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3D visualization systems improve operator efficiency during difficult laparoscopic cholecystectomy: a retrospective blinded review of surgical videos

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Abstract

Background: 3D visualization systems in laparoscopic surgery have been proposed to improve manual task handling compared to 2D, however, few studies have compared the intra-operative efficacy in laparoscopic cholecystectomy (LC). The aim of this study is to determine if there is a benefit in intra-operative efficiency when using a 3D visualization system in difficult LC compared to traditional 2D visualization systems.
Methods: Retrospective analysis of 'difficult' LCs (Grades 3 or 4) was completed. The assessor was blinded as all cases were recorded and viewed in 2D only. Variables collected included time to complete steps, missed hook diathermy attempts, failed grasp attempts, missed clip attempts and preparation steps for intra-operative cholangiogram (IOC). Multiple linear regression was undertaken for time variables, Poisson regression or negative binomial regression was completed for continuous variables.
Results: Fifty-two operative videos of 'difficult' LC were reviewed. 3D systems were associated with reduced operative times, although this was not statistically significant (CI: −2.93–14.93, *P*-value = 0.183). Dissection of the anterior fold to achieve the critical view of safety was significantly faster by 3.55 min (CI: 1.215–9.206, *P*-value = 0.002), and with considerably fewer errors when using 3D systems. Fewer IOC preparation errors were observed with a 3D system compared with a 2D system.
Conclusions: 3D systems appear to enhance operator efficiency, allowing faster completion of critical steps with fewer errors. This pilot study underscores the utility of video annotation for intra-operative assessment and suggests that, in larger multi-centre studies, 3D systems may demonstrate superior intra-operative efficiency over 2D systems during a 'difficult' LC.

Introduction

Laparoscopic cholecystectomy (LC) is one of the most common procedures in general surgery and Australia has the highest rates of LC per capita in the world as reported by The Organization for Economic Cooperation and Development (OECD) nations.[1] In 2020 alone, ~60 000 cholecystectomy procedures were performed in Australia and 95% of these cases were completed laparoscopically.[1]

Traditional two-dimensional (2D) laparoscopy requires the operator to mentally transform images through motion parallaxes, relative instrument positioning and shading from shadows to determine spatial relationships. This represents a significant visual and cognitive strain for the operator. With the introduction of three-dimensional (3D) systems, the operator can now perform laparoscopic procedures with stereopsis. Here, the laparoscope has two separate optic channels which provide individual images to each eye, resulting in binocular vision as with perception of the real world.[2]

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Currently, experimental evidence about the impact of 3D visualization in LC is limited. Specifically, a significant or clinically relevant benefit with 3D LC has not been demonstrated in terms of improved patient outcomes.[2] Prior studies have shown similar postoperative outcomes between 2D and 3D visualization systems in LC and no difference in rates of conversion to an open procedure.[3] However, isolating the impact of the camera system on complication rates is challenging, given the low incidence of serious events during LC.[4] For example, major bile duct injury occurs in ~0.1–0.3% of cases, and so, identifying the potential impact of the camera system on such events is problematic and would require a prohibitively large data set.[5]

Moreover, the impact of a 3D visualization system on improving the efficiency of the operator has not been well studied. Anecdotally, 3D camera systems provide the surgeon with enhanced identification of surgical planes and improved control over instrument movements.[6] However, data illustrating improvements have been variable, compounded by inconsistent definitions of the operative errors used to quantify differences.[3,7,8]

Consequently, there is a dearth in the literature about the exact relationship between the type of visualization system and intra-operative efficiency. Additionally, significant disparities may only become apparent in difficult and prolonged cases, where operator fatigue potentially increases error rates.

Hypothesis and aims

It is hypothesized that a 3D camera system provides improved identification of tissue planes and intra-operative efficiency in patients who have a 'difficult' LC (Grades 3 or 4 gallbladders). This study aims to determine whether there is an objective difference in intra-operative efficiency and error performance between 2D and 3D camera systems in patients who have a 'difficult' LC (Grades 3 or 4).

Materials and methods

Ethics and consent

Ethics approval was granted by The Ramsay Health Care NSW/VIC HREC in accordance with the National Statement on Ethical Conduct in Human Research, 2007 (NHMRC) (Approval no: 2020/RGO/0153). Patients consented to the storage and use of anonymized intra-operative videos as part of routine clinical care for research and teaching purposes.

Participants and video collection

Retrospective analysis was completed for patients who underwent LC by a single, experienced hepato-pancreatico-biliary (HPB) surgeon (TJH) at North Shore Private Hospital (Sydney, Australia). All cases were prospectively recorded and stored as part of routine clinical care. The 2D visualization system was used from 2011 to 2018 and the 3D visualization was used from 2019 to 2021. The operating surgeon was assisted by the same experienced assistant, and cases were selected for the study based on grading of the operative findings and completeness of the video recording for the purposes of analysis. An operative grade was assigned at the beginning of each procedure using the previously validated North Shore Grading System.[9] With an increasing grade of the GB, the operation is more technically challenging.[9,10] A 'difficult' laparoscopic cholecystectomy was defined as either Grade 3 or Grade 4 using the North Shore Grading System.

All videos were recorded and stored in 2D, and so the assessor was blinded as to which visualization system was used to perform the operation. 2D cases were completed using the Stryker 2D system (Stryker Corporation, Kalamazoo, Michigan, USA) with the SDC ultra (a management system that is used to capture operative videos) and a 1188 camera system (HD camera with 1280 × 1024 output, and a 3-chip camera). 3D cases were completed using the Olympus 3D system (Olympus Australia Pty Ltd., Notting Hill, VIC, Australia). A 26-in. HD monitor was with both the 2D and 3D systems.

Operative assessment

LC was completed using a standardized technique as described by Connor *et al*. (2014).[11]

This involved a four-port LC with routine thromboembolic prophylaxis and a minimum overnight hospital admission. Intraoperative cholangiography (IOC) using a standardized protocol was attempted routinely in all cases. Total operative time was defined as the time taken from insertion of the fourth laparoscopic port to extraction of the GB specimen, and each step annotated. IOC time, port insertion and closure were not included in total operative time due to the largely extra-corporeal natural of these steps and would not have been affected by the visualization system. The operation was subdivided into five individual steps, as shown in Figure 1, and time to complete the individual steps was collected.

An error was described in line with the consensus recommendation agreed to during the Bellagio Conference on human error.[12] A literature review was conducted, and errors deemed to meet these criteria were included. Errors and definitions are seen in Table 1 along with continuous variables collected.

Video annotation

All intra-operative videos were stored and then viewed in 2D by a single, blinded assessor who was unaware as to which visualization system was used intra-operatively. Each video was uploaded to the Touch Surgery (Medtronic, Minneapolis, MN, USA) video annotation platform, and the operative titles were anonymized and randomized. Operative videos were manually annotated twice sequentially using the SAGES framework for video annotation to ensure consistency and reliability.[13]

Statistical analysis

Statistical analysis was completed using SPSS 28 for Mac (IBM Corp., Armonk, NY, USA). Univariate binomial logistic regression was completed to identify predictors of grade from dependent variables. A model was created for each variable to maintain independence of observations. Multiple linear regression was completed for

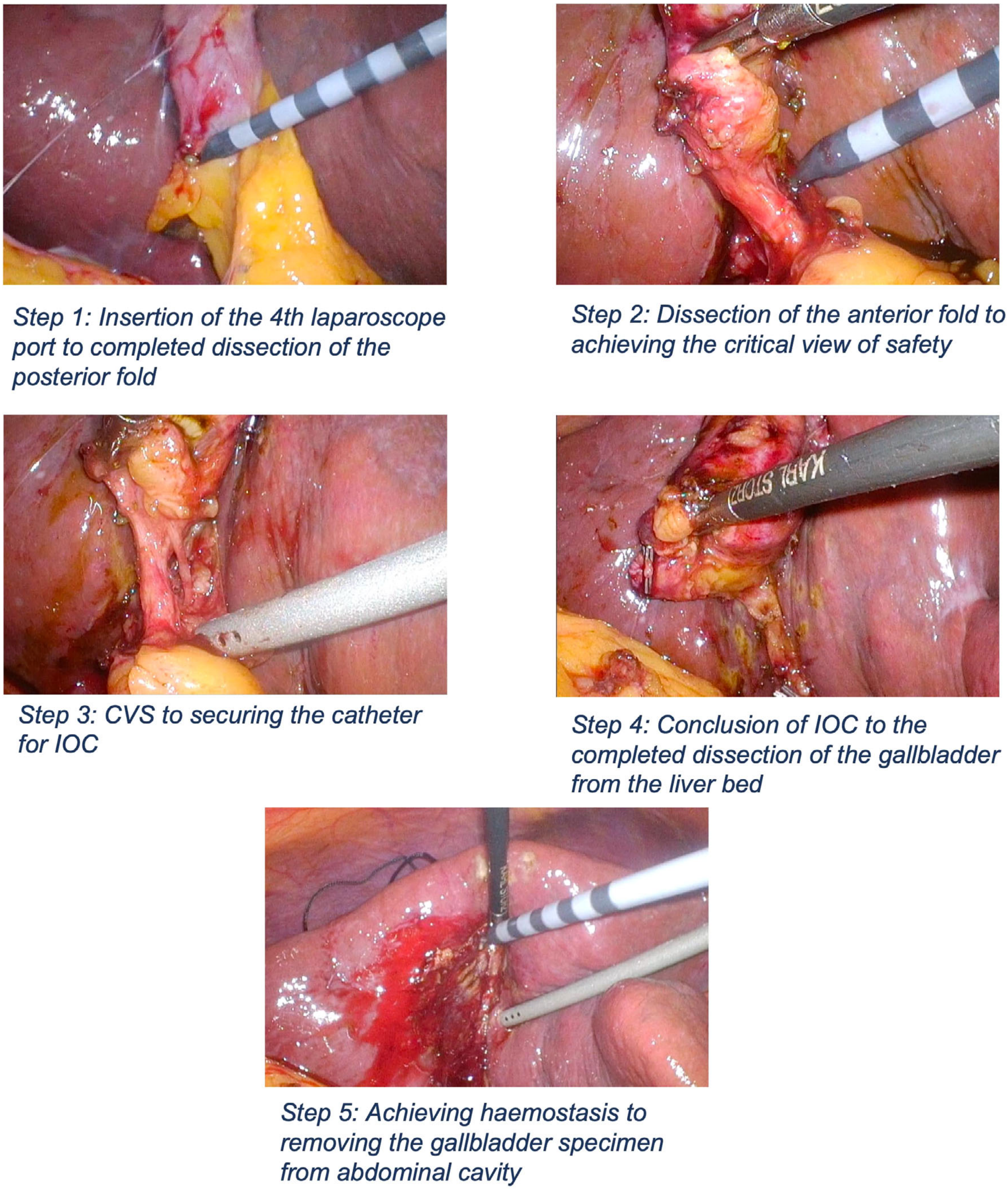

Fig. 1. Description of individual steps to complete laparoscopic cholecystectomy.

time variables when comparing 2D and 3D visualization systems, controlled for GB grade and whether intra-peritoneal suturing was required in the case. For continuous variables, Poisson regression or negative binomial regression was completed, controlling for GB grade to compare between 2D and 3D visualization systems. Poisson regression was completed for each variable initially, if Poisson distribution assumption was not met by assessing the goodness of fit model (through Pearson dispersion statistic), then non-binomial logistic regression was completed.

Results

Manual annotation of 52 intra-operative videos was completed. Descriptive statistics for the visualization system and grade are shown in Table 2. In 26.9% of cases, laparoscopic suturing was required as an additional step to complete the operation ($n = 5$ in 2D, $n = 9$ in 3D). Intra-peritoneal suturing was completed to repair a serosal tear to the second part of the duodenum secondary to adhesions, oversewing of the cystic duct, oversewing of

Table 1 Definition of variables collected during video annotation.

Variable	Definition	Rationale
Failed grasp attempt	The jaws of the instrument being opened and closed without retaining tissue, dropping tissue or re-grasping tissue within 5 s of grasping	Failed grasp attempts have been previously described as a valid method to measure skill in laparoscopic suturing as well as microsurgery, and therefore were used in this study to measure efficiency.
Missed hook diathermy attempts	A hook diathermy in view failing to capture tissue on swinging motion or failing to touch tissue when attempting blunt dissection	Extrapolated from failed grasp attempt as hook diathermy and clip applicator is commonly used in laparoscopic cholecystectomy
Failed laparoscopic clip application	Tissue entering between the ends of the clip applier but not clasping, missing tissue, the clip falling off the desired tissue or clip being removed	
Adverse event	The total number of failed grasp attempts, missed hook diathermy attempts, and missed clip attempts	The total of the errors collected.
Bleeding requiring intervention	Bleeding during case that required intervention, for example, diathermy cauterization or clip application	Any bleeding that required intervention (i.e., electro-cautery or staple application) was recorded as described previously in a human clinical reliability analysis. This was recorded up until Step 3 as bleeding is acceptable during dissection of the GB off the liver bed.
Partial cuts on cystic duct	When preparing cystic duct for IOC, the number of cuts required on cystic duct to cannulate for IOC was counted.	Collected as a surrogate marker to determine how effectively structures were skeletonized for preparation for completing the IOC and for achieving the critical view of safety.
Attempts to cannulate cystic duct for IOC	Number of times attempts to pass catheter into the cystic duct before IOC.	

Table 2 Descriptive statistics of visualization system versus grade

	2D	3D	Total
Grade 3	26	9	35
Grade 4	5	12	17
Total	31	21	52

a duct of Luschka, and closure of the common bile duct after exploration.

Grade 3 versus Grade 4

The results of the impact on grade, efficiency and error rates are summarized in Table 3. Unsurprisingly, longer overall operative times were associated with Grade 4 GBs compared with Grade 3 GBs. Similarly, Grade 4 GBs were associated with longer times to complete Step 1, Step 2, Step 4, and Step 5 compared to Grade 3 GBs. Total failed grasps had a statistically significant association with Grade 4 GBs (OR 1.204, CI 95%: 1.022, 1.417) when compared to Grade 3 GBs.

Intra-operative efficiency

Differences between the time to complete the operation and the individual steps with 3D compared to 2D are summarized in Table 4. Total operative time was 6 min faster in 3D LC although this was not statistically significant (P-value = 0.183, 95% CI: =14.928, 2.925). Step 2 was completed 3 min and 33 s faster in 3D LC compared to 2D LC. Further, in Step 2, there were 2.16 times (P-value = 0.021, 95% CI = 1.123, 4.149) as many missed hook diathermies in the 2D cases when compared to the 3D cases, suggesting that Step 2 is completed more efficiently with 3D visualization systems. Improvements in Step 2 translated to decreased errors in Step 3 when preparing for the intra-operative cholangiogram (IOC). With the 2D system, there were 1.55 times as many cuts required to open the cystic duct for the cholangiogram catheter insertion (P-value = 0.02, 95% CI = 1.063, 2.259) and 1.89 times as many attempts to insert the catheter into the cystic duct (P-value = 0.009, 95% CI = 1.173, 3.054). A summary of the results for errors and continuous variables comparing 3D and 2D are listed in Table 5. There were no statistically significant differences between the 2D and 3D visualization systems when comparing total failed grasps, total missed hook diathermy attempts, or total adverse events. There were increased incidence of missed hook diathermy attempts in Step 2 and Step 4 in the 2D group when compared to the 3D group.

Discussion

This study highlights the enhanced efficiency of the 3D visualization system over the 2D system when performing a 'difficult' LC. These findings are novel given that both operator experience and operative difficulty were controlled for in the study design, and that there was also separate phase analysis. Step 2 was the

Table 3 Results of binomial regression analysis for predictors comparing Grade 3 (reference group) to Grade 4

	Model for each predictor without covariates		
	B	OR (95% CI)	*P*-value
Total operation time	0.112	1.118 (1.044, 1.198)	0.001
Gallbladder aspiration	1.219	3.383 (0.917, 12.489	0.067
Step 1 time	0.249	1.283 (1.116, 1.474)	<0.001
Step 2 time	0.232	1.261 (1.059, 1.500)	0.009
Step 3 time	−0.059	0.943 (0.768, 1.157)	0.573
Step 4 time	0.091	1.095 (1.012, 1.184)	0.024
Step 5 time	0.619	1.857 (1.323, 2.607)	<0.001
Total failed grasps	0.185	1.204 (1.022, 1.417)	0.026
Total missed hook diathermy attempts	0.072	1.075 (0.997, 1.159)	0.060
Total missed clip application attempts	0.288	1.334 (0.783, 2.274)	0.29
Adverse events total	0.073	1.076 (1.013, 1.142)	0.017
Partial cut attempt for IOC of CD	−0.185	0.831 (0.587, 1.178)	0.298
Number of attempts to cannulate cystic duct for IOC	−0.555	0.574 (0.296, 1.114)	0.101
Bleeding requiring intervention	−0.691	0.501 (0.273, 0.919)	0.026

Table 4 Linear regression for time to complete the operation and individual steps when controlled for gallbladder grade and whether suturing was required for 2D (reference group) versus 3D

	Coefficient (minutes)	95% confidence interval	*P*-value
Operative time	−6.002	−14.928, 2.925	0.183
Step 1 time	3.996	−1.215, 9.206	0.130
Step 2 time	−3.550	−5.680, −1.420	0.002
Step 3 time	−1.036	−3.065, 0.994	0.310
Step 4 time	−3.456	−7.916, 1.004	0.126
Step 5 time	−1.902	−3.943, 0.139	0.067

Table 5 Poisson regression or negative binomial regression for quantitative intra-operative variables comparing 2D to 3D (reference group) visualization systems when controlling for gallbladder grade.

	IRR	95% confidence interval	*P*-value
Total failed grasps	0.784	0.397, 1.548	0.483
Total missed hook diathermy attempts	1.483	0.793, 2.775	0.217
Total adverse events (total of missed clip application attempt, failed grasp and missed hook diathermy attempt)	1.229	0.659, 2.291	0.517
Total adverse events, Step 1	1.042	0.540, 2.013	0.902
Total adverse events, Step 2	1.811	0.942, 3.483	0.075
Total adverse events, Step 3	0.856	0.369, 1.984	0.717
Total adverse events, Step 4	1.342	0.636, 2.832	0.439
Total adverse events, Step 5	0.253	0.091, 0.706	0.009
Partial cut of cystic duct for IOC†	1.550	1.063, 2.259	0.023
Attempts to cannulate cystic duct for IOC†	1.893	1.173, 3.054	0.009
Bleeding requiring intervention (Steps 1–3)	1.340	0.790, 2.271	0.278
Step 2: Missed hook attempt	2.159	1.123, 4.149	0.021
Step 4: Missed hook attempt	2.501	1.080, 5.791	0.032
Step 5: Failed grasp†	0.169	0.051, 0.556	0.003
Step 5: Missed hook attempt	0.270	0.078, 0.935	0.039

†Poisson regression model was used.

dissection of the anterior peritoneal fold to achieve the critical view of safety. This was completed more rapidly and with fewer errors using a 3D system compared to the 2D system, and arguably, Step 2 is the most important step during LC. Dissection of the hepatocystic triangle and achieving the critical view of safety in the setting of marked inflammation and/or adhesions (as in Grades 3 and 4 GBs) is challenging.[14] Therefore, completing this critical step efficiently and with fewer errors using 3D may be advantageous.

Consistent with previous findings, there was a trend towards reduced total operative time with the 3D system. Schwab *et al.*'s findings of a 12-minute improvement with 3D system when undertaking 'difficult' laparoscopic cases with 3D systems align with our observations.[15] Schwab *et al.* study used the 4-point Nassar operative difficulty scale which is broadly similar to the North Shore Grading System, reinforcing the consistency of our methodology.[9,10] The impact of visualization systems on a procedure can be influenced by surgical proficiency, where it has been shown previously that novice surgeons completed the cholecystectomy 12 min faster with 3D compared to 2D systems.[16] The current study involved a single, experienced HPB surgeon where cases were completed over 10 years after the surgeon had been practising as a consultant surgeon, minimizing the impact of the learning curve or case-load experience when performing LCs and compared to previous studies had overall shorter procedure time in difficult LCs.[17] Consequently, it is likely that the differences in operative time in the present study were likely due to the visualization system rather than differences in operative skills.

The potential for a 4K video system to rival the advantages of a 3D system has been examined previously. Dunstan *et al.*'s[7] randomized study showed no difference between 4K 2D systems and high-definition 3D systems in LC, even when performing difficult cases.[7] However, intra-operative time was collected from three surgeons and there was no attempt to control for surgeon experience or different experiences of the surgical assistants. When comparing 2D and 3D systems, it is impossible for the operating surgeon to be blinded as to which visualization system was used, and therefore, individual preference may lead to biases in performance. The current study mitigated potential bias by using an independent 'blinded' assessor who reviewed all videos in 2D and videos from separate time periods to minimize impact of bias from surgeon preference.

The impact of the current study's findings extends beyond operative time. Each operative decision, such as a failed grasp or missed hook diathermy, adds to the cognitive load of the surgeon, particularly during a difficult or prolonged operation. This can lead to decision fatigue, which is known to have a detrimental impact in other procedural contexts. The consequences of this have been highlighted previously by lower polyp detection in colonoscopies that are competed later in the day and after increasing number of procedures on the same list.[18] Therefore, theoretically at least, the reduced cognitive demand when using a 3D system is an important consideration. During specific steps where tissue plane identification is important, (i.e., Steps 2 and 4), there was a decrease in missed hook diathermy attempts with the 3D system. It might be hypothesized that there is improved efficiency during these steps as recognition of the surgical plane is vital to completing the dissection and this appears to be improved by 3D systems.

Existing literature use various error detection systems when comparing 2D and 3D laparoscopic cholecystectomy. Studies that have used the Technical Skills Checklist and Observed Clinical Human Reliability Analysis (OCHRA) have reported no significant differences between visualization systems.[7,15] In contrast, Hanna *et al.* used a subjective, unstructured scoring system for error assessment, determined by the supervising senior surgeon, when attempting to compare visualization modalities in LC.[19] This highlights the inherent subjectivity of error detection across various studies, particularly regarding the severity and management of errors. For instance, in the surgical checklist, a minor error could be a diathermy liver injury, while a major error might involve liver injury with clinically significant bleeding. These errors can be classified as corrected or uncorrected in the technical skills checklist for LC.[7] In reality, the classification of an incident as an error, and the surgeon's response to it can vary significantly. Different surgeons have varying thresholds for acceptable bleeding during dissection of the GB from the liver bed. One surgeon might let minor bleeding resolve spontaneously, leading to the classification as an uncorrected error, despite still being an appropriate response. Furthermore, the low incidence of these events means that a substantial number of procedures would be required to yield statistically significant findings. Therefore, instead, it is important to use objective measures for error detection to mitigate the influence of individual clinical experience.

The integration of video annotation software and machine learning presents a promising avenue for automating the assessment of intra-operative videos. Artificial intelligence (AI) has already demonstrated potential in some surgical fields, predicting surgical skills with 87% accuracy, and identifying operative phases and instrument movements.[20,21] As laparoscopic surgery relies on an active video stream, the application of AI could enhance the collection and analysis of a large, volume of laparoscopic procedure videos from multiple, centres, thereby, confirming and/or improving the generalisability of the current research findings.[6]

The utility of 3D visualization has been shown in other laparoscopic procedures. In laparoscopic gastrectomy, meta-analyses revealed a significant reduction in operative time by 14–28.57 min by using 3D systems, as well as a modest decrease in hospital stay and no difference in post-operative outcomes.[22,23] Previous meta-analysis of outcomes in laparoscopic liver resection indicated lower morbidity with the use of 3D systems, as well as a trend towards reduced operative time and blood loss compared to 2D, although, these findings were not statistically significant.[24] While robotic liver resections, which also uses 3D visualization, showed improved intra-operative efficiency, it is unclear if this was due to the visualization system, the instrument control, or both.[25] Furthermore, 3D systems have been found to reduce total operative time in transabdominal peritoneal inguinal hernia repairs, without impacting post-operative complications or recurrence rates.[26] Despite the lack of comparative studies in simpler procedures such as appendicectomy, the benefits observed in complex operations suggests potential advantages in these cases as well. That said, the upfront cost of 3D systems, including camera and monitors, needs to be considered, as there may not be an obvious advantage in straightforward cases.

This study's primary limitation is the small sample size and reliance on a single surgeon's experience, therefore, the findings may not be easily transferable. A second limitation is the exclusion of clinical data such as age, BMI, previous abdominal surgery and elevated CRP level, all known factors that can increase the difficulty of LC.[27] Although it is accepted that this might have influenced results to some degree, the stable performance of binomial regression in identifying predictors of GB grade suggests that the impact of these factors was likely minimal. Furthermore, many of these clinical factors are shown to be predictors of operative grade, which has been recognized as the most important determinant of operative difficulty and was controlled for in the present study.[28,29] Finally, within the statistical analysis, the numerous models increase the likelihood of type I error. However, given the exploratory nature of this study, p-values were not corrected to prevent type II errors.

Conclusion

3D visualization systems offer tangible benefits in complex LC, particularly in achieving the critical view of safety. While this study indicates improved efficiency in specific operative steps during 'difficult' cases, a larger sample size and broader studies are necessary to conclusively establish these advantages. This pilot study underscores the potential of 3D systems for enhancing intra-operative performance, paving the way for more comprehensive research in this area.

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Author contributions

Meet Patel: Conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft; writing – review and editing. **Isaac Tranter-Entwistle:** Methodology; validation; writing – review and editing. **Pramudith Sirimanna:** Methodology; supervision; writing – review and editing. **Thomas J Hugh:** Conceptualization; investigation; methodology; supervision; writing – original draft; writing – review and editing.

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Conflicts of interest

Dr. Meet Patel and Dr. Pramudith Sirimanna have no conflicts of interest to report. Professor Thomas J Hugh has undertaken consultancy work for Touch Surgery, Medtronic but unrelated to the current study. Dr. Isaac Tranter-Entwistle has received funding from Medtronic to undertake a PhD unrelated to the current study.

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