists at UVA. The United Kingdom (UK) has trained nurses to perform and interpret cystoscopy but our model obviates the need for RN interpretation. Due to the skill and experience needed to interpret cystoscopy, the USA urologic community has been reluctant to adopt a similar strategy. Tele-endoscopies have been used in gastroenterology,^{5,6} but to our knowledge, this is the first instance in the medical literature where real-time surveillance cystoscopies are performed using a telemedicine model. Once developed, this model could be adopted by numerous urology clinics in underserved areas.

Our first objective is to develop the technical infrastructure needed for a tele-cystoscopy system. This technical infrastructure, or tele-pack, consists of the cystoscope, video display interface (cable connector), wireless Internet, codec (compressor-decompressor), and receiver video monitor (Figure 1). The term 'codec' refers to a device or software that encodes and compresses data for transmission then decodes and decompresses it at the other end. S×10 and S×20 in the figure are dedicated video-conferencing systems. Pilot work showed that the specific component used, such as the type of cystoscope, codec, or Internet bandwidth, caused significant change in video image quality. Our initial attempts resulted in video transmissions deemed below diagnostic standards. The issue of video quality has been addressed by a few studies but their technical infrastructures were highly variable and solutions were equipment-specific.⁷⁻⁹

The crux of cystoscopy relies on the visual resolution of the scope and proper technique to maneuver the scope to visualize all parts of the spherical bladder. We employed both expert review and the newer, validated methodology of crowd-sourcing to judge our video quality. Crowd-sourcing is the assignment of work to an anonymous group of individuals. Amazon Mechanical Turk (AMT) is an online labor market that recruits Internet users to complete

small, defined tasks and has been increasingly used in medical research (www.mturk.com). It has been used to rate videos of varying levels of surgical skill with reliable concurrence with medical professionals.^{10,11} We recruited urologists and used an online crowd-sourcing tool, AMT, to rate the video quality.

Our purpose was two-fold. First, we sought to compare the video quality between combinations of components to determine which were adequate for medical surveillance as determined by both crowd and experts. Second, we created an efficiency frontier to compare the video quality with cost to determine the best trade-off among the combinations of components with the goal being to generalize these to any telemedicine clinic.

Materials and methods

Cystoscopy recording

The video optimization process required systematically testing all combinations of the tele-pack components. These combinations of components were then tested in a single Thiel-preserved cadaver. The Thiel fixation process retains the elasticity of the tissues, unlike the traditional formaldehyde method, so the bladder could be examined multiple times without exposing a patient to discomfort.¹² A single urologist performed multiple cystoscopies on this cadaver which had an incidentally noted bladder tumor noted (Figure 2).

Equipment

Two different cystoscopes from Storz were tested, named the C-view and the charge-coupled device (CCD). Both scopes have a charge-coupled device with the camera chip located at the distal tip. The CCD has light fibers coursing through the scope while the C-view has a light-emitting diode (LED) bulb at the distal tip. The two codec units we tested were the S×20 and S×10. The S×20 is capable of conferencing both using H.323 protocol and session initiation protocol (SIP) while the S×10 is a simplified model that will only support SIP. Our network is optimized for SIP and while we maintain compatibility with H.323 we consider it outdated technology in place for interoperability with older systems. Thus, the testing was done using SIP.

In order to record the videos we connected in an Internet protocol (IP)-based Content Server from Cisco. Because this introduced a third party to the video conference we needed to route the connections through our Cisco Multipoint Control Unit (MCU) rather than connect the cystoscope and the physician directly. The Content Server captured the video in Flash Moving Picture Experts Group (MPEG)-4 format at 854480 resolution. Long videos of the entire session were trimmed down to just the relevant portions and had their audio removed to protect protected health information (PHI) as well as mask who was performing the cystoscopy. They were then provided for evaluation in the same Flash MPEG-4 format as the original recording. The original recordings were shortened by editing the beginning and the end to create a length of no more than two minutes. No other modifications to the video quality were made. The videos were placed on the video hosting website, YouTube (1: <https://youtu.be/yio2OQfvenA>; 2: https://youtu.be/6YmF0iW_JVc; 3: <https://youtu.be/X0h4hyKFZyw>; 4: https://youtu.be/jl7cV7_TUu8; 5: https://youtu.be/R0ex_2iqGbos; 6:

<https://youtu.be/TM43Vlr8cbg>; 7: <https://youtu.be/grbHkL8WuXw>; 8: <https://youtu.be/jGq3wb61Yp0>), and randomized sequences of videos were sent to the experts as email links.

For this pilot phase, the physical distance the cystoscopy image and the end unit was less than 100 ft. However, the distance the image traveled along the cables is much less certain. While it was all routed within the UVA network the data had to pass through an assortment of routing equipment and pass through the telemedicine server equipment which is housed in a separate building.

The Internet connection speed was set both as a maximum and as a target. When the connection is negotiated the video codecs tailor the compression and resolution of the conference based on the bandwidth target they have been provided. If there are issues with speed and connectivity the systems can attempt to connect at a lower speed than specified, but they will not connect at a higher speed. For the test, we verified that the video conference connected at the speed we had specified.

The series of combinations tested is depicted in Figure 1. Eight cystoscopies with combinations of cystoscopes, cables, codec, and Internet bandwidth were recorded (Table 1).

The urologist performed all cystoscopies in an identical manner while watching the transmitted video (the same images that telemedicine consulting urologists would see in real time). If lag occurred, the urologist would slow the cystoscopy to generate the clearest video possible. Although the urologist alternated cystoscopes, the urologist was blinded to all other component combinations. All videos were edited to include the entire cystoscopy of insertion, visualization of the urethral orifices, and retroflexion. The videos ranged from 71–113s in length.

Video rating by experts and crowd-sourcing (non-experts)

The eight cystoscopy videos were presented to 18 expert raters consisting of board-certified urologists and urology chief residents blinded to the equipment used, and in a randomized order. They were asked to rate the quality of each video using a five-point Likert scale and whether they considered the video quality appropriate for medical use. No compensation was given.

The cystoscopy videos were also rated using AMT. AMT is composed of “requesters” who assign human intelligence tasks (HITs) and “workers” who complete them. Twenty three workers with unique IDs were recruited. These workers were culled to include only competent workers by requiring them to have completed greater or equal to 5000 HITs and have a HIT approval rating of at least 99%. Each worker was asked to complete one HIT, which consisted of watching eight cystoscopy videos and one negative control video of an out-of-focus cystoscopy (length 1/440s) in random order and answering two associated questions for each video (Figure 3). Each worker was compensated US\$0.50 for completing the HIT. Workers who rated the negative control video as good, very good, or excellent, or answered yes to question B (meaning they would feel comfortable having the video used to diagnose a problem with their bladder, Figure 3) had their answers excluded from the final results.

Efficiency frontier

For each cystoscopy video, we calculated the average rating by experts and the workers. We present scatterplots (one plot for experts and one plot for AMT workers) to display the trade-offs between average rating and estimated cost for each set of potential components. The plots were then analyzed using Pareto optimization and multi-objective trade-off analysis to identify the efficiency frontier, the set of points that are non-dominated in at least one of the outcomes of interest.¹³ The efficiency frontier allows decision makers to determine the equipment combinations that generate the appropriate trade-off between image quality and cost of components. We were primarily concerned with maximizing image quality while secondarily minimizing cost. Based on conversations with the companies, the costs for the components were as follows: US\$29,942 for the CCD scope, US\$16,806 for the C-Mos/C-View scope, US\$2302 for the S×10 codec, and US\$5574 for the S×20 codec. No costs were included in the analysis for the capacity of the Internet or the video display interface.

Concordance analysis

We assessed the concordance between the AMT responses and the responses of the expert reviewers using two metrics. First, we calculated the correlation between the mean responses of the AMT ratings to the mean responses of the expert ratings. We then calculated the mean and standard deviation of the differences (d_i) in mean responses for each question, where

$$d_i = x_i - y_i$$

where x_i is the expert reviewers' mean response to question i and y_i is the AMT mean response to question i .

Analysis of components

We used two-way analysis of variance (ANOVA) with replications to determine which components were significant with respect to the scoring of the video quality. The ANOVA was completed for the set of responses from the experts and separately for the set of responses from the AMT workers.

Results

Expert review

Of the 18 expert raters who received the randomized videos, eight (response rate 44%) completed the questionnaire over 41 days. The average expert ratings are shown in Table 2. Only three of the eight videos (1, 3, and 4) had a majority of experts deem them appropriate for medical use. Videos 3 and 4 had the highest scores at 3.6 and 3.9. Video 4, which was recorded with the CCD scope, higher quality codec, low bandwidth, and DVI-DVI formatting, was deemed by all expert raters as appropriate for medical surveillance purposes (Table 2) The average rating of each video was directly correlated with the percent deeming it medically appropriate ($R=0.971$).

Non-expert review

Out of the 23 unique AMT workers recruited, 18 met the screening criteria. The ratings were completed in 4 h 19 min, and on average it took each worker 13 min 38 s to rate eight test videos and one negative control video. We spent US\$37.50 in total. The experts and non-experts had almost uniform agreement with video 3 and 4 again performing the best. As shown in Table 2, Video 4 again received the highest rating at 3.1 and was deemed by 72% of raters as medically appropriate. Again, there was a direct correlation between video rating and medical appropriateness rating ($R=0.941$).

Efficiency frontier

Figure 4 displays the trade-offs between the average rating and estimated cost for the set of potential components. Based on the efficiency frontiers and a large enough budget, the recommendation would be to purchase the CCD cystoscope with the S×20 codec. While the AMT workers rated the S×10/CCD combination slightly higher when the fast Internet setting was used, the S×20/CCD combination performs well with both slow and fast Internet speeds according to both sets of raters. It is important for the combination of components to perform well under all Internet speeds, since this is based on the bandwidth of the remote telemedicine clinic.

Concordance results

The correlation of responses between the AMT workers and the experts was $R=0.974$, showing a very strong correlation between the sets of responses. Correlation does not show the entire picture, so the differences in mean responses for each question were also analyzed. The mean of the differences was 0.20 with a standard deviation (SD) of 0.43. Videos 1–6 were rated higher on average by the experts (mean difference 0.39, SD 0.27), while videos 6 and 7 were rated higher on average by the AMT workers (mean difference -0.38 , SD 0.16). Overall, the expert responses showed greater differentiation among the videos than the AMT responses showed. Finally, the mean absolute difference in responses was 0.38, so the crowd-sourced responses were less than half a point different from the expert responses on average. Overall we find there to be strong concordance of results.

Analysis of components

Using the expert responses, we find that the scope ($p<0.001$) and the codec ($p<0.001$) significantly affect the video quality rating. Internet speed and all interactions between the components were not significant. Using the AMT worker responses, we find that the scope ($p=0.001$) and the codec ($p<0.001$) significantly affect the video quality rating. The interaction between codec and Internet speed ($p=0.030$) was also significant.

Discussion

We created and tested the feasibility of a tele-pack of components for tele-cystoscopy that was deemed suitable for medical diagnosis by a group of experts. We further validated tele-cystoscopy video quality using both experts and recently validated crowd-sourcing. The two videos deemed to be the best quality were compared in terms of cost with video 4 being the highest quality although the most expensive. Our work provides a scientific rationale for the

tele-pack components needed to expand bladder cancer surveillance in rural regions via our innovative tele-cystoscopy model.

This study used expert opinion and crowd-sourcing to optimize the technical infrastructure of a novel tele-cystoscopy system for improving rural access to bladder cancer screening. We were able to show that crowdsourced ratings were concordant with expert ratings. To our knowledge, this is the first instance where crowd-sourcing was validated as a tool for identifying medically appropriate quality videos for telemedicine. We chose crowd-sourcing over other medical personnel for two reasons. First, crowd-sourcing has been validated in other studies as a method of rating the physical dexterity of a recorded surgery and this was precisely what we were measuring with our study. Second, crowd-sourcing is extremely efficient. The monetary cost is minimal and we received our data in days not weeks.

Our study was unique in several aspects. First, this study systematically tested *all* components of a telemedicine infrastructure for video quality. Previous studies examining telemedicine video quality focused on the transmission components with no mention of the endoscope or video display interface. For example, Rabenstein et al. tested components of the Internet transmission by sending the same endoscope video while varying the bandwidth, codec, and presence of impairments due to Internet traffic.¹⁴ Our study demonstrated the importance of including the endoscope in the optimization process. Between the C-MOS scope the CCD scope, we noted differences of up to 38% in the medical appropriateness rating by experts and up to 39% by AMT workers.

Second, we demonstrated a method for optimizing the component combination adaptable by most telemedicine clinics (figure 5). Any telemedicine setup should transmit high quality images, be reliable, relatively inexpensive, easy to install, and portable. Many possible equipment combinations can fulfill those criteria. For example, one study found that the minimum acceptable bandwidth was 1000 Kbps.⁷ However, the best quality video from this study was transmitted over the low bandwidth of 768 Kbps. Our model allows for low bandwidth Internet to still support telemedicine clinics but substitution of an inferior codex or scope was not acceptable.

Lastly, we employed a novel method of assessing video quality. Expert ratings have been widely used in similar studies because so far there is no adequate non-human method of evaluating video quality. We needed a system that quickly optimizes technical components of telemedicine that can be used by any telemedicine clinic. We demonstrated that AMT workers could rate medical appropriateness of video quality with the same concordance as experts. AMT has been increasingly used in academic research because of its versatility for data gathering. Its biggest advantage is that it is fast and inexpensive. We were able to elicit worker response in four hours compared with the 41 days it took eight out of the 18 solicited experts to respond. This similar response time difference between AMT workers and experts was seen in other AMT studies.¹⁰ In terms of cost, the average effective rate paid for AMT workers was US\$2.27 per hour, much less compared with board-certified urologists.

Numerous studies have demonstrated the concordance of AMT compared with experts in a specific field.^{15,16} Our study demonstrated the AMT could determine whether a video is of

medically appropriate quality as well as expert urologists. This was a reasonable assumption before the study began because the general population, through exposure to television and computers, would have a reasonable idea of what constitutes a good quality video. Moreover, expert urologists are likely basing their responses on video quality they encounter in everyday life. What is significant is that workers are equally able to set the threshold for *medically appropriate* quality videos as experts. Specifically, the experts deemed that five of the videos were not appropriate for medical use. We believe the problem with these recordings were due to sluggishness in transmission leading to poor resolution of the images. This poor resolution made it difficult to distinguish the normal from the abnormal.

There are several limitations to our study. The urologist was not blinded to the scope used and both of these cystoscopes were new to her as she had never used either before. Nonetheless, she may have subtly felt one scope would be better than the other and somehow biased the procedure. Given the scope is only one component, this potential bias should be minimal. For all videos, the urologist adjusted her camera movement to yield the best quality video possible to minimize any bias that could be introduced. Another limitation is that the Thiel cadaver is not widely available in the USA and would limit the ability to test the scope. However, our optimization method can certainly be adapted to whatever components are testable at a clinic, including patient volunteers. Finally, the British Association of Urological Nurses has developed a comprehensive training program to create specialist nurses who perform office cystoscopy. This methodology is somewhat controversial as Radhakrishnan et al. published their experience suggesting that this practice was leading to increased general anesthesia procedures based on the nurse referrals.¹⁷ Rattay et al. published a rebuttal after examining their own hospital practice and found only less than 1% of office cystoscopy was referred for surgery. We are proposing a different methodology that in no way diminishes the UK process.¹⁸

With the optimal components of the tele-cystoscopy found, we will proceed with a pilot study in a telemedicine clinic affiliated with UVA to test the equipment in the field.

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Figure 1. Tele-pack: components needed for tele-cystoscopy. HDMI: High-definition multimedia interface; CCD: Charge-coupled device; DVI: Digital visual interface.

Figure 2. Screenshot of the cystoscopy. Coincidentally, the cadaver had an exophytic bladder tumor that served as a landmark for the cystoscopy.

Click here to watch Video 1

1a. Rate Video 1's image quality:

- ☐ Excellent
- ☐ Very good
- ☐ Good
- ☐ Fair
- ☐ Poor

1b. Would you feel comfortable with this video's image quality to diagnose a problem with your bladder?

- ☐ Yes
- ☐ No

Figure 3.

Screenshot of a video link with two associated questions that were in the human intelligence task (HIT) posted on Amazon Mechanical Turk (AMT). Each HIT includes eight cystoscopy videos and one negative control video.

Figure 4.

Scatterplots depicting the trade-off between ratings and costs for each set of components. (a) presents the ratings for the experts, and (b) represents the ratings for the Amazon Mechanical Turk (AMT) workers. The efficiency frontiers for the slow Internet settings are shown with the dotted lines, and the efficiency frontiers for the fast Internet settings are shown with the solid lines.

CCD: Charge-coupled device.

Figure 5.
Flowchart of equipment optimization process.

Table 1.

The combinations of equipment that were tested in this study.

Video #	Length (m:ss)	Cystoscope ^a	Codec ^b	Internet bandwidth ^c	Cable ^d
1	1:20	C-Mos/C-view	S×20	Low	HDMI-HDMI
2	1:11	C-Mos/C-view	S×20	High	HDMI-HDMI
3	1:53	CCD	S×20	High	DVI-DVI
4	1:16	CCD	S×20	Low	DVI-DVI
5	1:26	CCD	S×10	Low	DVI-HDMI
6	1:37	CCD	S×10	High	DVI-HDMI
7	1:18	C-Mos/C-view	S×10	High	HDMI-HDMI
8	1:24	C-Mos/C-view	S×10	Low	HDMI-HDMI

^aCystoscope: The two scopes tested were the C-Mos/C-view and the CCD.

^bCodec (compressor-decompressor): compresses the video stream when sending and decodes the video when receiving the data to decrease the bandwidth requirement. S×20 is a more advanced codec than the S×10.

^cBandwidth: capacity of the Internet. Low=768 Kbps, high=1472 Kbps.

^dCable is otherwise known as the video display interface.

HDMI: High-definition multimedia interface; DVI: Digital visual interface; CCD: Charge-coupled device.

Table 2.

Average rating and percentage of subjects indicating video was appropriate for medical surveillance use.

Video #	Average expert rating (1–5)	% Expert appropriateness (n=8)	Average AMT worker rating (1–5)	% AMT worker appropriateness (n=18)
1	3.0	63	2.6	34
2	2.9	50	2.5	50
3	3.6	75	3.0	72
4	3.9	100	3.1	72
5	2.0	13	1.8	28
6	2.8	38	2.7	50
7	1.6	0	1.9	11
8	1.1	0	1.6	17

AMT: Amazon Mechanical Turk.