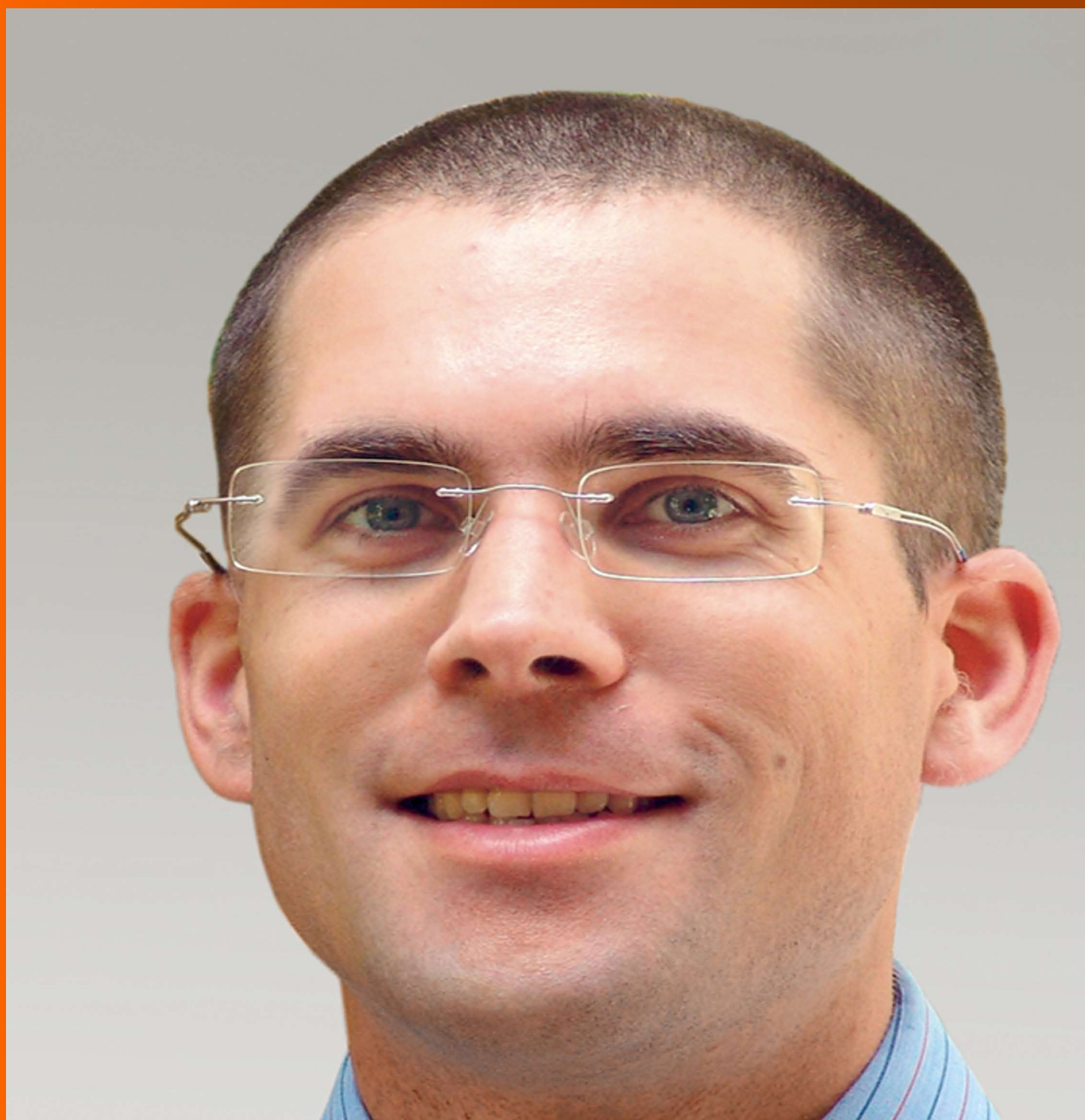


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WJGE covers topics concerning gastroscopy, intestinal endoscopy, colonoscopy, capsule endoscopy, laparoscopy, interventional diagnosis and therapy, as well as advances in technology. Emphasis is placed on the clinical practice of treating gastrointestinal diseases with or under endoscopy.

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Evolution of stereoscopic imaging in surgery and recent advances

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Abstract

In the late 1980s the first laparoscopic cholecystectomies were performed prompting a sudden rise in technological innovations as the benefits and feasibility of minimal access surgery became recognised. Monocular laparoscopes provided only two-dimensional (2D) viewing with reduced depth perception and contributed to an extended learning curve. Attention turned to producing a usable three-dimensional (3D) endoscopic view for surgeons; utilising different technologies for image capture and image projection. These evolving visual systems have been assessed in various research environments with conflicting outcomes of success and usability, and no overall consensus to their benefit. This review article aims to provide an explanation of the different types of technologies, summarise the published literature evaluating 3D vs 2D laparoscopy, to explain the conflicting outcomes, and discuss the current consensus view.

Key words: Three-dimensional laparoscopy; Endoscopy; Three-dimensional displays; Minimally invasive surgery; Stereoscopic

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Core tip: Capture of true stereopsis from the operative field is crucial for the subsequent projection of a high quality stereoscopic image. The latest three-dimensional (3D) systems using dual channel stereoendoscopes and passive polarizing stereoscopic projection generate high quality 3D images for minimally invasive surgery. There is subjective and objective laboratory based evidence supporting use of 3D vs two-dimensional for surgeons of all experience. However, their clinical application has yet to be addressed with Level 1 evidence.

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INTRODUCTION

When Phillippe Bozzini first designed and used his "Lichtleiter" in 1803 to peer into the human body, the medical world unwittingly became reliant on observing the endoscopic view of the human body in only two-dimensions (2D).

In 1838 Charles Wheatstone^[1] was the first to accurately describe and publish the phenomenon of stereopsis - "... the mind perceives an object of three dimensions by means of the two dissimilar pictures projected by it on the two retinae ...". He described in his paper how the illusion of light projecting outwards from the surface of a metal plate that had been turned on a lathe had brought him to this realisation. He demonstrated the validity of his proposed mechanism of stereopsis by creating the "Wheatstone Stereoscope". This created an illusion of stereopsis simply by projecting different images to each eye of the viewer. By adjusting each image to give an impression of the perspective that would have been seen by that eye the viewer was left with a sense of a three-dimensional (3D) image.

The first endoscopic procedures were performed with single eyepiece rigid scopes which provided a monocular view for the operating surgeon. In the 1970s these images were relayed *via* a camera to a video monitor. Thus was born the modern era of "off screen" videoscopic operating. In the late 1980s the first laparoscopic cholecystectomies were performed and popularity for laparoscopic surgery began to increase exponentially. This prompted a sudden rise in surgical and technological innovations as the benefits and feasibility of minimal access surgery became more universally recognised. As minimal access surgery became more widely adopted the steepness of the learning curve for surgeons became more apparent. In particular the monocular laparoscopic view providing two-dimensional viewing, and associated reduced depth perception, became the focus of technological advances. Attention therefore turned to producing a usable 3D endoscopic view for surgeons, utilising different technologies for image capture and image projection. These evolving visual systems have been assessed in various research environments with conflicting outcomes of success and usability, and no overall consensus to their benefit.

This review article aims to provide an explanation of the different types of technologies, summarise the published literature evaluating 3D vs 2D laparoscopy, to explain the conflicting outcomes, and discuss the current consensus view.

First stereoptic views

Binocular microscopes were first used in 1922 in

otolaryngology to overcome the lack of depth perception associated with monocular operating microscopes by surgeon Gunnar Holmgren (1875-1954), Head of the University Clinic of Stockholm^[2]. These provided a stereoptic magnified view of the operating field and were quickly adopted by Otolaryngology, Neurosurgery and Orthodontics. In the 1980s, a German surgeon, Dr. Gerhard Buess^[3], pioneered Transanal Endoscopic Microsurgery (TEMS) utilising the first "stereoendoscope" with two optical channels, viewed through binocular eye pieces. In 1992, his team trialed the first prototype laparoscopic stereoendoscope in animal studies and clinically during laparoscopic cholecystectomies, and concluded the stereopsis facilitated complex laparoscopy^[4].

Image capture

In the laparoscopic setting, an image of the operative field may be captured in one of two ways. A traditional rod-lens laparoscope may be used to transmit the light from the image to outside the patient where a video camera then captures the image and sends it as an electrical signal to an image processor. Rod lens technology is now being superseded by "chip on the tip" technology utilizing small camera chips which capture the image at the tip of the laparoscope and then transmit the electrical signal along the laparoscope to an image processor.

The technology used to capture the 3D characteristics of the operating field includes the laparoscope, the camera and the image processor. Various systems have been developed and trialed in the literature. Single channel systems attempt to extract two perspectives of the operative field from a single point of view by splitting the image either with a prism or filter. The result is therefore not a true binocular image^[5]. Dual channel systems provide two horizontally separated images and thus produce two truly different perspectives of the operative field. "Insect eye" scopes allow for multi images to be captured and processed simultaneously. There is significant variety in the design of the video capture systems, which results in differences in the quality of the perceived image.

Projection systems

Projection systems aim to deliver the 3D view to the observer. Early systems used active shuttering projection, where alternate left and right views are displayed at high frequency on a display. With these systems the operator wears active shuttering glasses so that each eye receives only the corresponding right or left eye image. Robotic systems evolved to use a fixed viewing environment, where, like in a microscope, the observer has a separate image displayed to each eye. This concept was used in Head Mounted Displays (HMDs) where each eye was provided with its own screen to achieve stereopsis. The latest commercial projection systems use passive polarizing technology, which allows for two images to be projected simultaneously in different polarized waveforms. A high definition image is made

up of 1080 horizontal pixel lines. For passive polarizing projection the image projected has odd horizontal pixel lines emitting light polarized vertically and even lines emitting light polarized horizontally. The user then wears lightweight polarizing glasses to separate the correct image to each eye. The horizontal resolution of the image is therefore reduced by half to 540 pixels but the vertical resolution remains at 1080 pixels and the resulting image therefore remains high quality. When this technology was transferred from cinema projection systems to home television monitors the opportunity to use this system in the operating theatre became a possibility.

More recently there has been the experimental development of complex waveform projection systems (advanced systems based on anaglyph separation), autostereoscopic "glass-free" displays and holographic displays.

LITERATURE REVIEW

We aimed to identify from the literature, all published work evaluating 3D laparoscopic systems compared to 2D standard "classical laparoscopic" systems. PubMed, EMBASE, Ovid and Medline were used as search engines to identify any published full English language papers since 1996 which referenced stereopsis, 3D, vs two-dimensional or 2D, laparoscopy, endoscopic surgery, imaging and 3D. Overall, 361 titles were identified and 275 were discounted on further review of their titles. Of the 86 abstracts reviewed, 45 were further discounted as they didn't compare 3D with 2D. Review of these 41 papers acknowledged another six papers not identified by the original search. In total, 47 papers reported assessing 3D imaging systems against 2D systems in laparoscopic surgery. A further four titles were discounted on reading the whole paper, leaving 43 to be assessed. Ninety-six percent of the studies describe laboratory based experiments, involving a variety of laparoscopic skills tasks, some from validated curriculum programmes and others designed to mimic advanced laparoscopic skills. The studies also use a variety of subjects from non-surgical participants to those with a variety of experience in laparoscopic surgery.

The number of tasks, repetitions, cross over in visual systems, assessment of a learning curve and number of individual subjects involved varied in each study. Universally, the common themes assessed in the majority of studies were the time for task completion and performance, either by clearly defined errors or by other assessment defined scoring systems.

There has been speculation for the last 18 years over the benefit of 3D operating visual systems, largely based on conflicting reports in the literature and the ongoing evolution of the system technology. We separated data by the type of optical or projection system in order to clarify the results and explain the conflicting outcomes observed by different researchers.

Single channel endoscope studies

We identified 13 studies which used single channelled scopes to capture the laparoscopic view (Table 1). Seven of these studies^[6-12] utilised active shuttering projection systems with only one study^[7] identifying a significant improvement in outcomes using the 3D system compared to the 2D standard. All of these studies also reported poor subjective outcomes associated with the 3D systems, including visual strain, headaches and nausea as well as an awareness of flickering of the screen. Four studies^[13-16] assessed a second-generation 3D system, which used a single channel scope and projected left and right images to head mounted display systems, allowing individual eye projection without loss of light or image quality. Three of the studies reported significant improvement in performance for novices. The HMDs, although bulky, did not cause any of the cortical disturbances reported by the active shuttering systems. The final two studies^[17,18] used single channel scopes and the latest passive polarizing systems. Neither identified a significant difference in respective outcomes with the 3D systems. Both studies reported that a period of adaptation was required to overcome any higher processing symptoms that the 3D visual system induced^[17].

Dual channel endoscope studies

Robotic "fixed screen" studies: Nine studies investigated the effect of stereopsis in laparoscopic surgery utilising the Da Vinci robotic system (Intuitive, California United States) (Table 2)^[19-27]. Stereopsis is achieved with a binocular endoscope and two camera heads for separate left and right image capture. Each image is received by the respective eye, simultaneously using a fixed console, alleviating the need for shuttering, polarizing or head mounted projection. All studies reported significant improvement in performance with the Da Vinci system in 3D mode over 2D mode. Notably, performance advantages were independent of participant experience^[27].

Studies using screen projection and eye-glass technology

Five studies reported outcomes with binocular stereo-endoscopes (Table 3), alternating screen image and active shuttering glasses^[28-32]. Four of the five studies reported significant improvements in performance with 3D systems^[28-32]. In the one study (Wentink *et al.*^[30], 2002) the screen was placed very close to the surgeon while the working environment from the stereoendoscope was 12 cm. This produces conflict between convergence and focus for the operating surgeon, and it is therefore unsurprising that the 3D system showed poorer performance.

Eight studies evaluated passive polarizing screen and glass technology (Table 3)^[33-40]. Two of these studies retrospectively compared a series of operations (laparoscopic cholecystectomies and laparoscopic

Table 1 Single channelled scopes

Ref.	Year	Projection system for 3D	Who and what assessed	Objective outcomes	Subjective outcomes
McDougall <i>et al</i> ^[6]	1996	Active shuttering screen and glasses	22 urological and gynaecological surgeons, non-novice Pig-lab, laparoscopic vessel dissection and securing, suturing and knot tying	Time for completion. No significant difference found	3D not felt to enhance image quality or enhance performance. Blurred vision and eye fatigue with 3D
Dion <i>et al</i> ^[7]	1997	Active shuttering screen and glasses	Surgeons and non-surgeons. Lab visual (<i>n</i> = 8) and motor skills (<i>n</i> = 9)	Time and errors. Improvement in both with 3D	Glasses bothersome and dizziness reported
Chan <i>et al</i> ^[8]	1997	Active shuttering screen and glasses	32 surgeons, 11 with and 21 without laparoscopic experience 1 × lab based skills task	Time for completion in 2D and 3D (1 repetition). No significant difference	50% felt no improved performance although 66% felt depth perception improved 40% felt reduced image quality and dimmer; 10% reported dizziness and eyestrain
Hanna <i>et al</i> ^[9]	1998	Active shuttering screen and glasses (A/S)	4 surgical SpRs performing 60 laparoscopic cholecystectomies	Time for completion and errors No significant difference	Visual strain, headache and facial discomfort with 3D system
Mueller <i>et al</i> ^[10]	1999	Active shuttering screen and glasses	30 subjects (10 with and 20 without laparoscopic experience) 4 × lab based skills tasks for all, then experienced did suturing tasks	Time for attempts, and success/failure of attempt No significant difference	Reported loss of concentration, headaches and distraction with 3D system
Herron <i>et al</i> ^[11]	1999	3D (active shuttering screen and glasses) and 3D HMD	50 laparoscopic novices 3 × lab based skills tasks	Time to completion of 3 skills tasks in each visual system (2 × repetitions) No significant difference	Although 48% preferred 3D A/S screen over all, 7% and 25% respectively reported headaches with 3D screen and 3D HMD. 82% found HMD uncomfortable
Mueller-Richter <i>et al</i> ^[12]	2003	3D (active shuttering screen and polarising glasses) and 3D Autostereoscopic screen	59 laparoscopic novices 3 × lab based skills tasks	Number of completions in time limit and subjective difficulty No significant difference	Flickering reported with both 3D systems
Bhayani <i>et al</i> ^[13]	2005	HMD	24 surgical residents, minimal laparoscopic experience. 1 × lab based skills task	Time for completion in 2D and 3D (1 repetition) Significant reduction in time	> 50% preferred the 3D system and found task easier in 3D No subjective assessment on physical symptoms
Patel <i>et al</i> ^[14]	2007	HMD	15 novices and 2 experts 5 × lab based skills tasks	Time and accuracy in 2D and 3D (1 repetition) of the novices compared to the experts Significant difference in both for novices only in 3D	NA
Bittner <i>et al</i> ^[15]	2008	HMD	2 novices, 2 intermediate and 2 experts 2 × lab based suturing tasks (based on handedness, visual system and articulating needle holder)	Time and accuracy in 2D and 3D (multi repetitions with each variable) No significant difference	83% felt improved depth perception. No reported physical symptoms
Votanopoulos <i>et al</i> ^[16]	2008	HMD	36 surgical residents and medical students (11 with and 25 without laparoscopic experience) 6 × lab based skills tasks (rpt 3/12 later)	Time and errors in 2D and 3D (1 repetition) Significant improvement in time and errors in novice group only	NA
Kong <i>et al</i> ^[17]	2009	Passive polarising screen and glasses	21 novices and 6 experienced surgeons 2 × lab based skills tasks	Time and errors in 2D and 3D (4 repetitions of each over 4 d) Significant reduction in errors in 3D novices, no other significant difference noted	Dizziness and eye fatigue in novice with 3D system which improved with time
Mistry <i>et al</i> ^[18]	2013	Passive polarising screen and glasses	31 medical students (novices) 4 × lab based skills tasks (MISTELS)	Task Performance in 2D and 3D as per MISTELS scoring system No significant difference	No detrimental symptoms with 3D

NA: Not available; 3D: Three-dimensional; 2D: Two-dimensional; HMD: Head mounted display.

Table 2 Dual channel laparoscopes - Robotic fixed screen

Ref.	Year	Projection system for 3D	Who and what assessed	Objective outcomes	Subjective outcomes
Falk <i>et al</i> ^[19]	2001	Da Vinci	15 experienced laparoscopic surgeons 6 × lab based skills tasks (increasing difficulty)	Time and errors in 2D and 3D and 2DHD (1 repetition in each view) Significant differences in time and errors in 3D	Only 33% felt 3D better view No detrimental symptoms reported
Munz <i>et al</i> ^[20]	2004	Da Vinci	11 experienced laparoscopic surgeons 4 × lab based skills tasks	Errors and performance (ICSAD assessment - time, no. movements and distance moved) Significant difference in both in 3D	NA
Moorthy <i>et al</i> ^[21]	2004	Da Vinci	10 surgeons of varying experience Lab based suturing task	Time and distance travelled of instruments in 2D and 3D Significant difference in both in 3D	NA
Badani <i>et al</i> ^[22]	2005	Da Vinci	7 surgeons (3 experienced with Da Vinci, 4 not)	Time and errors	NA
Blavier <i>et al</i> ^[23]	2007	Da Vinci	2 × lab based suturing tasks 40 medical students Lab based skills task	Significant difference in 3D in all areas Errors, performance and learning curve Significant difference in 3D	No detrimental symptoms reported
Byrn <i>et al</i> ^[24]	2007	Da Vinci	12 surgeons of varying experience 4 × lab based skills tasks	Time and errors in 2D and 3D Significant difference in 3D	No detrimental symptoms reported
Blavier <i>et al</i> ^[25]	2007	Da Vinci	60 medical students 4 × lab based skills task (increasing difficulty)	Specific performance metric score Significant difference in 3D in all tasks	No detrimental symptoms reported
Fishman <i>et al</i> ^[27]	2008	Da Vinci and prototype Ames stereoscopic camera	12 subjects of varying exposure to stereoptic systems	Time for completion while altering binocular disparity of stereoptic camera until 0% (matching 2D vision)	NA
Blavier <i>et al</i> ^[28]	2009	Da Vinci	Lab based skills task using Da Vinci manipulator 80 subjects (60 novice individuals and 20 expert laparoscopic surgeons) Lab based task	Significant difference with 3D from binocular disparity Time for task completion and estimation of time in 2D or 3D not both Significant difference in 3D for novices, similar results for experts	NA

NA: Not available; 3D: Three-dimensional; 2D: Two-dimensional.

Table 3 Dual channel laparoscopes - Screen projection and glasses

Ref.	Year	Projection system for 3D	Who and what assessed	Objective outcomes	Subjective outcomes
Birkett <i>et al</i> ^[26]	1994	Active shuttering screen and Active glasses then polarised glasses <i>vs</i> 2D	10 Subjects? experience 2 × lab based skills tasks	Time take for repetitive cycles; No difference in simples task, reduced time in complex task	NA
Peitgen <i>et al</i> ^[29]	1996	Active shuttering screen and glasses	60 subjects (20 novices, 20 beginners, 20 advanced laparoscopic surgeons) 2 × lab based skills tasks	Time and accuracy of tasks Both significantly improved in 3D, independent of experience	NA
Wentink <i>et al</i> ^[30]	2002	Active shuttering screen and polarised glasses <i>vs</i> TFT display <i>vs</i> projection <i>vs</i> standard (2D)	8 surgeons with laparoscopic experience Lab based skills task	Time for task completion, 10 repetitions but only 2 surgeons per visual system No improvement with 3D	Felt image quality poorer with 3D
Jourdan <i>et al</i> ^[31]	2004	Active shuttering screen and glasses	8 experienced laparoscopic surgeons 5 × lab based skills tasks	Time and errors, 10 repetitions each, in each visual system Significant improvement in both in 3D	NA
Feng <i>et al</i> ^[32]	2010	Active shuttering screen and polarised glasses (SD <i>vs</i> 2D SD <i>vs</i> 2D HD)	27 subjects (16 novices, 11 with varying laparoscopic experience) Lab based skills task	Time and economy of movement Time significantly improved over both 2D systems in 3D, economy of movement improved in 3D <i>vs</i> HD, not SD 2D	Felt improved depth perception in 3D
Hubber <i>et al</i> ^[33]	2003	Prototype passive polarising screen and glasses	16 Medical Students (novices) Lab based skills tasks	Time and performance (ICSAD) Improvements in 3D significant over 2D	NA
Honeck <i>et al</i> ^[34]	2012	Passive polarising screen and glassed	10 novices and 10 experienced laparoscopic surgeons 5 × lab based skills tasks	Time and errors (1 × repetition, in only 1 of the visual systems) No significant improvement in time, reduction in errors significant in both groups in 3D	No impairment felt in subjective feedback when using the 3D system
Smith <i>et al</i> ^[35]	2012	Passive polarising screen and glassed	20 novices 4 × lab based skills tasks	Time and errors (10 repetitions of each task in each visual condition) Significant improvement in time and errors in 3D	NA

Bilgen <i>et al</i> ^[36]	2013	Passive polarising screen and glassed	3 surgeons Clinical - 11 laparoscopic cholecystectomies performed in 3D (compared to 11 performed retrospectively in 2D)	Time Significant reduction in time when performed in 3D, compared to case matched lap choles performed previously in 2D	NA
Sinha <i>et al</i> ^[37]	2013	Passive polarising screen and glassed	Retrospective analysis of 451 clinical gynaecological surgery performed in 3D Case matched assessment of 200 hysterectomies performed in 3D vs 2D	Time Significant reduction in operating time and morcellation time when performed in 3D	NA
Cicione <i>et al</i> ^[38]	2013	Passive polarising screen and glassed	33 subjects (10 experts and 23 novices) 5 × lab based skills tasks (Basic Laparoscopic Urological Skills)	Time and errors Overall, significant improvement in time and errors (although experts only improved time in 1 task in 3D)	Subjective Questionnaire - felt tasks were easier in 3D universally
Lusch <i>et al</i> ^[39]	2014	Passive polarising screen and glassed	24 subjects (10 medical students, 7 residents, 7 expert surgeons) 6 × lab based skills tasks	Time and errors 4 out of 5 skills tasks had significantly improved time and errors when done in 3D, independent on experience	Optical resolution and depth perception improved in 3D
Smith <i>et al</i> ^[40]	2014	Passive polarising screen and glassed	20 experienced surgeons 4 × lab based skills tasks	Time and errors (10 repetitions of each task in each visual condition) Significant improvement in time and errors in 3D	Subjective assessments using NASA Task Load Index - improvements with 3D all sections

NA: Not available; 3D: Three-dimensional; 2D: Two-dimensional; HMD: Head mounted display.

gynaecological operations) with case matched procedures in standard 2DHD systems^[36,37]. Both reported a significant reduction in operating times for case matched procedures. Six laboratory based studies identified significant improvements in most of the tested parameters when tasks were performed in 3D^[33-35,38-40]. Two other studies (Honeck *et al*^[34], 2012, and Cicione *et al*^[38], 2013) found varied performance improvements in 3D. Honeck found reduced errors but no significant time improvements, while Cicione *et al*^[38] (2013) found an overall significant improvement with 3D over 2D. These advantages were only observed in the expert subgroup when performing one task, the "Peg Transfer". However both studies only allowed for a single repetition of tasks in 3D and 2D before comparison. In studies which allowed for repetitions and plateauing of the learning curve in both visual environments before comparison, there was a universal improvement when comparing 3D over 2D, independent of experience^[33,35,39,40].

Comparing different scopes and projection systems

Four papers described using more than one type of 3D system in their comparison of 3D vs 2D (Table 4)^[41-44]. Hanna *et al*^[42] (2000) assessed single-channel scope and dual-channel scope systems, both using active shuttering screen/glasses systems compared to a standard 2D system when performing laboratory based bowel anastomosis. The 3D systems were evaluated together, rather than separately and showed no significant difference in time or precision compared to 2D. However, closer analysis of the data implies the dual channel scope demonstrated a trend of improved time and precision compared to its single channel

counterpart. Visual strain was reported using both stereoendoscopes. Wilhelm *et al*^[43] (2014) reported all performance parameters were superior in 3D over 2D using a variety of experimental and commercially available systems, although visual disturbance related to the autostereoscopic screen only. Finally, Wagner *et al*^[44] (2012), compared single channel scope with HMD technology (in 3D and 2D settings) with robotic dual channel fixed screen technology (2D and 3D settings) and demonstrated significant time reductions with robotic 3D across all other laparoscopic outcomes.

Other prototype projection systems

Four publications assessed prototype projection systems (Table 5)^[45-48]. Three used autostereoscopic screen technology with binocular scopes thus negating the need for eyewear^[45,46,48]. Improvements in all outcomes were seen with the 3D group. Storz *et al*^[47] (2011) used a novel projection system with a wavelength multiplex camera and monitor with wavelength polarizing eyewear (a technology based on original anaglyph systems). This again returned a true sense of stereopsis and improvements in outcomes were significant in 3D over 2D.

DISCUSSION

There is subjective and objective laboratory based evidence supporting use of 3D vs 2D for surgeons of all experiences as it provides the most realistic view of the operating field. It is also evident that stereoscopic imaging technology is continuing to evolve to generate higher quality 3D images.

Table 4 Comparing multisystems

Ref.	Year	Projection system for 3D	Who and what assessed	Objective outcomes	Subjective outcomes
van Bergen <i>et al</i> ^[441]	1998	2 × single channelled and 2 × dual channelled scopes + active shuttering screen <i>vs</i> 2D	40 subjects - novices Variety of different models and skills tasks	Times and errors Objectively - significant improvement in 3D throughout	Subjectively - all tasks judged easier in 3D
Hanna <i>et al</i> ^[442]	2000	Single-channel scope + active shuttering screen and glasses; double-channel scope + active	10 experienced surgeons Lab based endoscopic anastomotic suturing	Time, precision of suture placement and pressure leakage score of anastomosis (2 × repetitions in each visual system) 3D systems evaluated together, no significant difference noted in 3D	Visual strain reported with 3D systems
Wilhelm <i>et al</i> ^[443]	2014	Dual channel scope + passive polarising screen and glasses <i>vs</i> 2D <i>vs</i> autostereoscopic screen	48 subjects, varying experience Lab based suturing task	Time, economy of movement (electromagnetic tracking) and workload assessments (using NASA Task Index Score) All performance parameters were superior in 3D	No symptoms in 3D PP system, visual disturbance reported with autostereoscopic display
Wagner <i>et al</i> ^[444]	2012	Single-channel scope + HMD <i>vs</i> robotic dual channel scope + fixed head view	34 subjects (18 novices) 3 × lab based skills tasks	Time 3D robotic performance faster than all others, significantly	NA

NA: Not available; 3D: Three-dimensional; 2D: Two-dimensional; HMD: Head mounted display.

Table 5 Other prototype projection systems

Ref.	Year	Projection system for 3D	Who and what assessed	Objective outcomes	Subjective outcomes
Taffinder <i>et al</i> ^[445]	1999	Dual channel scope with autostereoscopic/glass free screen	28 subjects (16 novices and 12 experienced laparoscopic surgeons) Novices = basic grasping and cutting lab based skills Experienced = suturing and complex cutting lab based skills	Time and performance score (ICSAD assessment tool) Significant improvement in 3D over 2D laparoscopy	No side effects reported with 3D
Ohuchida <i>et al</i> ^[446]	2009	Dual channel scope with “Cyberdome” projection system	23 novices 6 × lab based skills tasks	Time, errors and performance Significant improvement in all parameters in 3D with cyberdome over 2D	NA
Storz <i>et al</i> ^[447]	2011	Dual-channel scope + wavelength multiplex camera and monitor with polarising glasses	30 subjects (20 medical students and 10 experienced laparoscopic surgeons) 5 × lab based skills tasks	Time and errors In 4 out 5 tasks, significant reduction in time in 3D, in 4 out of 5 tasks, significant reduction in errors	NA
Khoshabeh <i>et al</i> ^[448]	2012	Dual-channel scope + Multiview autostereoscopic display/glass free screen	3 experienced laparoscopic surgeons 2 × lab based skills tasks	Time and errors Reduced time and errors using 3D	NA

NA: Not available; 3D: Three-dimensional; 2D: Two-dimensional.

Capture of true stereopsis from the operative field is crucial for the subsequent projection of a true stereoptic image. However, with such focus on producing an effective projection system, the acquisition and true stereopsis of the image has sometimes been overlooked. It is clear from this review that in systems that compromised on the capture of two truly separate images of the operative field, they yielded no advantage for the participants using 3D over 2D. In studies using dual channel stereoendoscopes, the separate lenses within the laparoscope provided a greater spatial impression of stereopsis^[449-51]. Consequently, for the operator, there is a more accurate appreciation of depth. Fishman *et al*^[27] (2008) concluded there was deterioration in laparoscopic performance by reducing

horizontal lens separation in an experimental dual channel scope (thereby reducing stereopsis impression). However single channel systems produce images of greater clarity and resolution due to the greater size of the single optic channel for light transfer^[52]. Single channel optics can produce convincing stereopsis only at close operating distances, whereas dual channel systems provide significant stereopsis in larger cavities, where there is greater distance from the end of the stereoendoscope to the operating site^[51]. Close operating or near field objects with dual channel systems can cause visual discomfort due to the fixed focal point of the two lenses and our natural convergence conflicting. Therefore it is not surprising that the majority of studies which utilised single channel

laparoscopes did not show a benefit of 3D laparoscopy as all used target operating points distant to the scopes key stereoptic capabilities, irrespective of the projection system employed.

Modern projection systems attempt to provide as true a representation of the natural 3D view as possible, whilst balancing comfort and visual ease for the observer(s) and maintaining the brightness and resolution quality of the image. Active systems caused visual disturbances, headaches and symptoms of nausea due to the conflict of convergence and accommodation, as well as flickering and discomfort for the viewer due to the cumbersome battery powered glasses.

Early 3D images had poor resolution and luminosity as early cameras could not cope with low light levels or capture at high resolution. Projection systems were equally constrained by low refresh rates, low resolution and brightness. This added to discomfort and degraded the early 3D view^[51]. Falk *et al.*^[19], 2001, demonstrated that image quality is vital for precision and surgical performance, as 2DHD systems produced better results when compared with standard view 2D and 3D. The use of polarizing glasses and filters over the shuttering screen provides a more comfortable wear experience for the observer but this is at the expense of image brightness.

Head-mounted displays provide good quality images with no degradation in quality or light and preserve the normal hand-eye axis^[53]. However open sided head units, which do not block surrounding visual stimuli, can cause headaches and dizziness due to conflicting information from visual input and body position whilst with sealed units the surgeons are isolated from their surroundings and unable to react to unforeseen environmental incidents^[42].

The Da Vinci robotic system (intuitive, United States) allows for fixed console viewing and so provides an unparalleled quality of stereopsis for the surgeon. All the studies which assessed binocular and biocular (same view through each eye, therefore 2D view)^[51], showed statistically significant advantages with 3D performance for time and errors, reduced motion, and all other comparative markers for surgical performance. There can be no doubt that the advantages noted were purely due to the improvement in view provided by reintroduction of natural stereoptic depth cues. However use of the robot is limited to a relatively small number of procedures where advantage of the robotic platform over standard laparoscopic techniques has been established.

Later studies (Table 3), which used binocular endoscopes and the latest passive polarizing projection systems, identified no subjective impairment or "side effects" to using the 3D systems. The majority identified significant differences in their respective markers of surgical performance when comparing classical laparoscopy to 3D systems. Whilst surgeon experience does affect outcomes, it must be appreciated that

experience in classical laparoscopy leads to the development of techniques to overcome the lack of stereopsis. This therefore favours poorer outcomes with the 3D system in studies where the assessment was made after short exposure times and single repetition of skills^[34,38,39]. Studies which accounted for learning curves by allowing familiarisation with the system with multiple repetitions and well powered sample sizes demonstrate clearly the benefits in performance achievable with 3D laparoscopy^[31,33,35,40].

High quality experimental studies have shown that the latest 3D systems using dual channel stereo-endoscopes and passive polarizing technology provide a "near natural" view, almost comparable to that observed by the Da Vinci. However, their clinical application has yet to be addressed with Level 1 evidence. The only randomised clinical trial assessing 3D systems^[9], and addressed by Cochrane review^[54], showed no discernible difference for laparoscopic cholecystectomy performance. However, this study is over ten years old and the system assessed used a single channel scope and active shuttering projection, which was unlikely to have provided a true spatial impression of the operating field throughout. Studies that investigated the clinical application of the latest 3D systems identify performance advantages but are underpowered^[36,37]. Establishing the benefits of these systems can only truly be addressed within randomised clinical trials, using appropriately powered sample sizes.

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