Three-dimensional versus two-dimensional vision in laparoscopy: a systematic review

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REVIEW

Three-dimensional versus two-dimensional vision in laparoscopy: a systematic review

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Abstract
Background Laparoscopic surgery is widely used, and results in accelerated patient recovery time and hospital stay were compared with laparotomy. However, laparoscopic surgery is more challenging compared with open surgery, in part because surgeons must operate in a three-dimensional (3D) space through a two-dimensional (2D) projection on a monitor, which results in loss of depth perception. To counter this problem, 3D imaging for laparoscopy was developed. A systematic review of the literature was performed to assess the effect of 3D laparoscopy.
Methods A systematic search of the literature was conducted to identify randomized controlled trials that compared 3D with 2D laparoscopy. The search was accomplished in accordance with the PRISMA guidelines using the PubMed, EMBASE, and The Cochrane Library electronic databases. No language or year of publication restrictions was applied. Data extracted were cohort size and characteristics, skill trained or operation performed, instrument used, outcome measures, and conclusions. Two independent authors performed the search and data extraction.
Results Three hundred and forty articles were screened for eligibility, and 31 RCTs were included in the review. Three trials were carried out in a clinical setting, and 28 trials used a simulated setting. Time was used as an outcome measure in all of the trials, and number of errors was used in 19 out of 31 trials. Twenty-two out of 31 trials (71 %) showed a reduction in performance time, and 12 out of 19 (63 %) showed a significant reduction in error when using 3D compared to 2D.
Conclusions Overall, 3D laparoscopy appears to improve speed and reduce the number of performance errors when compared to 2D laparoscopy. Most studies to date assessed 3D laparoscopy in simulated settings, and the impact of 3D laparoscopy on clinical outcomes has yet to be examined.

Keywords Laparoscopy · Three-dimensional imaging · Laparoscopic training · Surgical skills · Three-dimensional laparoscopy

During the past 20 years, the development of new surgical techniques such as laparoscopy has improved treatment of surgical patients by minimizing surgical trauma, accelerating postoperative recovery, and reducing the length of hospital stays [1–4]. However, laparoscopy is more difficult to learn and requires different psychomotor skills than open laparotomy partly because the surgeons have to work in a three-dimensional space and are guided by two-dimensional images [5, 6]. Therefore, surgeons lose depth perception and spatial orientation, and thus experience a higher visual and cognitive load [7–9]. Three-dimensional imaging was developed as an alternative to conventional two-dimensional imaging to overcome some of the challenges associated with laparoscopy [4, 9–12]. However, although 3D technology was introduced in the early 1990s, its equipment is still not standard at hospitals [13, 14]. This omission may be the result of the previous observation of side effects when using 3D vision systems, a degraded

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viewing condition from poor image resolution, the requirement to wear uncomfortable eyewear, and the system's high cost compared with standard 2D equipment [6, 15].

Only one previous systematic review evaluated the effect of 3D vision on laparoscopic performance [16]. This review only included one randomized clinical trial with high risk of bias. The purpose of this systematic review was to present an overview of the available literature regarding the effect of 3D vision on laparoscopic performance compared with conventional 2D laparoscopy, both in clinical and in simulated settings.

Methods

A systematic review was conducted in accordance with the PRISMA guidelines to identify randomized controlled trials comparing 3D with 2D laparoscopy (Fig. 1) [17]. The literature search was completed on October 15, 2014. The electronic databases MEDLINE/PubMed, Excerpta Medica Database (EMBASE), and The Cochrane Library were used. The following search terms were used: "3D" OR "Depth Perception" OR "Image Processing, Computer-Assisted" OR "Diagnostic Imaging" OR "Video Recording" OR "Imaging, Three-Dimensional" AND "Endoscopy" OR "Laparoscopy" OR "Laparoscopes" AND "Education" OR "In-service Training" OR "Evaluation Studies" OR "Staff Development" OR "Learning" OR "Surgical Procedures, Operative/Education" OR "Task Performance and Analysis" OR "Clinical Competence." See "Appendix 1" for the full search strategy. The search terms were used as free text and MeSH terms. No restrictions existed regarding year of publication or language. The search string was discussed and developed by the primary author with the assistance from a research librarian at the Copenhagen University Library. Two authors (SS and MS) independently performed the initial search and identified all relevant articles by screening titles and abstracts. Two authors (SS and MS) made the final selection of articles after reading the full-text articles and references, and their selection was based on the reporting of all necessary data and in accordance with the pre-defined inclusion and exclusion criteria. Differing opinions on whether to include or exclude papers were resolved through discussion by two authors (SS and MS). If agreement could not be reached, a third author (FB) reviewed the paper and made the final decision. Furthermore, the reference lists of the included RCTs were examined to find additional relevant trials.

Relevant papers were included in the systematic review based on the following eligibility criteria:

Study design Only randomized controlled trials (RCTs) were included. We defined RCTs as studies with abstracts or full texts that stated that the trial participants were randomly assigned to practice or operate using either 2D or 3D laparoscopic vision conditions.

Intervention 3D laparoscopy with different types of 3D vision technology.

Control Conventional 2D laparoscopy.

Data extraction Data extracted from the included RCTs were: year of publication, cohort size, population characteristics, type of skills trained and equipment used, outcome measures, and conclusion. A quantitative meta-analysis was not included given the heterogeneity in the studies in terms of methodology, type of tasks practiced, 3D equipment used, and outcome measures. If the included trial also examined robotic surgery, these data were not included in the results.

Results

A total of 340 articles were screened for eligibility, and 39 potentially relevant trials were identified and read in the full text. Of the 39 trials, six were excluded because they did not state whether they randomized the participants and two were excluded because only the conference abstracts were available (Fig. 1). Thus, we included 31 trials, of which three were performed in a clinical setting (Table 1) and 28 in simulated environments (Table 2). The included participants in the trials were either medical students or surgeons with different experience levels. Tables 1 and 2 present the characteristics of the included trials.

The included RCTs were categorized into four groups according to the effect of 3D vision on (1) performance time, (2) precision, (3) side effects, and (4) cognitive workload.

3D versus 2D effect on performance time

All 31 included trials compared performance time using 3D vision versus 2D vision. Twenty-two trials (71 %) reported significantly reduced performance time using 3D vision systems compared with 2D vision systems. Nine trials (29 %) reported that no significant differences were observed [18–26]. No trials reported that 3D vision resulted in longer performance time.

3D versus 2D effect on precision/errors

A total of 19 articles investigated 3D vision effects on error rate or precision. Twelve trials (63 %) reported a lower rate of errors when the task was performed with 3D vision

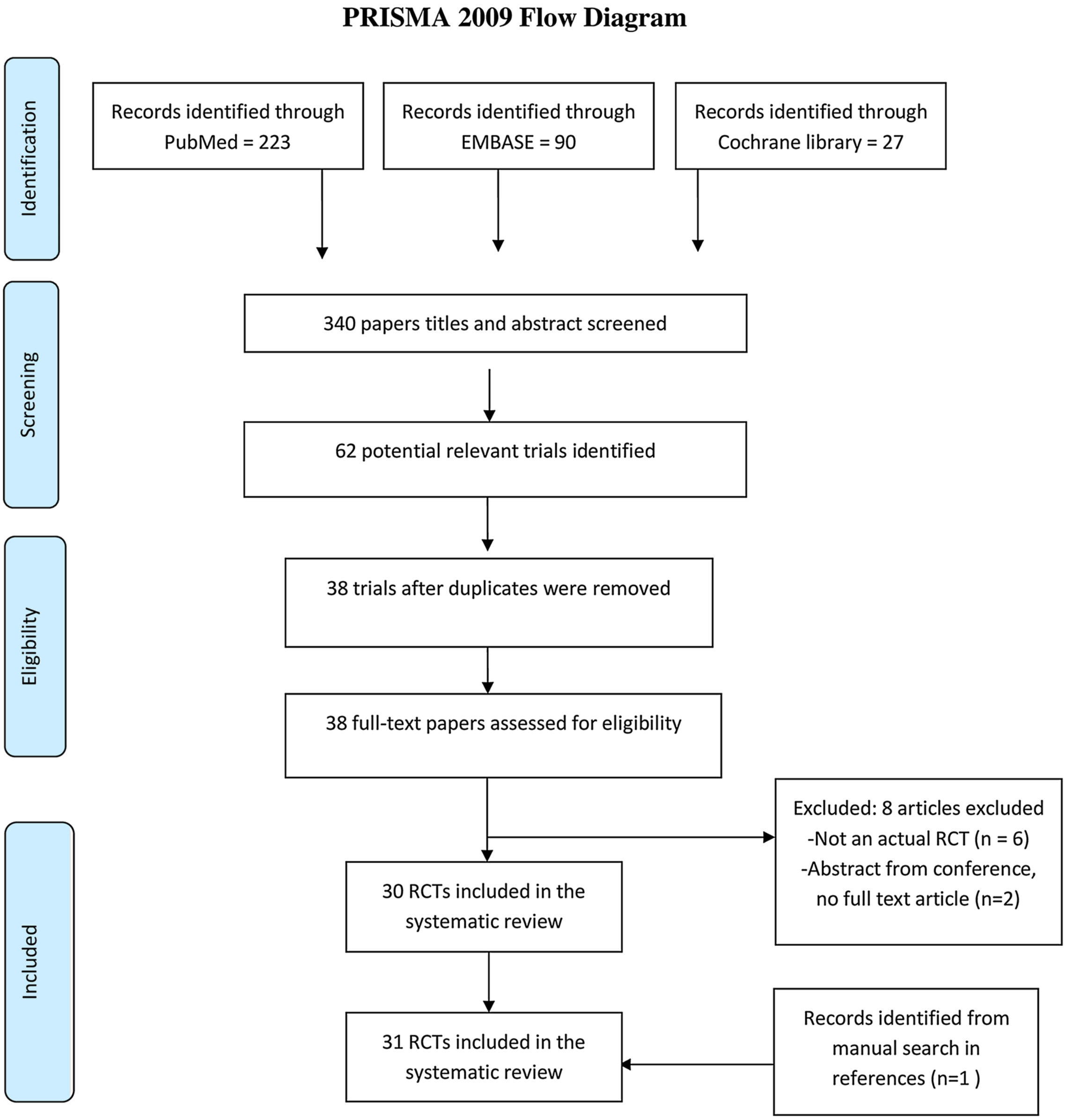

Fig. 1 Flowchart of the selection process of included articles. *RCT* randomized clinical trial

compared with 2D vision [5, 7, 9, 14, 15, 27–33]. Two trials reported more accurate performance in some tasks but not in others [6, 34]. Five trials reported no significant difference in precision/errors using 3D instead of 2D vision [19, 20, 23, 24, 35]. No trials reported a higher number of errors when using 3D.

3D versus 2D effect on laparoscopic side effects

Eighteen of 31 trials measured whether participants felt any side effects when using 3D vision technology. Half of the trials reported side effects [4, 15, 18, 22–26, 34], whereas the other half did not [5, 6, 9, 19, 21, 27, 36–38]. The side effect measures were diverse; however, the most commonly investigated were discomfort, dizziness, eye strain, nausea, and tiredness.

3D versus 2D effect on cognitive workload

Only two studies used a validated workload questionnaire (NASA-TLX) to compare cognitive workload when using either 2D or 3D vision [6, 9]. One of these trials reported a significantly reduced workload when using 3D vision [9], and one trial could not find any significant difference between the two vision systems [6]. Eight trials investigated the subjective evaluation of cognitive workload. Of those eight trials, five trials favored 3D visualization [18, 30, 35,

Table 1 Characteristics of the included RCT carried out in clinical settings

Study	Number of surgeons	Number of patients	Procedures performed	3D equipment	Results	Conclusion
Sahu et al. [4]	One experienced surgeon	3D: 13 patients 2D: 40 patients	Laparoscopic cholecystectomy: 37 Inguinal hernioplasty: 5 Adhesiolysis: 4 Incisional hernioplasty: 3 Ovarian cystectomy: 2 Distal gastrectomy with gastro-jejunostomy: 2	Viking 3D HD vision system	3D surgery showed: Reduced operating time Improved operative parameters ↑ ↑imaging quality, depth perception, hand-eye coordination, intra-corporeal knotting, visual strain	3D laparoscopy is advantageous compared with 2D given the reduced operating time and improved operative parameters, except for operative strain
Kaufman. et al. [38]	One novice and two experienced surgeons	3D: 44 patients 2D: 44 patients	Diagnostic laparoscopies: 21 Bilateral salpingooopherectomies: 16 Unilateral salpingooopherectomies: 8 Ovarian cystectomies: 15 Bilateral tubal ligations: 6 Subtotal hysterectomies: 18 Total laparoscopic hysterectomies: 4	VS-1'insect eye' system: Visionsense	3D surgery showed: Reduced operating time No changes in patient blood loss Subjective evaluation showed an increased depth perception, confidence, efficiency, anatomical understanding and no side effects	3D decreased surgery duration for both novices and experienced surgeons. 3D was associated with increased surgeon confidence and satisfaction with the vision system, without user side effects
Hanna et al. [24]	Four experienced surgeons	3D: 30 patients 2D: 30 patients	Laparoscopic cholecystectomies: 60	Carl Zeiss 3D vision system	3D surgery showed: No change in operating time or error rate ↑depth perception ↓sharpness, contrast, ghosting ↑ visual strain, headache, facial discomfort, ear discomfort, physical discomfort	3D shows no advantage over 2D systems in laparoscopic cholecystectomy. User side effects were worse when using 3D

39, 40] and three reported no significant differences [14, 27, 32].

Discussion

Although 3D vision technology for laparoscopy has substantially improved, thus providing new and better visualization possibilities for the surgeon, it is still not the common standard for laparoscopy. Most of the trials in this systematic review showed a significant reduction in performance time, yet one-third could not find any significant difference between the commonly used 2D vision systems and the 3D vision systems. This lack of a difference may be explained by the diversity of 3D vision systems used in the different trials. The newest RCTs show a benefit in almost 80 % of the studies (2004–2014), whereas only 40 % of the older studies (1994–2004) reported this benefit, possibly attributable to the development of improved 3D visualization equipment (Tables 1, 2). Moreover, observational studies comparing 3D versus 2D vision show the same tendency; the earliest 3D system failed to show any difference, but a more recent study showed the benefits of 3D vision [8, 41]. If 3D equipment reduces operating or training time for new surgeons, the equipment may be a worthwhile investment. Three-dimensional technology is still more expensive than standard 2D equipment [9, 15]. Nevertheless, 3D laparoscopy is more affordable than robotic systems, which also provide 3D vision. However, robotic systems also have the advantage of articulated

Table 2 Characteristics of the included RCT carried out in simulated settings

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Smith et al. [9]	$n = 20$ Experienced	Rope-passing Paper-cutting Needle-capping Knot-tying Repetition 10 NASA (task load index)	3D EndoStereovision (passive eyewear)	3D showed: ↓time ↓errors ↓path length ↑smoothness ↓grasping frequency ↓workload -significant in 4 out of 6 parameters	Passive polarizing 3D displays improved performance and reduced subjective workload dimension ratings for experienced surgeons compared with 2D. A significant advantage exists for experienced laparoscopists when depth perception is introduced in 3D compared with 2D. 3D further enhanced their dexterity
Alaraimi et al. [15]	$n = 50$ Novices	FLS tasks Until proficiency Adverse effect questionnaire (inter-study and post-study)	3D Sony Camcorder model (passive eyewear)	3D showed: → time ↓errors ↓repetitions *Side effects:* ↑ headache and eye strain (1/25) →no reported nausea, dizziness, ↓tiredness	Overall lower performance time for 3D (except for peg transfer median), fewer repetitions with 3D, and fewer errors. Significant values. Stereoscopic vision improved operator accuracy, an effect that was more pronounced for advanced skills (intra, extracorporeal suturing)
Wilhelm et al. [6]	$n = 48$ Intermediates ($n = 24$) Experienced ($n = 24$)	Knot benching repetition 1 NASA (task load index)	(A) 3D HD Sony (polarizing eyewear) (B) 3D Fraunhofer autostereoscopic (display) (C) 3D Frauenhofer custom-built mirror (display)	3D showed: (A) ↓time →precision, ↑precision points per minute →path length ↑instrument velocity →visual discomfort (B) → time →precision, → precision points per minute →path length →instrument velocity ↑visual discomfor (C) ↓time ↑precision, ↑precision points per minute ↓path length ↓instrument velocity →visual discomfort	Faster task performance, greater suturing precision, and no higher mental workload for novel 3D displays compared with 2D. Superior visualization for 3D compared with 2D displays. Benefitting both experienced and inexperienced. NASA: no significant difference

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Lusch et al. [7]	$n = 24$ Novices ($n = 10$) Intermediates ($n = 7$) Experienced ($n = 7$)	Ring transferring (2 min) Ring threading (2 min) Line cutting (2 min) Suturing (1 min) Knot tying (3 min) Peg transferring (2 min)	3D HD Sony (passive polarized eyewear)	3D showed: *ring transferring:* → time, ↓number of rings left, ↓number of rings dropped *ring threading:* ↑number of rings, ↓number of errors *line cutting:* →distance *suturing:* →number of throws *knot tying:* →number of knots, ↑precision *peg transferring:* ↓time, ↓number of pegs left, ↓errors	3D laparoscopy significantly improved depth perception, spation location, precision of surgical performance compared with 2D. Plus, reduction in correctional moved, higher degree of accuracy during grasping, and suturing skill task
Mistry et al. [18]	$n = 31$ Novices	MISTELS (FLS tasks) repetition 1 Subjective evaluation	3D stereoscopic VisionSense VSII (VisionSense 3D eyewear)	3D showed: ↓ MISTEL score: peg transfer → MISTEL score: endoloop, extracorporeal and intracorporeal knot *Subjective evaluation:* In general favor of 3D visualization and 3D eyewear. Discomfort rated 1.43 out of potential 5	No additional benefits when using 3D in naive trainees
Cicione et al. [14]	$n = 33$ Novices ($n = 23$) Experts ($n = 10$)	E-BLUS: peg transfer, cutting, knot tying, clip and cut, needle handling repetition 1 Subjective evaluation	3D Karl Storz camera system	3D showed: ↓time ↓error *Subjective evaluation:* similar easiness for 3D and 2D	Overall, better performance with 3D regarding time, number of errors. Experts were only faster in one task, the novices in three out of five tasks; 3D seems to facilitate the performance of those without laparoscopic experience
Kneist et al. [19]	$n = 44$ Novices ($n = 29$) Intermediates ($n = 10$) Experts ($n = 5$)	Novices: coordination, appendectomy. Intermediates and experienced: ring transfer, fine dissection, cholecystectomy Repetition 1 Subjective evaluation	VRL Simulator (LapSim, SurgicalScience, software version 2011) with 22-Zoll-120-Hz-LCD-monitor. Shutter eyewear	3D showed: →time →error →movement economy subjective evaluation: preference for 3D	3D imaging showed no significant improved performance compared with 2D imaging

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Tanagho et al. [27]	$n = 33$ Novices ($n = 23$) Intermediates ($n = 5$) Experts($n = 3$) Unsure ($n = 2$)	FLS tasks Repetition 5 Subjective evaluation	Viking 3D HD Laparoscopic Vision System	3D showed: ↓time ↓errors ↑ease, ↑efficiency *Subjective evaluation*: →eye strain, headache, dizziness, disorientation, physical discomfort, poor visualization	3D is superior to 2D laparoscopy both regarding objective measures (greater speed, fewer error, fewer attempts to achieve proficiency) and subjective measures: efficiency, accuracy
Honeck et al. [30]	$n = 20$ Novices ($n = 10$) Experienced ($n = 10$)	Ring transfer Peg transfer Needle management Suture cutting Knot tying Repetition 1 Subjective evaluation	3D HD Einstein system	3D showed: →time ↓missed grasps ↓loss of material *Subjective evaluation:* In favor of 3D visualization	Favoring 3D regarding the amount of missed grasps and loss of working material compared with 2D (significant results). Subjective evaluation reported improved spatial orientation and depth perception when using 3D (insignificant)
Smith et al. [29]	$n = 20$ Novices	Rope pass Paper cut Needle capping Knot tying Repetition 10	Passive polarizing stereoscopic display	3D showed: ↓time ↓errors	3D displays significantly improved performance time and precision of novice surgeons
Storz et al. [28]	$n = 30$ Novices ($n = 20$) Experienced ($n = 10$)	Positioning 1 Positioning 2 Ring threading Stitching Suturing Repetition 1	3D HD 6CCD stereo endoscopic camera head. Wavelength multiplex stereoscopic monitor. Stereoglasses (INFITEC GmbH, Ulm, Germany)	3D showed: ↓time ↓errors	3D was superior in four out of five tasks. Participants made fewer errors and were faster, even compared with "up-to-date" 2D HD systems
Silvestri et al. [35]	$n = 16$ Novices	Pick-and-place Peg-in-hole Cutting Suturing Repetition 1 Subjective evaluation	Autostereoscopic monitor (AM) 19-in. (Pavonine Korea Inc) Head-mounted binocular visor (BV) display (HMD), eMagin Z800	3D showed: *pick-and-place:* ↓time (AM and BV)*peg-in-hole:* →time (AM and BV), → errors (AM and BV) *cutting*: →time (AM), ↑time (BV), → errors *suturing:* ↓time *(AM and BV)* *Subjective evaluation:* In favor of 3D visualization	3D interfaces increase accuracy and decrease execution time compared with 2D. 3D vision was significant better for two out of four assignments, and all the participants appreciated the 3D vision systems

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Feng et al. [40]	$n = 27$ Novices ($n = 21$) Experts ($n = 6$)	"Hand-eye coordination" task Time limited: 10 s Subjective evaluation	Stereovision camera (Welch Allyn) 3D goggles	3D showed: →time, ↑speed, →movement economy *Subjective evaluation:* in favor of 3D depth perception	Faster performance with 3D monitor compared with HD and 2D monitor
Votanopoulus et al. [34]	$n = 36$ Novices ($n = 25$) Experts ($n = 11$)	Peg drop (PD) Ring board exchange (RBE) Rope passing (RP) Duct cannulation (DC) Instrumental spatial(IS) Navigation(*N*) Suturing(S) Repetition 1 Subjective evaluation	Endosite 3Di Digital Vision System (Viking Systems). Stereo digital scope (dual 3CCD optical channel). Dual miniature LCD screens attached to a Helmet-type headset	3D showed: *Novices:* ↓time (RBE; DC; *N*), → time: (PD; RP; S) ↓error: (RP; *N*; S), → error: (PD; RBE; DC) *Experienced:* ↓time (DC), → time (PD; RBE; RP; *N*; S) →error (all tasks) *Subjective evaluation:* no nausea, dizziness reported. 20 % inexperienced and 9 % experienced complained of discomfort wearing the head gear	3D imaging is only significantly advantageous in teaching laparoscopic skills to inexperienced versus experienced surgeons
Bittner et al. [36]	$n = 6$ Novices ($n = 2$) Intermediates ($n = 2$) Experts ($n = 2$)	Suturing Knot tying Repetition 2 Subjective evaluation	EndoSite 3Di Digital Vision System (Viking Systems Inc)	3D showed: →time *Subjective evaluation:* excellent graphics, no fatigue, headache, visual disturbances	3D did not improve overall test performance. Subjective assessment showed preference for 3D
Lagrange et al. [20]	$n = 27$ Novices ($n = 17$) Intermediates ($n = 5$) Experts ($n = 5$)	Peg transfer Ring manipulation Cannulation Time limited: 5 min	EndoSite 3Di Digital Vision System (Viking Systems Inc)	3D showed: →time →error	Overall, no significant improvement from 3D compared with 2D. Although 3D seems advantageous (fewer errors and shorter time), in some complex tasks, no significant results were found

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Patel et al. [31]	$n = 17$ Novices ($n = 15$) Experts ($n = 2$)	Linear cutting and suturing Curved cutting and suturing Tubular suturing Dorsal vein complex suturing Urethrovesical anastomosis Repetition 1	3D visualization system (Viking EndoSite, Viking Systems)	3D showed: *Novices:* ↓time ↑accuracy *Experienced:* →time	Trend toward improved task performance using 3D imaging. Improved accuracy and decreased error rates with 3D imaging for novices
Blavier et al. [32]	$n = 40$ Novices	Needle transfer through rings repetition 6 Subjective evaluation	3D video monitor (Storz endoscope)	3D showed: ↑performance score (number of rings passed in 4 min) ↓error *Subjective evaluation:* no significant difference in satisfaction	3D view showed better performance and faster improvement in learning compared with 2D view
Bhayani et al. [39]	$n = 24$ Novices	Bead transferring repetition 1 Subjective evaluation	3D system (EndoSite 3Di) with a head-mounted display	3D showed: ↓time *Subjective evaluation:* in favor of 3D visualization, which was viewed as the easiest	The task was performed significantly more rapidly with 3D imaging than 2D imaging. 3D improves the learning curve. Subjective evaluation: Participants favored 3D imaging as the easiest/preferred imaging
Tevaearai et al. [37]	$n = 9$ Novices ($n = 3$) Intermediates ($n = 3$) Experts ($n = 3$)	Touching dots with needle Passing needle through holes Repetition 5	Vista Series 8000 (Medtronic)	3D showed: ↓time No complaints of side effects (fatigue sensation, headache or muscle strain)	3D vision significantly improved performance and accuracy
Sun et al. [21]	$n = 34$ Novices	Object-pick-up Spatial orientation test Repetition 1	DeepVision (Automated Medical Products Corp)	3D showed: →time No reported dizziness, nausea or vomiting	No significant benefits were gained by 3D imaging
Mueller et al. [22]	$n = 30$ Novices ($n = 20$) Experts ($n = 10$)	Object-pick-up Object transfer Elastic bands transfer Band cutting and removal Repetition 1 Subjective evaluation	3D system (Zeiss) and 3D glasses (unspecified)	3D showed: →time *Subjective evaluation:* adaptation time needed (5), loss of concentration (8), headache (4), distraction by 3D glasses (2)	No significant benefits were gained by 3D imaging

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Taffinder et al. [5]	$n = 28$ Novices ($n = 16$ Experts ($n = 12$)	Experienced: suturing and knot tying Novices: grasping and cutting Repetition 6	Stereomonitor (Surgical Vision)	3D showed: ↓time ↓distance ↓number of movements →knot quality *Subjective evaluation:* No headaches or difficulties	3D improved laparoscopic precision of novices and experienced surgeons without side effects
Herron et al. [23]	$n = 50$ Novices	Rope pass Cup drop Triangle transfer Repetition 1 Subjective evaluation	3D video monitor (Zeiss, Endolive), 3D head-mount display (Vista Medical Technologies)	3D showed: →time →error *Subjective evaluation*: Glasses comfortable to wear (70 %), head-mount display comfortable (18 %). Headache 3D glasses (7 %) head-mount (25 %)	3D shows no advantage over 2D system
Chan et al. [25]	$n = 32$ Novices ($n = 21$) Experts ($n = 11$)	Stringing up beads onto a suture Repetition 2 Subjective evaluation	3D laparoscope (Baxter-V. Mueller VS7700)	3D showed: →time *Subjective evaluation:* 3D improved depth perception(66 %), less clear image resolution (40 %), dizziness/eyestrain (10 %)	No significant benefits were gained by 3D imaging
Peitgen et al. [33]	$n = 60$ Novices ($n = 20$) Intermediates ($n = 20$) Experts ($n = 20$)	Tube test: object grasping and transferring Loop test: needle passing through loops Repetition 1	3D video system (Laser Optik Systeme) (shutter glasses)	3D showed: ↓time ↓errors	3D significantly improved performance (speed and accuracy) regardless of laparoscopic experience
Jones et al. [26]	$n = 30$ Novices ($n = 10$) Intermediates ($n = 10$) Experts ($n = 10$)	Checkerboard Loop pass Suture clip applier Loop ligature Simple suture Repetition 3: novices 1: experienced Subjective evaluation	3DSCOPE model 3000 (American Surgical Technologies Corporation) (passive eyewear)	3D showed: →time *Subjective evaluation:* more instrument control, accuracy (60 %), headache (3 %), nausea (0), eye strain (17 %), in addition to poor lighting (53 %)	No significant difference between 2D and 3D imaging

Table 2 continued

Study	Cohort size (n) and subjects	Study task	3D equipment	Results	Conclusion
Birkett et al. [45]	*Non-surgery:* -movement of objects = 9 operators; -manipulation of needle = 10 subjects; Surgery: n = not explicitly stated	Non-surgery: Movement of objects Manipulation of needle Repetition 3 Surgery: 3D: 50 2D: uncertain	3DSCOPE	3D showed: *Non-surgery:* →time (movement of beans) ↓time (passing of needles) *Surgery:* ↓time ↓errors Subjective evaluation: depth perception made procedures easier, increased anatomical orientation	Subjective higher ratings of 3D than 2D. Objectively, 3D was significantly quicker than 2D imaging in the suturing task (complex task). The simple task was insignificant with respect to the comparison of duration

instruments [9, 15]. Robotic systems may not be necessary for many routine procedures with benign conditions, for which 3D laparoscopy vision systems may be a more relevant option.

In 63 % (12/19) of the trials, 3D vision showed a reduction in errors, and no trial found that 3D negatively affected the error rate (Table 1) [6, 9, 15].

One research group attempted to explore causes and prevention of laparoscopic injuries and found that the most common reasons for surgical laparoscopic injuries were visual misperception. This result was based on 252 cases of laparoscopic bile duct operations, and for 97 % of all errors the reason was visual misperception [42]. Therefore, the enhancements of 3D vision on visual depth perception may improve the quality of laparoscopic surgery and patient safety [15].

However, 3D vision systems could cause side effects for surgeons, such as eye strain, headaches, dizziness, disorientation, and physical discomfort [22, 25]. These side effects were investigated several times, and the literature showed inconsistent results [6, 24, 27, 34, 37].

More recent studies had a tendency to show fewer or no side effects compared with previous 3D vision models. This tendency may be attributable to the decreased image quality in the initial studies compared with the more advanced systems used today [6, 7, 9, 15].

The most important benefit of using 3D vision systems is improved depth perception, which may reduce the surgeon's cognitive workload [27]. Only two studies focused on the effect of 3D vision on cognitive workload under laparoscopic surgery, and the results were contradictory. Therefore, additional studies investigating the effect of 3D vision on cognitive workload need to be carried out before any conclusion can be reached.

Several studies investigated the effect of 3D vision on the performance of surgical novices, and the majority found that 3D vision improved performance [15, 27, 29, 30, 35, 40]. The claim was made that experienced laparoscopic surgeons learned to manage the loss of depth perception attributable to their extensive 2D laparoscopy experience, thus leading to the conclusion that no additional benefit can be gained using 3D vision systems. Some studies confirmed this statement [14, 31]; however, recent studies showed that the performance of even experienced surgeons improved when using 3D vision [4, 6, 9].

Moreover, 3D vision was suggested as primarily giving surgeons an advantage during more complex laparoscopic operations or simulation tasks [2, 9, 15, 43]. Nevertheless, studies reported that 3D laparoscopy is also advantageous for non-complex tasks [6, 27–29].

Given the quality of the included RCTs, coming to a definite conclusion is difficult. Only one of the studies [15] included in this review followed the CONSORT statement

[44]. Moreover, only five of the 31 trials included presented study flow charts [6, 15, 24, 28, 34], and approximately 35 % of the trials included explained the type of randomization model used [5, 6, 9, 14, 15, 20, 23–25, 29, 34]. The remaining two-thirds of the randomization models used in the RCTs were unknown, resulting in high risk of bias. An a priori sample size calculation with sufficient power estimation was performed in only three of the included RCTs [9, 15, 29].

Because of the aforementioned limitations and the heterogeneity of the included studies, a meta-analysis was not included, which is a limitation of the current review. The RCTs included are heterogenic with respect to task type, outcome measures, and applied equipment. This heterogeneity could explain the contradictory results of the effects of 3D vision on laparoscopic performance.

Future studies of higher quality using better methodology and validated assessment tools in simulation settings are needed. In addition, only a few clinical studies examined 3D visualization, and these showed contradictory results. Thus, additional clinical studies are required before being able to conclude whether 3D is effective in the clinical setting and, more importantly, has an effect on patient outcomes.

Overall, 3D laparoscopy appears to improve speed and reduce the number of performance errors when compared to 2D laparoscopy. The side effects associated with 3D laparoscopy are less common when using the newest technology. Most studies to date examined 3D in simulated settings; the effect of 3D laparoscopy on clinical outcomes has yet to be explored.

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Appendix 1: Full search strategy

PubMed (223 articles)

Search ((((((((((((3d OR "three dimensional") AND laparoscop* AND (training OR education OR "task performance") NOT medline [45])) OR (((((3d) OR (("Depth Perception"[Mesh]) OR "Image Processing, Computer-Assisted"[Mesh] OR "Diagnostic Imaging"[Mesh:NoExp] OR "Video Recording"[Mesh:NoExp] OR "Imaging, Three-Dimensional"[Majr:noexp]))) AND ((("Endoscopy"[Majr] AND laparoscopy)) OR "Laparoscopy"[Majr] OR Laparoscopes)) AND ((((("Education"[Mesh] OR "Inservice Training"[Mesh] OR "Evaluation Studies as Topic"[Mesh:NoExp] OR "Staff Development"[Mesh]) OR "Learning"[Mesh]) OR "Surgical Procedures, Operative/education"[Mesh])) OR "Task Performance and Analysis"[Mesh] OR "Clinical Competence"[Mesh])))))))))))

EMBASE (90 articles)

3D.mp./or exp depth perception/or image processing/or exp *three dimensional imaging/AND exp *laparoscopy/or Laparoscopy.mp./AND exp medical education/or exp clinical competence/or exp in service training/or exp training/or exp staff training/or exp surgical training/or exp task performance

Cochrane Library (28 articles)

("3D" or "depth perception" or "three dimensional imaging") and ("laparoscop*")

In Title, Abstract, Keywords in Cochrane Reviews'

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