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The effect of a second-generation 3D endoscope on the laparoscopic precision of novices and experienced surgeons

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Abstract

Background: Endoscopic surgeons rely on visual feedback to control their movements but lack stereopsis, an important depth cue. Previous three-dimensional (3D) systems alternated images on a two-dimensional (2D) screen, which was uncomfortable for surgeons. A second-generation 3D system provides continuous stereoscopic images on a monitor suspended at arm's length. We studied its effect on the laparoscopic precision of novices and experienced surgeons.

Methods: Experienced laparoscopic surgeons ($n = 12$) and novices ($n = 16$) performed a total of 672 tasks in 2D, 3D, and under direct vision. Precision was assessed using the Imperial College Surgical Assessment Device (ICSAD), which generates objective scores of performance by analyzing the movements of surgical instruments.

Results: We found that 2D endoscopic vision impaired performance by 35–100% when compared with direct vision, whereas 3D reduced this endoscopic handicap by 41–53% in novices and experienced surgeons ($p < 0.03$). No side effects were reported with the new 3D system. Even in 2D, novices performed better with an image at arm's length ($p < 0.03$).

Conclusions: Second-generation 3D significantly improved the laparoscopic precision of novices and experienced surgeons, without the side effects reported from previous systems. This technology is expected to improve the ease and safety of laparoscopic surgery.

Key words: Laparoscopic surgery — 3D laparoscope — 2D laparoscope — Performance — Assessment

Laparoscopic surgery places unusual demands on surgical dexterity. The visual feedback necessary to control movements in three-dimensional (3D) space is currently displayed on a two-dimensional (2D) monitor, tactile feedback is limited, and movement of the instruments is restricted because of the fixed pivot point on the abdominal wall. Although some information about the position of objects in space can be appreciated on a flat screen [7], binocular disparity, which is one of the strongest depth cues, requires different images to be presented to the left and right eyes. Without an accurate judgment of the position of objects in space, precise movements are difficult.

Studies in other disciplines have identified two phases of visual control of precision movement. Initially, the relative position of the target is judged and a "ballistic" movement is started. Correctional submovements then control the rest of the movement in response to visual feedback during the task [4]. Impaired visual information affects both these phases, accuracy and efficiency deteriorate, and additional correctional movements are needed to complete a task. However, training reduces the number of movements required [9].

The difficulty of judging depth in conventional laparoscopy causes surgeons to be less efficient and make more correctional movements than they would in open surgery. Laparoscopic novices are severely handicapped by the lack of stereopsis and make potentially dangerous past-pointing errors. Experienced surgeons use a number of techniques to avoid injury to tissue, such as aligning the horizontal (x) and vertical (y) axes in front of the target before moving in the depth (z) axis. Tracking the movements in x, y, and z of an experienced surgeon using conventional laparoscopic equipment demonstrates this "z lag" (Fig. 1). Both these techniques result in wasted movement.

The potential benefits of 3D imaging in laparoscopy were recognized in 1991 [6], and a prototype was developed in 1992 [1]. A number of studies since have looked at the effect of 3D on performance in the laboratory [2, 3, 5, 8, 13, 15, 16, 19] and in the operating theater [1, 12, 14, 20]. Even

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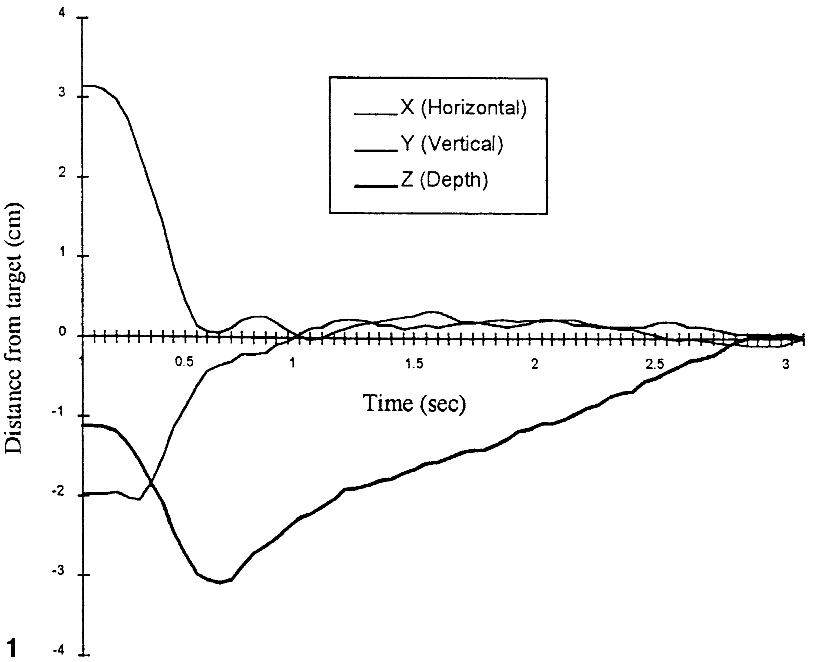


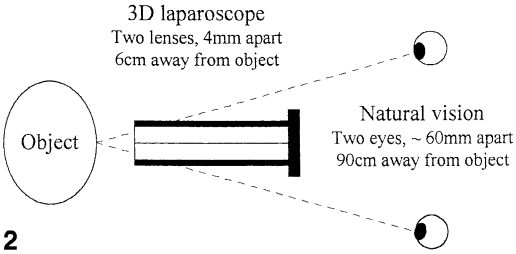


Fig. 1. Tracking of the movement of a single laparoscopic instrument in x, y, and z as it reaches to grasp a target. The horizontal and vertical axes align near the beginning of the movement, but the correct depth positioning of the instrument takes longer. The instrument has been brought in front of the target and then slowly moved backward in line until contact was made.

Fig. 2. Diagram illustrating how the correct retinal disparity can originate from a 3D endoscope with lenses only 4 mm apart.

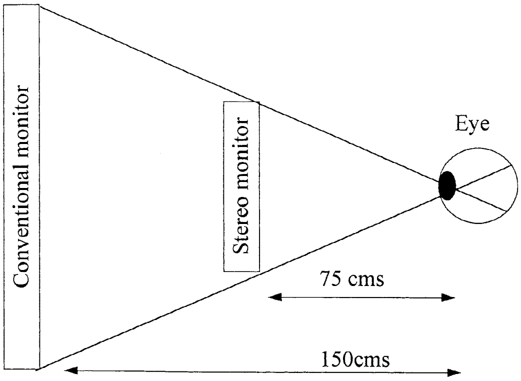
though the majority of studies have demonstrated a significant benefit [1, 2, 8, 13, 15, 16, 19, 20], 3D systems have not been widely used. Many subjects found the image and the glasses uncomfortable. Headaches, nausea, ocular fatigue, and dizziness were reported. A number of investigators recognized that the 3D images created by the first-generation systems were of poor quality and refinements in the technology were needed [3, 12, 14].

A new 3D endoscopic system has been developed that has theoretical advantages over previous systems. This system addresses the problems of flicker, distortion, and the conflict between mismatched depth cues. First-generation 3D endoscopic systems created apparent binocular disparity on a 2D monitor by flickering each image alternately at high frequency (50–60 Hz for each eye). Surgeons were obliged to wear glasses that occluded each eye at the appropriate moment.

The current system presents right- and left-eye views simultaneously on a single monitor and does not alternate the images or occlude the eyes. The equipment is manufactured in two formats. The sophisticated version detects the observer's location and projects the light for each eye's image effectively from the same image plane, but it does so in such a way that the other eye does not receive it. The technology is proprietary (it is a special monitor) and provides the two images simultaneously. Knowledge of the observer's location allows this system to optimize the image for any viewing location. There is no intrusive headgear. The less sophisticated system does not detect the observer's location; instead, it polarizes the light for one eye differently from that for the other. Simple passive glasses allow both images to be observed simultaneously by each respective eye. The glasses-free system is currently in clinical use, while the glasses system was used in the laboratory setting. Except for minor improvements in the subjective image quality of the glasses-free system, the geometry of image acquisition and presentation is identical for both systems.

First-generation 3D systems used a single-lens endoscope (or two smaller lenses), which did not always provide two correct points of view and suffered from image distortion. The current endoscope uses a proprietary optical design, within a standard 10-mm diameter tube, in common with conventional laparoscopes. It requires no special trocars and provides two points of view spaced 4 mm apart. The working distance for the scope can vary considerably while maintaining a comfortable stereo image. At an operating distance of ~60 mm from the end of the endoscope, the relationship between binocular disparity and convergence for the observer is matched to an arm's-length viewing distance (~90 cm) (Fig. 2). Moving the endoscope toward or away from the task causes the degree of binocular disparity to increase or decrease accordingly. This mirrors the effect in natural vision of moving our eyes nearer or further away from an object.

Previous 3D systems presented the images on a monitor placed at the conventional distance (1.5–2.5 m) away from the surgeon's eye. This causes conflict. The eyes converge as we look at near objects, and the angle of that convergence is a strong depth cue. In normal vision, there is no paradox between the angle of convergence and the degree of retinal disparity. If the eyes are forced to converge on a monitor placed the other side of the patient, while the image disparity presented on the monitor is of an object apparently at arm's length, the two sources of depth information contradict. Presenting the 3D image at arm's length from the surgeon should theoretically help to resolve that conflict without affecting the size or resolution of the image on the retina (Fig. 3). The new monitor is provided with a sterile handle. With the aid of a counterbalanced articulated arm, it can be positioned at a comfortable distance from the surgeon's eyes, suspended above the sterile field. The aim of this study was to assess the effect of this second-generation system on the surgical dexterity of novices and experienced laparoscopic surgeons.



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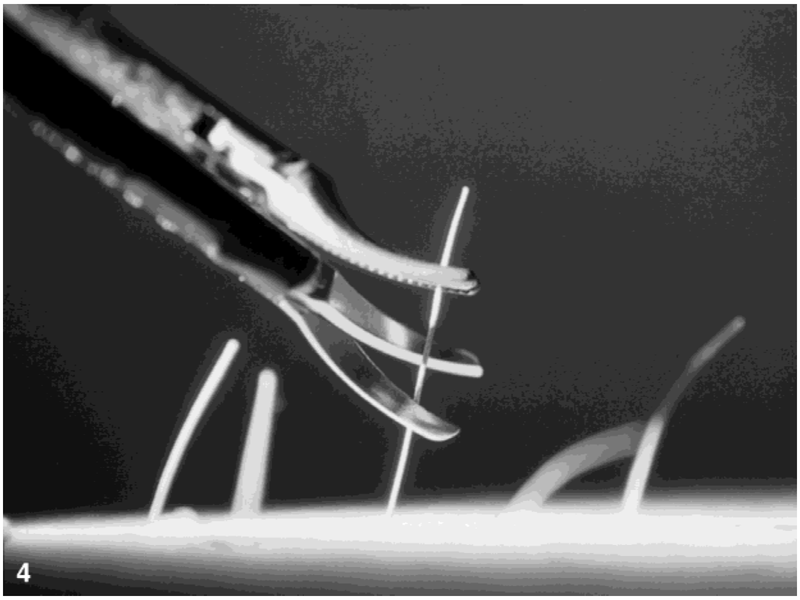


Fig. 3. Diagram illustrating that a conventional monitor at 150 cm and a smaller monitor at arm's length produce identically sized retinal images.

Fig. 4. Novice subjects were tested on a two-handed task, grasping and cutting lengths of suture material.

Methods

Experienced laparoscopic surgeons ($n = 12$) and medical students who had no laparoscopic experience ($n = 16$) volunteered for the study (Table 1). Tasks were performed in a standard closed box laparoscopic trainer under the following four different visual conditions: (a) 2D using a standard 14-in monitor at 150 cm from the subjects' eyes (Storz, London, UK), (b) 2D using the stereo monitor providing a picture half this size at half the distance (Surgical Vision, Reading, UK), (c) 3D using the same stereo monitor as for condition (b), (d) direct vision (by taking the top off the closed box trainer). To control for the effect of magnification, the field of view was the same for all endoscopic systems; therefore, the size of the image on the retina was identical for both the large and small monitor (Fig. 3).

The endoscope was fixed in position (to avoid introducing another variable of having an assistant) at an angle of 45° to the base of the box. The instruments were fixed at a manipulation angle of 60°, to optimize operating conditions [11], and the monitors were at the level of subjects' eyes. The tasks were all set at 60–100 mm from the tip of the endoscope, which matched average operating distances in real life and was a comfortable compromise between magnification, field of view, and stereopsis. The 3D effect works outside this range, but the degree of disparity decreases with distance as it does with natural vision.

The exercises set for the novices and the surgeons differed. Surgeons were asked to perform six suturing tasks in each visual condition: a single running suture (five bites), and five single sutures with a locking square knot as described by Szabo et al. [17] and taught on endoscopic suturing courses. A latex glove (Shermond, UK) was stretched over a pinboard to simulate tissue. Five pairs of circles 6 mm in diameter, 8 mm apart, and spaced at 10-mm intervals were marked in ink on the gloves. All surgeons used Szabo needleholders (Storz) and Vicryl 2/0 suture material (Ethicon, Edinburgh, UK). Because knot tying was a complex task, the quality of the end result was scored. The gloves were coded and the sutures scored by three independent assessors for accuracy and knot tension (maximum score, 25).

Novices were asked to perform six repetitions of a simple grasping and cutting task in each visual condition. Five lengths of suture material protruded 1 cm from holes in a corkboard (Fig. 4). A grasper held by the nondominant hand pulled each suture out a short distance, and scissors in the other hand then cut off the top 1 cm. The order of the different visual conditions was dictated by a Latin square design, which controlled for any carryover effects, such as a learning curve, as well as adding power to the study by enabling comparison both within and between subjects.

Performance end points were quantified using the Imperial College Surgical Assessment Device (ICSAD), which tracks the movements of the laparoscopic instruments. The x, y, and z positions of both instrument tips are recorded 20 times per second. The data are then analyzed to calculate the total distance traveled, the number of movements made, and the time taken to complete the tasks. ICSAD has been validated as an objective assessment device in previous work [18]. Performances under each visual condition were compared. All subjects filled in a questionnaire about the image clarity and user comfort of the 3D system.

Table 1. Details of novices and experienced surgeons

	Novices	Surgeons
Number	16	12
Median (range) age (yr)	20 (18–24)	34 (30–55)
Median (range) laparoscopic experience (yr)	0	5 (2–9)
Median (range) laparoscopic sutures placed in last year	0	50 (20–90)
Handedness (right:left)	14:2	11:1
Corrected vision (yes:no)	6:10	5:7

Statistics

The data were skewed and logarithmic transformation was applied to produce a normal distribution. The geometric mean and 95% confidence intervals were used to describe the data. Within-subject analysis was used to compare the different visual conditions. Performance for each endoscopic visual condition was expressed as percentage impairment compared with direct vision for each individual. The different visual conditions were compared using one-way ANOVA and a priori linear contrasts. The Statistical Package for Social Sciences (SPSS) was used for the analysis, and $p < 0.05$ was considered significant.

Results

There were significant differences in precision and speed of task completion across the four visual conditions (Table 2). For the endoscopic conditions, subjects moved their instruments further, made more correctional movements, and took longer to complete the tasks than with direct vision. There was wide variation in performance between subjects, with some individuals performing better in 2D than others did with direct vision (Fig. 5). Performance in each endoscopic condition was therefore compared with performance under direct vision for each individual surgeon. The difference

Table 2. Objective measurement of time taken, distance the instrument tips traveled and number of movements made to complete task under four different visual conditions

Subject	End point	Direct vision	3D (at arm's length)	2D (at arm's length)	2D (150 cm from subject)
Surgeons (suturing)	Time (sec)	88 (70–110)	115 (93–140)	137 (115–164)	132 (107–162)
	Distance (cm)	412 (339–500)	480 (387–596)	564 (472–672)	538 (443–652)
	Number of movements	79 (64–98)	98 (78–122)	118 (101–138)	110 (89–136)
	Knot score	22.7 (19–24)	22.7 (16–25)	21.8 (18–24)	22.5 (16–25)
Novices (grasp and cut)	Time (sec)	38 (34–43)	55 (46–67)	64 (54–76)	83 (71–96)
	Distance (cm)	94 (83–106)	115 (102–130)	122 (106–140)	153 (129–180)
	Number of movements	18 (16–21)	27 (24–35)	29 (24–35)	38 (31–47)

The laparoscopic surgeons performed a suturing task; the novices performed a simple grasping and cutting task
Values are expressed as geometric mean (95% confidence intervals) except for the knot scores, which are median (range)

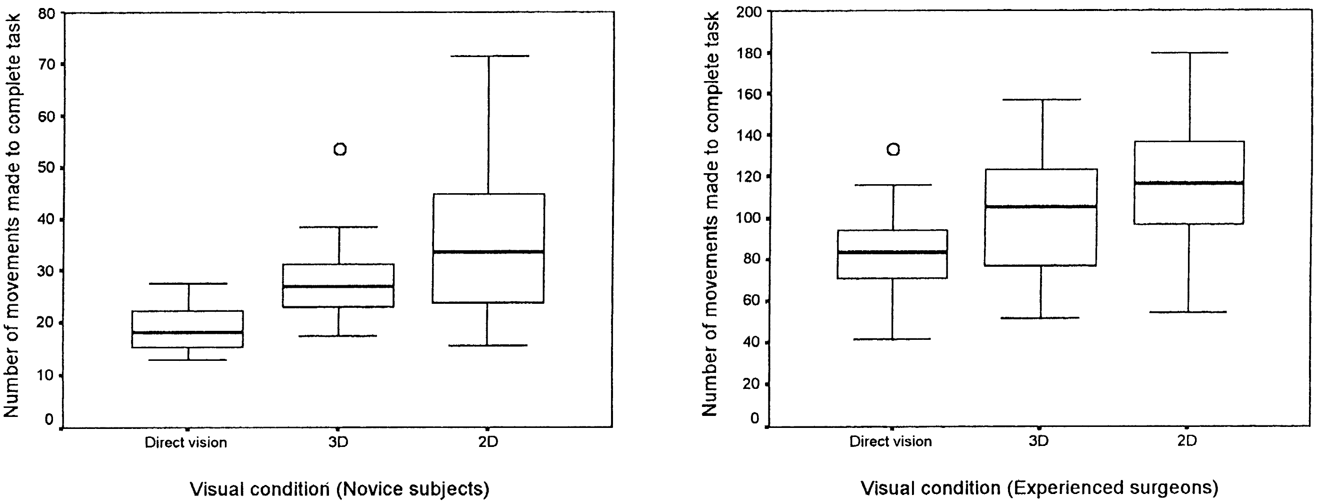
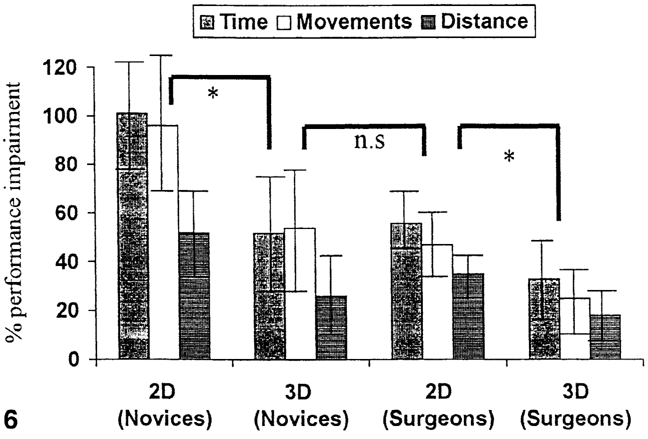


Fig. 5. Box and whisker plot (median, IQR, and range) showing variation among novices and experienced surgeons across all visual conditions.



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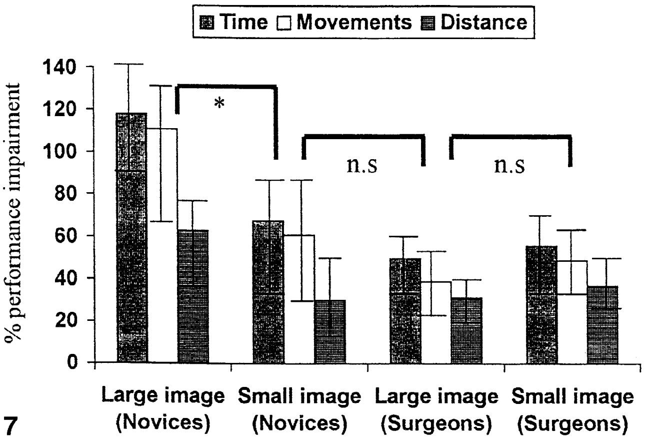

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Fig. 6. The effect of 3D imaging on the performance of novices and experienced surgeons. Mean (95% confidence intervals) impairment of performance when compared with direct vision. *$p < 0.03$ (3D vs 2D, ANOVA, a priori contrasts), ns = not significant.

Fig. 7. The effect of monitor size on the performance of novices and experienced surgeons in 2D. Mean (95% confidence intervals) impairment of performance when compared with direct vision. *$p < 0.05$ (small vs large, ANOVA, a priori contrasts), ns = not significant.

was expressed as percentage impairment; thus, novices made 96% more movements, took 101% longer, and moved their instruments 52% further in 2D than with direct vision. Experienced surgeons adapted well to the 2D environment; their performance was impaired by 47%, 56%, and 35%, respectively. The 3D system halved the additional time, distance, and number of movements needed to complete the tasks. This benefit was significant for both novices and experienced surgeons ($p < 0.03$) (Fig. 6). Monitor size had no significant effect on the experienced surgeons when carrying out procedures in 2D, but novices performed better with a small monitor at arm's length than with the more conventional arrangement of a larger monitor further away ($p < 0.05$) (Fig. 7).

There was no significant difference in the knot quality score for all the visual conditions (Table 2), which ensured that the tasks being performed were identical. No subjects experienced any headaches or difficulties with the 3D view.

Discussion

Surgeons need visual information about depth in order to control the precise movements of their instruments. While there are many depth cues present in an endoscopic image, stereo disparity is lacking. When compared with natural vision, current 2D systems impair performance by up to 100%. A second-generation 3D system reduced this visual handicap in both novices and experienced surgeons by 40–50%. This benefit is larger than has been found in previous studies of 3D systems. These are a number of factors that might explain the differences.

First, there has been progress in 3D technology. Many of the acknowledged problems with the older systems [3, 12, 14] have been addressed. The new 3D system presents binocular disparity in a more natural way, thus perhaps enabling the surgeon to judge the relative position of objects and instruments in space more accurately.

Second, by tracking the movement of surgical instruments, we have been able to objectively measure precision as well as speed. The use of speed alone to assess performance [13, 14, 16] can alter operative strategy. If a stopwatch is used, there is a natural tendency for the subject to rush, regardless of safety issues. Although time is clearly an important factor for theater managers and for planning operating lists, an efficient and accurate technique is likely to have a more significant impact on outcome. Perhaps we should measure the benefit of technological advances not by the number of seconds saved but by the increased ease of the procedure and consequent reduction of risk to the patient.

The third possible reason for the difference between our findings and those from other groups is a purely statistical one. We demonstrated a wide variation in laparoscopic dexterity, with as much as fourfold differences between individuals under the same visual condition (Fig. 5); some subjects performed worse under direct vision than others did in 2D. We were interested in how the visual condition affected performance regardless of how skilled the surgeon was. When comparing a single individual's performance with 3D, 2D, or direct vision, we treated the scores as coming from related samples. Other investigators have measured the effect of a 3D camera by analyzing their data as though they had come from unrelated samples [12] and because of the variation between individuals, failed to find significance despite large differences in the means.

Although previous workers have found that horizontal and vertical displacement of the image influences performance [10], our finding that a smaller 2D image nearer to the subjects' eyes resulted in a significant benefit to novice subjects was a surprise. The amount of information conveyed is related to the number of pixels and not the size of the screen. We therefore expected that monitor size would have a limited effect because the field size and retinal image were identical for both monitors.

One possible explanation for this finding lies in the apparent velocity of instruments as they move across a screen. We draw conclusions about the speed of a passing object by knowing how far away it is. For example, an airplane in the distance may cross our retinal field at the same apparent speed as a bird, yet we are conscious that the distant object is traveling faster. A surgical instrument viewed on a large monitor some distance away will appear to be traveling faster than one on a smaller monitor at arm's length; novices may have found it harder to adapt than experts. The experienced surgeon has spent many years practicing with a monitor at a distance and would be expected to perform slightly better with a larger 2D image farther away than with a smaller 2D image at arm's length, as was indeed the case, although this effect did not reach significance.

About 2% of the normal population have no stereo vision and would not be expected to benefit from the 3D image. Some degree of stereo deficiency is present in a further 15%, and 3D may have limited benefit for those surgeons. Stereopsis was not formally tested in this study, but all the subjects reported being able to perceive the 3D image. Although this study was looking at surgical tasks such as cutting and suturing, it did not evaluate the effect of 3D technology in a clinical setting.

It is difficult to prove that improvements in surgical performance benefit patients. Many variables influence the outcome of surgery, and a large study would be required to control for all the confounding factors. The role of perception in human error is also difficult to quantify; decision processes and experience play an important role. Common sense suggests that improving the visual information available is likely to make any laparoscopic procedure easier and safer. 3D endoscopy could help to decrease operative risk, reduce operative time, and help to widen the minimally invasive repertoire.

The most important factor influencing technical performance in this study was the experience of the individual surgeon. A 3D camera cannot make up for poor technique or bring advanced procedures into the realm of the untrained laparoscopist, but endoscopic surgery needs to be performed safely and efficiently by the average surgeon. In order to achieve that goal, adequate training, accreditation, and the provision of equipment that reduces the difficulty of laparoscopy would seem sensible. This paper addresses results obtained in a laboratory setting. Clinical evaluation, now under way, will provide further data. Initial evidence suggests that the new system increases precision in cautery and dissection.

In conclusion, conventional 2D endoscopic systems impair performance by up to 100% when compared with direct vision. A second-generation 3D system halved this endoscopic handicap in all the objective parameters measured. This benefit was seen in both novices and experienced surgeons. A 3D endoscopic system that improves surgical precision and can be tolerated by surgeons could have important benefits for patients, as well as improving the safety and ease of endoscopic surgery.

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References

1. Becker H, Melzer A, Schurr MO, Buess GAD (1993) 3-D video techniques in endoscopic surgery. Endosc Surg Allied Technol 1: 40–46
2. Birkett DH, Josephs LG, Este-McDonald JSO (1994) A new 3-D laparoscope in gastrointestinal surgery. Surg Endosc 8: 1448–1451
3. Chan A, Chung S, Yim A, Lau J, Ng E, Li A (1997) Comparison of two-dimensional vs three-dimensional camera systems in laparoscopic surgery. Surg Endosc 11: 438–440
4. Chua R, Elliott D (1993) Visual regulation of manual aiming. Hum Mov Sci 12: 365–401
5. Crosthwaite G, Chung T, Dunkley P, Shimi S, Cuschieri A (1995) Comparison of direct vision and electronic two- and three-dimensional display systems on surgical task efficiency in endoscopic surgery. Br J Surg 82: 849–851
6. Cuschieri A (1991) Minimal access surgery and the future of interventional laparoscopy. Am J Surg 161: 404–407
7. Cuschieri A (1996) Visual display technology for endoscopic surgery. J Min Inv Ther 5: 427–434
8. Dion YM, Gaillard F (1997) Visual integration of data and basic motor skills under laparoscopy: influence of 2-D and 3-D video-camera systems. Surg Endosc 11: 995–1000
9. Elliott D, Chua R, Pollock BJ, Lyons J (1995) Optimizing the use of vision in manual aiming: the role of practice. Q J Exp Psych 48: 72–83
10. Hanna G, Shimi S, Cuschieri A (1998) Task performance in endoscopic surgery is influenced by location of the image display. Ann Surg 227: 481–484
11. Hanna GB, Shimi S, Cuschieri A (1997) Influence of direction of view, target-to-endoscope distance and manipulation angle on endoscopic knot tying. Br J Surg 84: 1460–1464
12. Hanna GB, Shimi SM, Cuschieri A (1998) Randomised study of influence of two-dimensional versus three-dimensional imaging on performance of laparoscopic cholecystectomy. Lancet 351: 248–251
13. Jones D, Brewer J, Soper N (1996) The influence of three-dimensional video systems on laparoscopic task performance. Surg Laparosc Endosc 6: 191–197
14. McDougall EM, Soble JJ, Wolf JS, Nakada SY, Elashry OM, Clayman RVAD (1996) Comparison of three-dimensional and two-dimensional laparoscopic video systems. J Endourol 10: 371–374
15. Peitgen K, Walz MV, Holtmann G, Eigler FW (1996) A prospective randomized experimental evaluation of three-dimensional imaging in laparoscopy. Gastrointest Endosc 44: 262–267
16. Pietrabissa A, Sarcello E, Carobbi A, Mosca F (1994) Three-dimensional versus two-dimensional video system for the trained endoscopic surgeon and the beginner. Endosc Surg Allied Technol 2: 315–317
17. Szabo Z, Hunter J, Berci G, Sackier J, Cuschieri A (1994) Analysis of surgical movements during suturing in laparoscopy. Endosc Surg Allied Technol 2: 55–61
18. Taffinder NJ, McManus IC, Jansen J, Russell RCG, Darzi A (1998) An objective assessment of surgeons’ psychomotor skills: validation of the MIST-VR laparoscopic simulator. Br J Surg 85 (Suppl 1): 75
19. van Bergen P, Kunert W, Benell J, Buess G (1998) Comparatives study of two-D and three-D vision systems for minimally invasive surgery. Surg Endosc 12: 948–954
20. Wenzl R, Lehner R, Vry U, Pateisky N, Sevelda P, Husslein PSO (1994) Three-dimensional video-endoscopy: clinical use in gynaecological laparoscopy. Lancet 344: 1621–1622