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ORIGINAL ARTICLE

Study on augmented reality for robotic surgery bedside assistants

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Abstract
Robotic surgery bedside assistants play an important role in robotic procedures by performing intra-corporeal tasks while accommodating the physical presence of the robot. We hypothesized that an augmented reality headset enabling 3D intra-corporeal vision while facing the surgical field could decrease time and improve accuracy of robotic bedside tasks. Bedside assistants (one physician assistant, one medical student, three surgical trainees, and two attending surgeons) performed validated tasks within a mock abdominal cavity with a surgical robot docked. Tasks were performed with a bedside monitor providing 2D or 3D vision, or an optical see-through head-mounted augmented reality device with 2D or 3D vision. The effect of augmented reality device resolution on performance was also evaluated. For the simplest task of touching a straw, performance was generally high, regardless of mode of visualization. With more complex tasks, including stapling and pulling a ring along a path, 3D augmented reality decreased time and number of errors per task. 3D augmented reality allowed the physician assistant to perform at the level of an attending surgeon using 3D augmented reality ($p=0.08$). All participants had improved times for the ring path task with better resolution (lower resolution 23 ± 11 s vs higher resolution 14 ± 4 s, $p=0.002$). 3D augmented reality vision with high resolution decreased time and improved accuracy of more complex tasks, enabling a less experienced robotic surgical bedside assistant to function similar to attending surgeons. These data warrant further study with additional complex tasks and bedside assistants at various levels of training.

Keywords Video-assisted surgery · Video display · Augmented reality · Laparoscopy · Robotic surgery · Minimally invasive surgery

Introduction

Bedside assistants play an essential role in the workflow of robotic procedures [1]. In addition to exchanging robotic instruments, they must also perform a variety of laparoscopic intra-corporeal tasks such as inserting and removing sutures, cutting sutures, applying clips, stapling tissues, irrigating, and aspirating fluids from the surgical field [1]. Currently, this must all be performed with a traditional laparoscopic two-dimensional (2D) monitor, while accommodating the physical presence of the robot as a potential obstruction to the video display. It has previously been reported that laparoscopic task performance significantly improves when the laparoscopic view is straight in front of the operator's head and forearms [2], that laparoscopic learning curves are faster under 3D vision [3], and that novices perform laparoscopic tasks better under 3D vision [4]. Thus, the ability of the robotic surgery bedside assistant to view the laparoscopic surgical field in 3D while in proper ergonomic position could significantly impact the operative time and success of the procedure. We hypothesized that an optical see-through head-mounted augmented reality device that permits forward-facing three-dimensional (3D) visualization of the intra-corporeal field regardless of position relative to

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a bedside screen could improve time and accuracy of tasks performed by the robotic surgery bedside assistant.

Materials and methods

Robotic surgery bedside assistants with differing levels of surgical expertise were asked to perform bedside tasks with a da Vinci Xi surgical system docked to trocars inserted into a mock abdominal cavity intended for surgical practice exercises. Participants included a physician assistant (PA), a medical student, three surgical trainees with < 3 years robotic experience, and two attending physicians with 5+ years of robotic experience. Participants were stratified in this manner to most accurately reflect differences in technical skill. Each participant was asked to perform multiple bedside tasks with the robot docked. Tasks included inserting a Maryland laparoscopic dissector and using the instrument to touch a particular straw among other straws (straw touch), inserting a manual endo-gastrointestinal stapler and placing it across rubber tubing at a pre-marked area for the desired staple line (endo-GIA stapling), and moving an elastic ring back and forth along a metal S-shaped pathway using a Maryland laparoscopic dissector to reach different targets (ring path) (Fig. 1a–c). These tasks were selected based on expected bedside assistant maneuvers (straw touch, endo-GIA stapling), and the time/precision required to complete the tasks (ring path).

Tasks were completed with four different visual platforms for the bedside assistant:

(1) A traditional 2D bedside monitor (LMD-X310MT 31-inch 4 K 3D/2D LCD medical monitor, resolution 720P, Sony, New York, NY).
(2) A visual eye shield for 3D visualization with a bedside monitor (LMD-X310MT 31-inch 4 K 3D/2D LCD medical monitor, Sony, New York, NY with CFV-E30SK 3D Eye Shield Kit, Sony, New York, NY).
(3) An optical see-through head-mounted augmented reality (AR) device with 2D visualization of the intra-corporeal field within the user's forward gaze visual field (HoloLens version 1, Microsoft, Redmond, WA).
(4) An optical see-through head-mounted augmented reality device that permits 3D visualization of the intra-corporeal field within the user's forward gaze visual field (HoloLens version 1, Microsoft, Redmond, WA).

Participant position and view are demonstrated in Fig. 1d–f. It should be noted that participants donned the

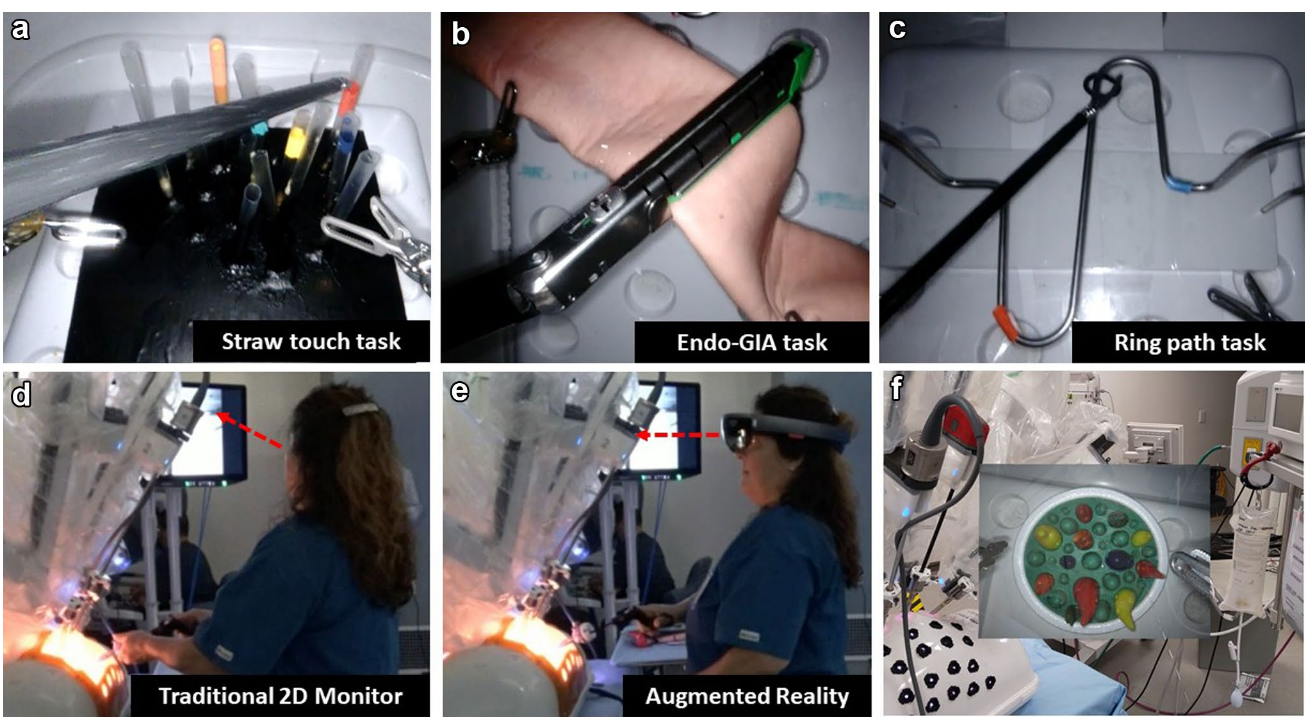

Fig. 1 Experimental tasks performed. **a** Insertion of a Maryland dissector and touching a pre-specified straw (straw touch task). **b** Insertion of an endo-GIA stapler and closing it on a pre-specified location (endo-GIA task). **c** Moving an elastic ring back and forth along a metal S-shaped pathway using a Maryland laparoscopic dissector to reach different targets (ring path task). **d** Use of a traditional 2D bedside monitor with the robot docked. **e** Use of the augmented reality headset with the robot docked; dotted red arrows indicate line of sight for the bedside assistant. *2D* 2 dimensional. **f** User's view with optical see-through head-mounted augmented reality device in place

augmented reality headset with the robotic camera view projected the entire time during exercises in which augmented reality was used, without removal to interact with the surrounding physical space (picking up instruments, placing instruments in trocars, etc.) Testing was first performed with an augmented reality headset with a resolution of 320 × 340 pixels per eye. Testing was repeated with an updated version of the headset which had improved resolution of 640 × 480 pixels per eye. Tasks were all first practiced five times with the traditional 2D bedside monitor to help eliminate influence of practice on times, and then repeated five times with each visual platform. Times were averaged over the five repetitions. The order of the visual platforms tested for each task was varied by participant to further help eliminate the influence of practice on times. Testing was timed and video recorded. Videos were reviewed for the number of errors made per task, and then divided by 5 to produce the average number of errors per task. Errors were defined as follows: straw touch—passing point requiring pulling back, collision with other straws; endo-GIA stapling—passing point requiring pulling back, collision with rubber tube; ring path—passing point requiring pulling back, failed grasping of ring, dropping of ring, pulling the ring in the opposite direction of intended motion.

Values are reported as averages ± standard deviation, and comparisons between groups are made with two-tailed Student's *t* test. Statistical analysis was performed using Microsoft Excel for Mac version 16.4 (Microsoft, Redmond, WA). This research was approved by the IRB at City of Hope National Medical Center and was performed in accordance with all relevant guidelines and regulations. Written informed consent was obtained from all participants. The datasets generated and/or analyzed during the current study are not publicly available due to the large file sizes but are available from the corresponding author on reasonable request.

Results

Task times and errors by visual platform with low resolution

Task times and number of errors by experience level and visual platform with the low-resolution (320 × 340 pixels per eye) augmented reality headset are described in Table 1. Inserting a Maryland dissector and touching a pre-specified straw (straw touch task) took < 9 s with < 1 error per task, regardless of participant experience or mode of visualization. Inserting an endo-GIA stapler and closing it on a pre-specified location (endo-GIA task) was a more difficult task. The physician assistant, medical student, and surgical trainees all had significantly decreased times with 3D and 3D augmented reality vision when compared to traditional 2D visualization for the endo-GIA task. There were no differences in the number of errors per task by operator level or visual platform. By comparison, with the longer and more complex task of moving an elastic ring back and forth along a metal S-shaped pathway using a Maryland laparoscopic dissector to reach different targets (ring path task), only the surgical trainees had decreased times with 3D augmented reality vision compared to traditional 2D visualization (25.7 ± 8.7 vs. 19.1 ± 3.7, $p = 0.04$). There was a general trend towards decreased times with enhanced visualization for the less surgically experienced participants, but these were not statistically significant due to wide standard deviations for times. Again, there were no differences in the number of errors per task by operator level or visual platform. Despite evidence that the augmented reality headset was beneficial, the consensus among the participants was that the low resolution (320 × 340 pixels per eye) was not sufficient for routine use in the operating room. It was also comforting that given the choice between speed or errors, all surgeons in this study chose to be slower to have no errors.

Task times and errors by visual platform with high resolution

All tasks were repeated using a higher resolution augmented reality headset (640 × 480 pixels per eye). During this set of experiments, attending surgeons with > 5 years of robotic experience also participated. All participants agreed that this level of resolution was acceptable for routine use in the operating room.

Task times and number of errors by experience level and visual platform with the high-resolution augmented reality headset are described in Table 2. The straw touch and endo-GIA stapling tasks both took < 9 s with < 1 error per task, regardless of participant experience or mode of visualization. Significant differences by operator level and visual platform were identified with the longer and more complex ring path task. Surgeons (attending surgeons and surgical trainees) generally performed similarly with the ring path task regardless of mode of visualization, in 11.9 ± 6.2 s with 0.9 ± 1.1 errors, however, the physician assistant could perform at the level of an attending surgeon using 3D augmented reality ($p = 0.08$). There was a stepwise decrease in time for the physician assistant as visualization improved, from 2D → 2D augmented reality → 3D → 3D augmented reality (Fig. 2). A similar trend was noted in the number of errors during this task, and there were significantly fewer errors made when the 3D augmented reality vision was used compared to traditional 2D vision (1.0 ± 0.7 vs 4.4 ± 2.7, $p = 0.03$). As noted above, varying test order among participants and pre-testing practice were used to help eliminate a learning bias from affecting these results.

Table 1 Task time and errors by visual platform and operator level with low resolution

	2D time	2D errors	2D AR time	2D AR errors	3D time	3D errors	3D AR time	3D AR errors
Task: straw touch								
Physician assistant	2.1 ± 0.3	0	**2.8 ± 0.6 (*0.04)**	**0.8 ± 0.6 (*0.02)**	**3.6 ± 0.5 (*< 0.001)**	0.2 ± 0.4 (0.34)	3.3 ± 1.9 (0.19)	**0.8 ± 0.6 (*0.02)**
Medical student	2.6 ± 1.2	0.4 ± 0.5	3.5 ± 2.2 (0.11)	0 (0.14)	8.9 ± 6.6 (0.07)	0 (0.14)	4.7 ± 2.0 (0.07)	0 (0.1)
Surgical trainee	5.5 ± 2.2	0	4.8 ± 1.5 (0.38)	0 (1.0)	**2.6 ± 0.6 (*< 0.001)**	0 (1.0)	**2.7 ± 0.7 (*< 0.001)**	0 (1.0)
Task: endo-GIA								
Physician assistant	16.1 ± 1.6	0.4 ± 0.5	14.7 ± 8.2 (0.72)	0.4 ± 0.5 (1.0)	**10.3 ± 1.8 (*< 0.001)**	0.8 ± 0.8 (0.39)	**10.6 ± 2.2 (*0.002)**	0.2 ± 0.4 (0.54)
Medical student	9.6 ± 2.6	0.8 ± 0.8	10.9 ± 4.3 (0.58)	0.2 ± 0.4 (0.19)	**6.4 ± 1.0 (*0.04)**	0.2 ± 0.4 (0.19)	**5.0 ± 0.7 (*0.005)**	0 (0.06)
Surgical trainee	10.6 ± 2.0	0.4 ± 0.5	10.8 ± 1.9 (0.88)	0.7 ± 0.5 (0.19)	**7.0 ± 1.7 (*< 0.001)**	0.1 ± 0.3 (0.13)	**5.3 ± 1.7 (*< 0.001)**	0.2 ± 0.6 (0.45)
Task: ring path								
Physician assistant	48.7 ± 33.7	2.4 ± 3.0	60.7 ± 15.6 (0.62)	4.0 ± 2.0 (0.41)	42.6 ± 42.3 (0.81)	2.2 ± 3.3 (0.92)	31.5 ± 16.2 (0.33)	1.3 ± 2.2 (0.49)
Medical student	25.3 ± 11.1	0.8 ± 0.8	**65.2 ± 35.5 (*0.04)**	1.2 ± 0.8 (0.47)	21.7 ± 7.5 (0.56)	0.6 ± 0.5 (0.67)	18.0 ± 8.2 (0.27)	0.2 ± 0.4 (0.19)
Surgical trainee	25.7 ± 8.7	0.8 ± 1.9	33.3 ± 11.1 (0.11)	1.7 ± 2.1 (0.33)	24.0 ± 15.1 (0.76)	0.8 ± 1.3 (1.0)	**19.1 ± 3.7 (*0.04)**	0.8 ± 1.3 (1.0)

Values are presented as average ± standard deviation (*p* value). The *p* value is for the difference between the traditional 2D platform and other visual platforms)

2D 2 dimensional, *3D* 3 dimensional, *AR* augmented reality

*Bold = significant

Table 2 Task time and errors by visual platform and operator level with high resolution

	2D time	2D errors	2D AR time	2D AR errors	3D time	3D errors	3D AR time	3D AR errors
Task: straw touch								
Physician assistant	4.8 ± 0.3	0.6 ± 0.9	**6.0 ± 1.1 (*0.01)**	0.0 ± 0.0 (0.17)	4.8 ± 1.9 (0.98)	0.4 ± 0.55 (0.68)	5.0 ± 1.0 (0.65)	0.8 ± 0.45 (0.45)
Surgical trainee	3.7 ± 2.0	0.1 ± 0.3	4.3 ± 1.1 (0.48)	0.2 ± 0.4 (0.56)	3.3 ± 1.0 (0.58)	0.0 ± 0.0 (0.36)	3.9 ± 0.9 (0.83)	0.4 ± 0.5 (0.13)
Surgical attending	3.0 ± 1.1	0.2 ± 0.4	4.5 ± 1.0 (0.23)	0.5 ± 0.5 (0.18)	3.9 ± 0.9 (0.08)	0.1 ± 0.3 (0.55)	3.6 ± 1.2 (0.12)	0.2 ± 0.4 (1.0)
Task: endo-GIA								
Physician assistant	6.9 ± 2.3	0.4 ± 0.5	8.3 ± 1.2 (0.20)	0.8 ± 0.4 (0.24)	5.9 ± 1.3 (0.35)	0.0 ± 0.0 (0.1)	8.3 ± 3.1 (0.40)	0.6 ± 0.5 (0.58)
Surgical trainee	5.8 ± 1.4	0.4 ± 0.5	5.9 ± 1.3 (0.89)	0.3 ± 0.5 (0.66)	5.8 ± 1.6 (0.96)	0.4 ± 0.5 (1.0)	5.4 ± 1.1 (0.96)	0.4 ± 0.5 (1.0)
Surgical attending	6.6 ± 2.0	0.4 ± 0.5	5.8 ± 3.6 (0.47)	0.4 ± 0.5 (1.0)	**5.1 ± 1.6 (*0.04)**	0.1 ± 0.3 (0.13)	6.5 ± 2.8 (0.89)	0.5 ± 0.5 (0.67)
Task: ring path								
Physician assistant	26.4 ± 10.3	4.4 ± 2.7	23.9 ± 13.0 (0.70)	2.0 ± 1.9 (0.14)	20.2 ± 7.3 (0.23)	2.4 ± 1.7 (0.20)	**16.7 ± 3.1 (*0.04)**	**1.0 ± 0.7 (*0.03)**
Surgical trainee	8.3 ± 1.4	0.6 ± 0.5	10.2 ± 3.7 (0.10)	0.7 ± 0.8 (0.75)	9.7 ± 9.4 (0.59)	0.7 ± 0.7 (0.71)	11.9 ± 3.5 (0.59)	0.8 ± 0.9 (0.71)
Surgical attending	13.9 ± 4.8	0.9 ± 1.4	**18.6 ± 4.3 (*0.02)**	2.1 ± 1.3 (0.06)	9.7 ± 7.3 (0.09)	0.8 ± 1.2 (0.87)	13.3 ± 4.1 (0.75)	0.5 ± 0.7 (0.44)

Values are presented as average ± standard deviation (*p* value). The *p* value is for the difference between the traditional 2D platform and other visual platforms)

2D 2 dimensional, *3D* 3 dimensional, *AR* augmented reality

*Bold = significant

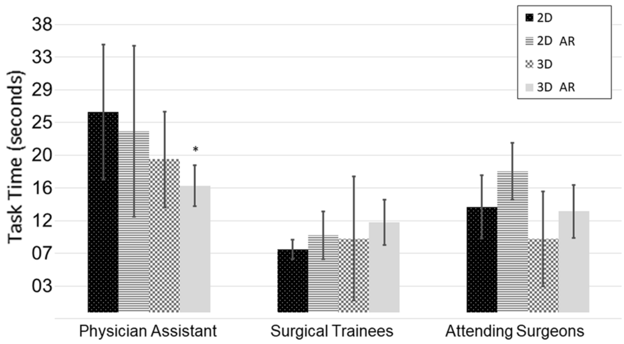

Fig. 2 Ring path task time by operator level and visual platform, high-resolution augmented reality. Bars represent the average time (s) to pull a ring along a metal path by operator level and visual platform using the high-resolution augmented reality headset; error bars are standard deviation, asterisks indicate significant difference from 2D, *2D* 2 dimensional, *3D* 3 dimensional, *AR* augmented reality

Task times and errors by resolution

Task time and errors were compared by level of augmented reality resolution and by dimensions of visualization for both the physician assistant and surgical trainees who participated in both sets of experiments. The endo-GIA stapling task was significantly shorter for surgical trainees using higher resolution 2D augmented reality vision compared to lower resolution (5.9 ± 1.2 s vs 10.8 ± 1.9, $p < 0.001$). There were non-significant trends towards shorter endo-GIA stapling task times with higher resolution compared to lower resolution for trainees with 3D vision and for the physician assistant with 2D and 3D vision. There were 0–1 errors and no significant differences by operator or resolution level. Since the ring path task was more time consuming and of higher complexity, it was best able to quantitatively demonstrate the differences in benefits of higher resolution (Table 3; Fig. 3). Time to complete the ring path task was significantly shorter with higher resolution for both 2D and 3D vision for surgical trainees ($p < 0.001$ for both), and for 2D vision for the physician assistant ($p = 0.002$). While errors ranged from 0 to 6 per ring path task, no differences in errors were detected for surgical trainees or the physician assistant related to resolution alone.

Discussion

Here, we present our experience using an optical see-through head-mounted augmented reality device while performing bedside assistant tasks with a da Vinci Xi surgical system docked to a mock abdominal cavity. This see-through augmented reality device enables bedside assistants to have a forward-facing 3D view of the robotic camera, similar to the console surgeon, while still being able to see their actual physical surroundings to perform instrument exchanges/pass equipment through trocars (Fig. 1e–f). This is imperative, since the user's view of the operating room is not blocked or dependent on device power [5]. Experiments compared outcomes based on image resolution and level of technical skill/experience. We found that when the lowest technically skilled participant, a physician's assistant, performed the most complex tasks, time and number of errors both

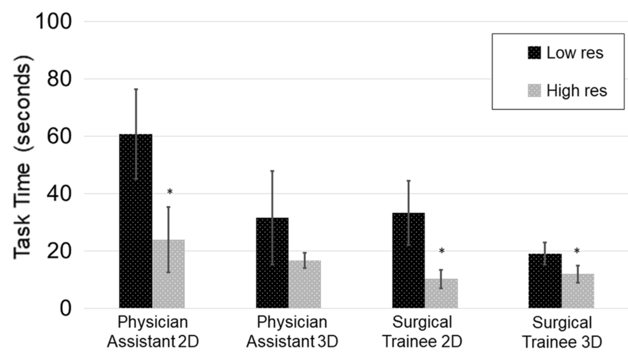

Fig. 3 Ring path task time by operator and augmented reality resolution. Bars represent the average time (s) to pull a ring along a metal path by operator level and augmented reality resolution; error bars are standard deviation, asterisks indicate significant difference from lower resolution, *Res* resolution

Table 3 Ring path task time and errors by level of resolution with the augmented reality headset

	Low Res 2D AR time	Low Res 2D AR errors	High Res 2D AR time	High Res 2D AR errors	Low Res 3D AR time	Low Res 3D AR errors	High Res 3D AR time	High Res 3D AR errors
Physician assistant	60.7 ± 15.6	4.0 ± 2.0	**23.9 ± 11.3 (*0.002)**	2.0 ± 1.9 (0.14)	31.5 ± 16.2	1.3 ± 2.2	16.7 ± 2.7 (0.08)	1.0 ± 0.7 (0.85)
Surgical trainee	33.3 ± 11.1	1.7 ± 2.1	**10.2 ± 3.1 (< 0.001)**	0.7 ± 0.8 (0.18)	19.1 ± 3.7	0.8 ± 1.3	**11.9 ± 3.0 (*< 0.001)**	0.9 ± 0.9 (1.00)

Values are presented as average ± standard deviation (*p* value). The *p* value is for the difference in performance between the lower and higher resolution augmented reality headsets by operator level

Low Res lower resolution, *High Res* higher resolution, *2D* 2 dimensional, *3D* 3 dimensional, *AR* augmented reality

*Bold = significant

significantly improved with 3D augmented reality vision. The decrease in time and number of errors made these values comparable with those from attending surgeons using 3D augmented reality vision. We also found that resolution of the augmented reality headset was important. Specifically, lower resolution (320 × 340 pixels per eye) translated into longer task times for the longer and more complex task when compared to the higher resolution headset (640 × 480 pixels per eye). Participants universally reported they did not feel they could routinely use the lower resolution headset. Thus, we recommend use of 640 × 480 pixels per eye resolution or better when using an optical see-through head-mounted display augmented reality device in the operating room. Our findings taken together suggest that use of such a headset may improve task time and errors specifically for less experienced robotic surgery bedside assistants. Robotic surgery bedside assistants typically have the least amount of surgical experience, especially at training institutions. As such, the use of 3D augmented reality vision for bedside assistants could potentially improve patient safety and decrease operative times, while also decreasing console surgeon frustrations and concerns. This hypothesis should be tested in trials of AR use in clinical robotic surgery.

The augmented reality device used in this study has the potential to support a robotic surgery bedside assistant in two ways: first by enabling the assistant to have their head and body facing forward, in line with the laparoscopic instruments with improved ergonomics, and second by enabling three-dimensional vision of the surgical field. Poor ergonomics and surgeon discomfort during and after surgery can have real implications for career longevity and overall surgeon health [6]. While discomfort varies by surgical approach, with the greatest during laparoscopy, and the least during robotic surgery [7], it should be noted that assessments of ergonomics during robotic surgery are often only performed only for the console surgeons [8]. The bedside assistants in robotic surgery, by comparison, are performing traditional laparoscopic surgery, which has greater physical and temporal demand [9]. One study showed that surgeons spent 98% of the time during laparoscopic procedures with their heads rotated a median of 21° [10]. Another study showed that 73% of robotic bedside assistants reported being uncomfortable for prolonged periods of time during surgery [11]. Viewing the intra-corporeal field in three dimensions also has described benefits. Hinata et al. compared 2D to 3D visualization specifically for robotic surgery bedside assistants with straight forward simulated tasks including suctioning, scissor cutting and applying clips [12]. These authors showed that both novice and experienced participant times improved with 3D visualization [12]. There have been many studies comparing 2D to 3D laparoscopic vision showing decreased operative time [13, 14]; a systemic review noted that the percentage of studies showing a benefit for 3D visualization has increased over time, which may be due to an improvement in the technology [15].

Augmented reality may be used to overlay pre-operatively obtained 3D renderings of axial imaging onto the patient or video monitor, enabling the surgeon to “see” below the surface [16–20]. Patient/image registration, however, is a computationally complex task that remains the greatest limitation of this technology in surgery currently [21]. An advantage of augmented reality headsets, such as used here, is that they do not compromise sterility [20]. A headset can be donned prior to surgery, and the surgeon’s head is not included in the sterile field. These technologies are nascent, but we anticipate they will play a greater role as they develop. Whether registration of 3D reconstructions of cross-sectional imaging onto the patients’ anatomy will have added value will require future studies.

This study has limitations. Attending surgeons were not included in the initial experiments using a lower resolution device, and the sample size was small in this pilot study. The focus of this pilot study was on performance related to time and accuracy; we did not assess user comfort or usability beyond asking participants if the image quality was sufficient. It should be noted that the optical see-through head-mounted augmented reality device used in this study requires an initial calibration to place images in the user’s field of vision. Optical see-through as a methodology for AR has other limitations, including the potential appearance of the AR image floating on top of the background physical surroundings due to issues with occlusion (which image appears closer) [22]. Occlusion of bedside equipment by the projected image was not specifically evaluated in this study, but it should be noted that the projected image was semi-transparent. Other methods for viewing head-mounted augmented reality, such as video see-through [22, 23], were not assessed in the current study. Further, added equipment cost was also not assessed in the current study.

In conclusion, we show here that 3D augmented reality vision with high resolution decreased time and improved accuracy of more complex laparoscopic tasks when compared to traditional 2D laparoscopic monitors. This technology allowed a less experienced robotic surgical bedside assistant to function similar to attending surgeons. There are many potential uses for augmented reality in the surgical arena which are under development. These data warrant further study of head-mounted display augmented reality devices for use during surgery. Future work should assess additional complex tasks, bedside assistants at various levels of training, assessing cost for the use of additional equipment, and determining how AR affects the bedside assistant’s ability to view the docked robot/patient, communication between the bedside assistant and console surgeon, and bedside assistant ergonomics.

Author contributions Research design was performed by the authors CLS, GP, SD, SW, JS, and YF. Data collection was performed by the authors CLS, AF, GP, SD, KL, KT, SW, and YF. Data analysis was performed by the authors CLS and YF. Manuscript drafting was performed by CLS, AF, KL, and KT. Critical revisions to the manuscript were performed by GP, SD, SW, JS, and YF. All the authors reviewed the manuscript.

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Data availability The datasets generated and/or analyzed during the current study are not publicly available due to the large file sizes but are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The data presented here were presented at the SAGES 2020 Annual Meeting, Abstract ID 103931. The authors GP, SM, and JS are employees and stockholders of Intuitive Surgical. The author YF is a scientific consultant for Medtronic, Johnson and Johnson, Olympus, Avra Robotics, Perfint Robotics, and Intuitive Surgical. The author SW is a scientific consultant for Intuitive Surgical. The authors CLS, AF, KL, and KT have no conflicts of interest to disclose. The authors CLS, AF, KL, SW, KT, and YF received no payment of any type from Intuitive Surgical for this work. All data collections were recorded, and all data were analyzed by the participants without conflicts or competing interests.

Ethical approval This study was approved by the IRB at City of Hope National Medical Center.

Consent to participate Written informed consent was obtained from all the participants.

Consent for publication All the authors have reviewed and approved the current version of the manuscript. Written informed consent was obtained from Ms. Kirsten Tallmon to publish her photograph in an online open-access publication within Fig. 1 of the manuscript.

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