Utility and usability of laser speckle contrast imaging (LSCI) for displaying real-time tissue perfusion/blood flow in robot-assisted surgery (RAS): comparison to indocyanine green (ICG) and use in laparoscopic surgery

Yao Z. Liu[1,4] · Shinil K. Shah[2] · Christina M. Sanders[3] · Chibueze A. Nwaiwu[1,4] · Alyson F. Dechert[4] · Saloni Mehrotra[3,4] · Steven D. Schwaitzberg[3] · Peter C. W. Kim[1,4] · Erik B. Wilson[2]

Abstract

Background Utility and usability of laser speckle contrast imaging (LSCI) in detecting real-time tissue perfusion in robot-assisted surgery (RAS) and laparoscopic surgery are not known. LSCI displays a color heatmap of real-time tissue blood flow by capturing the interference of coherent laser light on red blood cells. LSCI has advantages in perfusion visualization over indocyanine green imaging (ICG) including repeat use on demand, no need for dye, and no latency between injection and display. Herein, we report the first-in-human clinical comparison of a novel device combining proprietary LSCI processing and ICG for real-time perfusion assessment during RAS and laparoscopic surgeries.

Methods ActivSight™ imaging module is integrated between a standard laparoscopic camera and scope, capable of detecting tissue blood flow via LSCI and ICG in laparoscopic surgery. From November 2020 to July 2021, we studied its use during elective robotic-assisted and laparoscopic cholecystectomies, colorectal, and bariatric surgeries (NCT# 04633512). For RAS, an ancillary laparoscope with ActivSight imaging module was used for LSCI/ICG visualization. We determined safety, usability, and utility of LSCI in RAS vs. laparoscopic surgery using end-user/surgeon human factor testing (Likert scale 1–5) and compared results with two-tailed t tests.

Results 67 patients were included in the study—40 (60%) RAS vs. 27 (40%) laparoscopic surgeries. Patient demographics were similar in both groups. No adverse events to patients and surgeons were observed in both laparoscopic and RAS groups. Use of an ancillary laparoscopic system for LSCI/ICG visualization had minimal impact on usability in RAS as evidenced by surgeon ratings of device usability (set-up 4.2/5 and form-factor 3.8/5). LSCI ability to detect perfusion (97.5% in RAS vs 100% in laparoscopic cases) was comparable in both RAS and laparoscopic cases.

Conclusions LSCI demonstrates comparable utility and usability in detecting real-time tissue perfusion/blood flow in RAS and laparoscopic surgery.

✉ Peter C. W. Kim
  pkim@activsurgical.com

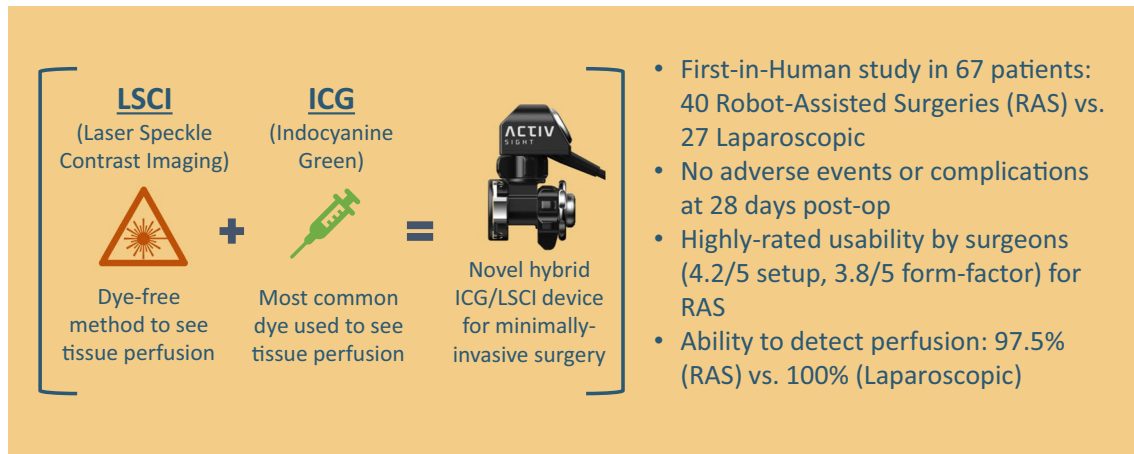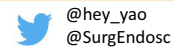1 Department of Surgery, Brown University, Providence, RI, USA

2 University of Texas Health Science Center at Houston, Houston, TX, USA

3 Department of Surgery, University of Buffalo, Buffalo, NY, USA

4 Activ Surgical, 30 Thomson Place, 2nd Floor, Boston, MA 02127, USA

Graphical abstract

How does a hybrid ICG/LSCI device perform in detecting perfusion in Laparoscopic vs. Robot-Assisted Surgery?

LSCI
(Laser Speckle Contrast Imaging)

Dye-free method to see tissue perfusion

+

ICG
(Indocyanine Green)

Most common dye used to see tissue perfusion

=

ACTIV SIGHT

Novel hybrid ICG/LSCI device for minimally-invasive surgery

- First-in-Human study in 67 patients: 40 Robot-Assisted Surgeries (RAS) vs. 27 Laparoscopic
- No adverse events or complications at 28 days post-op
- Highly-rated usability by surgeons (4.2/5 setup, 3.8/5 form-factor) for RAS
- Ability to detect perfusion: 97.5% (RAS) vs. 100% (Laparoscopic)

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@hey_yao
@SurgEndosc

Keywords Intraoperative · Perfusion · Robotic · Laparoscopic · Laser speckle

Tissue perfusion is known to be a key determinant of optimal tissue healing and consequent surgical outcomes. Intestinal perfusion has traditionally been measured through naked eye inspection and estimates of serosal discoloration, intestinal peristalsis, palpable mesenteric vessels, and bleeding from tissue edges though these subjective measures are known to be unreliable [1–3]. More recently, as advanced visualization systems have become more commonplace, fluorescence angiography has helped move the field toward more objective intraoperative perfusion assessment [4].

Indocyanine Green (ICG) is the most widely used fluorescent dye for intraoperative perfusion visualization [5]. ICG dye is injected intraoperatively to highlight plasma protein-bound ICG in blood volume as it moves through vessels and tissue. In gastrointestinal surgery, ICG imaging is increasingly used to assess anastomotic perfusion to reduce leaks, however the evidence for lowering the anastomotic leak rate remains mixed [5–10]. ICG has been widely studied across other applications as well, especially extrahepatic biliary anatomy identification, lymph node detection, and hepatobiliary lesion localization, among others [11, 12]. However, ICG imaging is not without its drawbacks: it requires injection of an external fluorophore (dye), is limited by pharmacokinetics in repeat assessments, can cause rare instances of anaphylaxis, and is interpreted subjectively [4, 13–15].

As laparoscopic and robotic-assisted surgery (RAS) adoption expands across general surgery procedures, newer advanced visualization technologies that augment intraoperative scenes and provide perfusion information for surgeons are playing an increasing role. One such technology is Laser Speckle Contrast Imaging (LSCI), which detects tissue blood flow and perfusion through laser scatter [14, 16–19]. LSCI uses the dynamic interference pattern produced when coherent laser light illuminates moving objects such as red blood cells and generates a color heatmap of real-time blood flow [19, 20]. LSCI advantages over ICG imaging for perfusion visualization include repeat use on demand, lack of need for external dye injection, and no latency between dye injection and perfusion display [16, 17, 21]. Disadvantages to LSCI include motion/flow sensitivity and depth penetration into tissue, which limits perfusion visualization to the most superficial 1–2 mm of tissue [22].

Current advanced visualization systems do not allow for integration of both ICG fluorescence angiography and LSCI technology in an MIS-compatible format. In addition, the utility and usability of minimally invasive LSCI in detecting/displaying real-time tissue perfusion in RAS have not been reported. This prospective, multi-center study reports on the first-in-human clinical comparison of a novel, MIS-compatible device combining visualization of ICG and LSCI signals processed through proprietary systems and methods for intraoperative perfusion assessment across RAS and laparoscopic surgery, and determines the safety, feasibility, and usability [23]. Our hypothesis is that this novel, hybrid device combining

LSCI and ICG in an MIS-compatible form-factor is safe, usable, and effectively provides intraoperative perfusion visualization.

Materials and methods

The device used for this study, ActivSight™ Imaging Module (Activ Surgical, Boston, MA), is FDA-510(k) cleared for endoscopic fluorescence and near-infrared imaging (NIR) in minimally invasive surgery. ActivSight is cleared for surgeons to visually assess vessels, blood flow, and related tissue perfusion using fluorescence and NIR, and visualize extrahepatic biliary structures using fluorescence. ActivSight consists of three components: an Imaging Module that fits between standard laparoscopic camera heads and laparoscopes, a Light Engine, and a bifurcated Light Cable (Fig. 1). The imaging module allows for simultaneous imaging of near-infrared light (LSCI and ICG) using an infrared sensor and visible white light using a white light camera. Images from the white light camera and the infrared sensor are combined to create a real-time overlay of either Activ Perfusion™ proprietary LSCI perfusion colormap or Activ-ICG™ ICG fluorescence on the white light camera image.

From November 2020 to July 2021, we studied ActivSight device use in 67 adult patients undergoing elective robotic-assisted and laparoscopic cholecystectomies, colorectal, and bariatric surgeries. Patients were ineligible for enrollment if they were pregnant, lactating, or had known allergic or history of adverse reaction to iodides or ICG. Informed consent was obtained for every enrolled patient. This study was registered with clinicaltrials.gov (NCT# 04633512) and was conducted at four sites across two institutions under Institutional Review Board-approved protocols (#20-0967 and #20-003).

In laparoscopic surgeries, the imaging module was attached to the standard operating laparoscope and was in place throughout the case. For robotic surgeries, an ancillary laparoscope with ActivSight imaging module was inserted through pre-existing robotic port sites at key intraoperative moments by operating surgeons to visualize the operative field for tissue perfusion assessment.

The primary outcome of this study was the safety of using LSCI technology in MIS surgery. Safety was defined by any adverse events to patients, surgeons, or surgical systems. Patients were followed for 28 days to identify any postoperative complications. Secondary outcomes included the utility and usability of using a combined LSCI and ICG NIR fluorescence technology device in MIS. Utility was defined as an ability to detect/display perfusion with LSCI, and usability as device display quality, form-factor, and ease of setup. End-user/Surgeon human factor testing was performed with a Likert scale (1–5) to assess both utility and usability. End-users included surgical scrub techs, surgical assistants, and the case's primary attending surgeon. Statistical analyses were performed in Microsoft Excel, with student's t test used to compare RAS and laparoscopic surgery groups. Statistical significance was set at $P < 0.05$.

Results

Procedure list

A total of 67 surgeries were performed during this first-in-human clinical trial, including 40 (60%) RAS and 27 (40%) laparoscopic cases (Table 1). All efforts were made
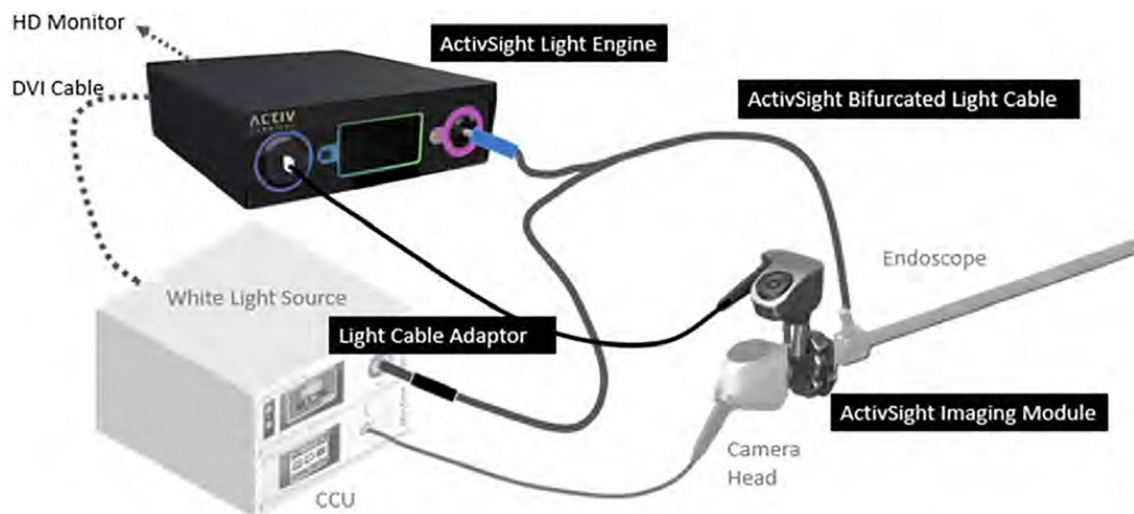

Fig. 1 ActivSight schematic diagram

Table 1 Case composition and adverse events by robotic-assisted surgery (RAS) vs. laparoscopic surgery

	RAS	Laparoscopic	Total
Type of case	**40**	**27**	**67**
Bariatric	**14**	**9**	**23**
Sleeve gastrectomy	4	6	10
Roux-en-Y gastric bypass	10	3	13
Colorectal	**16**	**1**	**17**
Right colectomy	7	0	8
Left and/or sigmoid colectomy	4	0	4
Low anterior resection (LAR)	5	1	5
Cholecystectomy	**10**	**17**	**27**
Adverse events	**0**	**0**	**0**

Bold values indicate category mean/SD for the components of each category

Table 2 Patient demographics by robotic-assisted surgery (RAS) vs. laparoscopic surgery

Demographics	RAS (n=40)		Laparoscopic (n=27)		p value
	Mean	SD	Mean	SD	
Age (years)	56.4	13.6	49.7	14.9	0.08
BMI	33.9	8.6	38.0	9.8	0.09
Sex—Female %	75%		67%		0.47
Race—White %	75%		70%		0.68

for consecutive inclusion during the COVID-19 pandemic period. Surgical approach, whether RAS versus laparoscopic, was left to individual surgeon preference. Among RAS, colorectal was the most-performed type of surgery (n=16 or 40% of RAS cases) and included right colectomy (n=7), low anterior resection (n=5), left and/or sigmoid colectomy (n=4). There were 14 robotic-assisted bariatric surgeries (35% of RAS cases), of which 4 (29%) were sleeve gastrectomy and 10 (71%) were Roux-en-Y gastric bypass. Among laparoscopic cases, cholecystectomy was the most common (n=17 or 63% of laparoscopic cases) followed by bariatric (n=9) and colorectal (n=1, right hemicolectomy). Of the 9 laparoscopic bariatric cases (33% of RAS cases), 6 (67%) were sleeve gastrectomy and 3 (33%) were Roux-en-Y gastric bypass. 16 attending surgeons (14 male, 2 female) were included in the study. Operative time averaged longer in the RAS group compared to the laparoscopic group: 168 min (±73 min) vs. 69 min (±42 min).

Patient demographics

Patients were comparable in both groups and any differences in patient demographics between RAS and laparoscopic groups were not statistically significant (Table 2). Patient race and sex in this cohort trended toward white (75% RAS vs. 67% Laparoscopic) and female (75% RAS vs. 70% Laparoscopic). Patients in the RAS group tended to be older (56.4 RAS vs 49.7 years old Laparoscopic) with lower BMI (33.9 RAS vs. 38.0 Laparoscopic).

Representative examples and comparison of LSCI and ICG display

To test the feasibility of detecting and displaying real-time tissue perfusion during RAS and laparoscopic surgery, standard white light (A), LSCI overlay (B), LSCI contrast (C), and ICG grayscale (D) views of partially devascularized colon during a Sigmoid Colectomy (Fig. 2A–D) and partially devascularized stomach during a Sleeve Gastrectomy (Fig. 3A–D), respectively were examined (Figs. 2, 3). ICG view of tissue perfusion was obtained immediately after first ICG injection during first-pass ICG kinetics in blood. LSCI perfusion colormap correlates warmer colors (red/orange) to higher tissue perfusion and cooler colors (blue) to lower tissue perfusion. Figures 2A or 3A demonstrates devascularized colon/stomach under white light. Figures 2B–C or 3B–C show devascularized colon/stomach with low perfusion which appear blue on LSCI perfusion colormap compared to more perfused colon/stomach which appear red/yellow/orange on colormap. Figures 2D or 3D shows ICG fluorescence does not reach devascularized colon/stomach within two minutes of ICG injection. LSCI (Figs. 2B–C or 3B–C) and ICG (first-pass kinetics, Figs. 2D or 3D) demonstrate concordance in displaying the margin between perfused vs. ischemic intestinal tissue.

Given the dual visualization capability of the technology (LSCI and ICG visualization), we examined extrahepatic bile ducts during laparoscopic and RAS cholecystectomy. Figure 4 demonstrates a representative extrahepatic biliary duct visualization using white light (Fig. 4A), ICG overlay (Fig. 4B), ICG grayscale (Fig. 4C), and ICG contrast (Fig. 4D) views during laparoscopic cholecystectomy. Extrahepatic biliary duct visualization was performed at least 30–45 min after ICG injection, during second-pass ICG hepatic clearance. Figure 4 shows the Gallbladder (GB), cystic duct (CD), and common hepatic/common bile duct (CHD/CBD) as green structures under ICG fluorescence.

Safety to patients, surgeons, and systems

No adverse intraoperative events were detected to patients, surgeons, and/or systems during RAS and laparoscopic procedures. In addition, no complications were reported by post-operative day 28 through outpatient follow-up in either the RAS or laparoscopic surgery groups (Table 1).
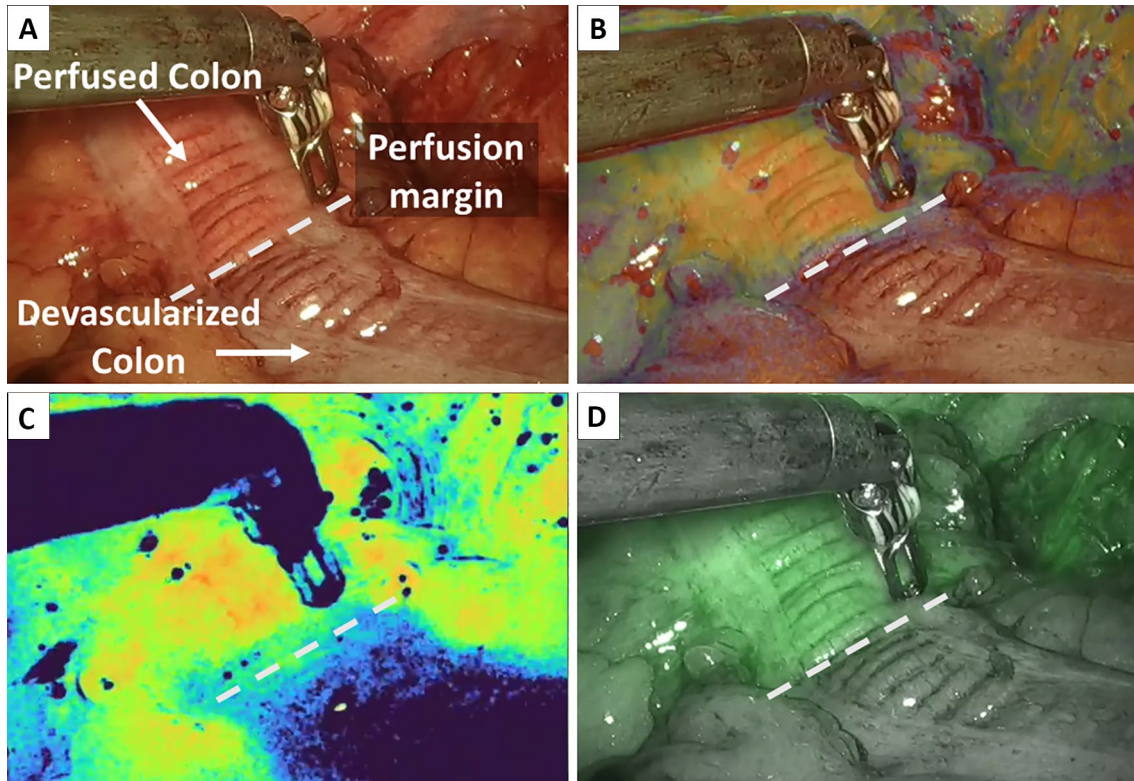
Fig. 2 Colon perfusion

The complications assessed in this study included all device- and surgery-related adverse events, including but not limited to surgical site infection, anastomotic leak, prolongation of post-operative hospital admission, and hospital readmission.

Usability of the device

Despite the fact that use of the ActivSight™ Imaging Module in RAS required an ancillary laparoscopic system, end-users rated ActivSight usability highly in both RAS and Laparoscopic surgery: Set-up (4.2/5 RAS vs. 4.1/5 Laparoscopic, $p=0.70$); Form factor (3.9/5 RAS vs. 3.7 Laparoscopic, $p=0.02$); Display quality (4.1/5 RAS vs. 4.1 Laparoscopic, $p=0.92$) (Table 3). Interestingly, form-factor was rated slightly higher for the RAS compared to Laparoscopic group with statistical significance ($p<0.02$). Given that ancillary laparoscopic camera systems are commonly present and required for initial abdominal entry in operating rooms with robotic surgery platforms, these usability results indicate that using an ancillary laparoscopic system for LSCI and ICG visualization in RAS was acceptable for workflow.

Utility of LSCI perfusion visualization

Surgeons' rating of the device's ability to display tissue perfusion using LSCI was equally high across both RAS and Laparoscopic groups: 97.5% RAS vs. 100% Laparoscopic ($p=0.32$).

Discussion

This first-in-human clinical comparison of ActivSight™ imaging module, a novel device combining proprietary LSCI and ICG in 67 patients between RAS and Laparoscopic surgeries demonstrates that the device is safe, usable and provides real-time intraoperative tissue perfusion information in both surgical approaches. There were no adverse events or post-operative complications reported in this study cohort., Use of the device using an ancillary laparoscopic system had minimal impact on workflow and usability during RAS as evidenced by favorable surgeon ratings of device usability (set-up 4.2/5 and form-factor 3.8/5). Importantly, surgeons rated the utility of ActivPerfusion™ LSCI perfusion detection similarly high across both groups (97.5% RAS vs. 100% Laparoscopic), which is on par with current standards of ICG fluorescence angiography [24].

Advanced visualization technology to assess anastomotic perfusion is drawing increasing attention as conventional methods of bowel perfusion assessment have proven to be unreliable [25]. However, while methods like ICG fluorescence angiography are increasingly adopted in colorectal
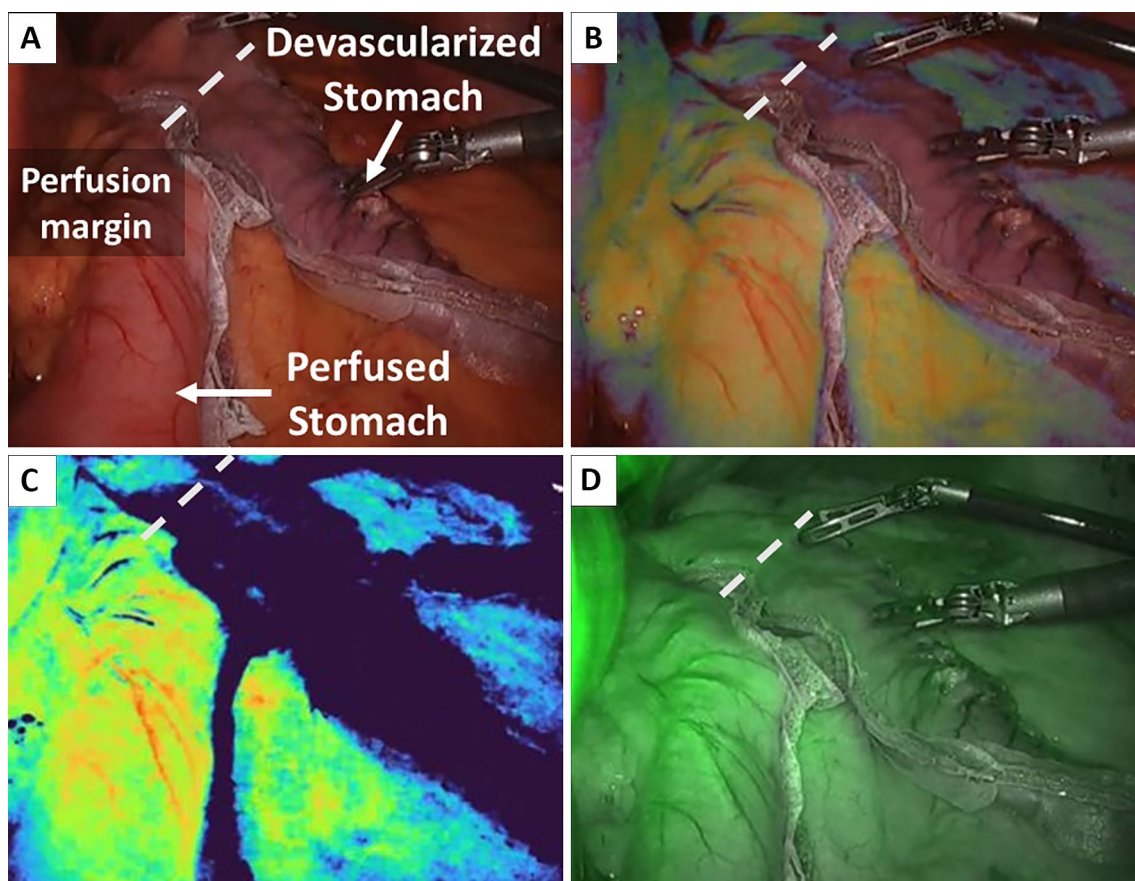
Fig. 3 Gastrectomy perfusion

surgery, the evidence is not yet conclusive to support a reduced anastomotic leak rate [6, 8, 10, 24]. A recent randomized, multi-center trial of perfusion assessment with ICG fluorescence angiography in low pelvic anastomoses (PILLAR III) found a high rate of successful microperfusion assessment at anastomoses (95.4%) but was underpowered to demonstrate a reduction in anastomotic leak rate [24]. Our study shows LSCI can assess intestinal perfusion at a similarly high rate (97.5–100%) compared to ICG visualization. Though this study did not specifically study intestinal anastomoses, LSCI may potentially offer complementary perfusion information to ICG for anastomotic assessment.

The complementarity of LSCI for real-time, continuous blood *flow* information and ICG for blood *volume* information may offer a more comprehensive understanding of tissue perfusion [14, 26]. In this study, our results demonstrate high concordance between LSCI and ICG view of tissue perfusion (within two minutes of first dose of ICG injection) in partially devascularized colon and stomach, respectively. However, ICG is known to cause fluorescent dye diffusion and tissue infiltration over time in surrounding tissue soon after injection and is not optimal for repeated injection for angiography [11]. LSCI does not

require dye injection, is easily repeatable, has imperceptible latency to perfusion display compared to ICG [16, 17, 21]. In prior comparisons of LSCI and ICG perfusion visualization in devascularized porcine intestine, surgeons were able to identify the margin of mesenteric devascularization best using LSCI or ICG less than two minutes after initial ICG dye injection [27]. The highest discordance in devascularization margin detection occurred when more than five minutes passed after initial ICG injection, with an average error of 37 mm. These findings illustrate the spatiotemporal accuracy of LSCI and the initial reliability of ICG fluorescence angiography for perfusion assessment that decreases when time from injection increases.

LSCI and ICG fluorescence imaging are both moving toward more objective perfusion quantification metrics by using algorithms to translate fluorescence intensity and LSCI perfusion colormaps, respectively, into relative perfusion values [14, 28–31]. In contrast to ICG fluorescence imaging which functionally visualizes metabolized forms of ICG in extrahepatic biliary anatomy or intrahepatic tumors, LSCI also promises to provide additional optical signals and tissue signature depending on additional wavelengths of coherent light sources used. The
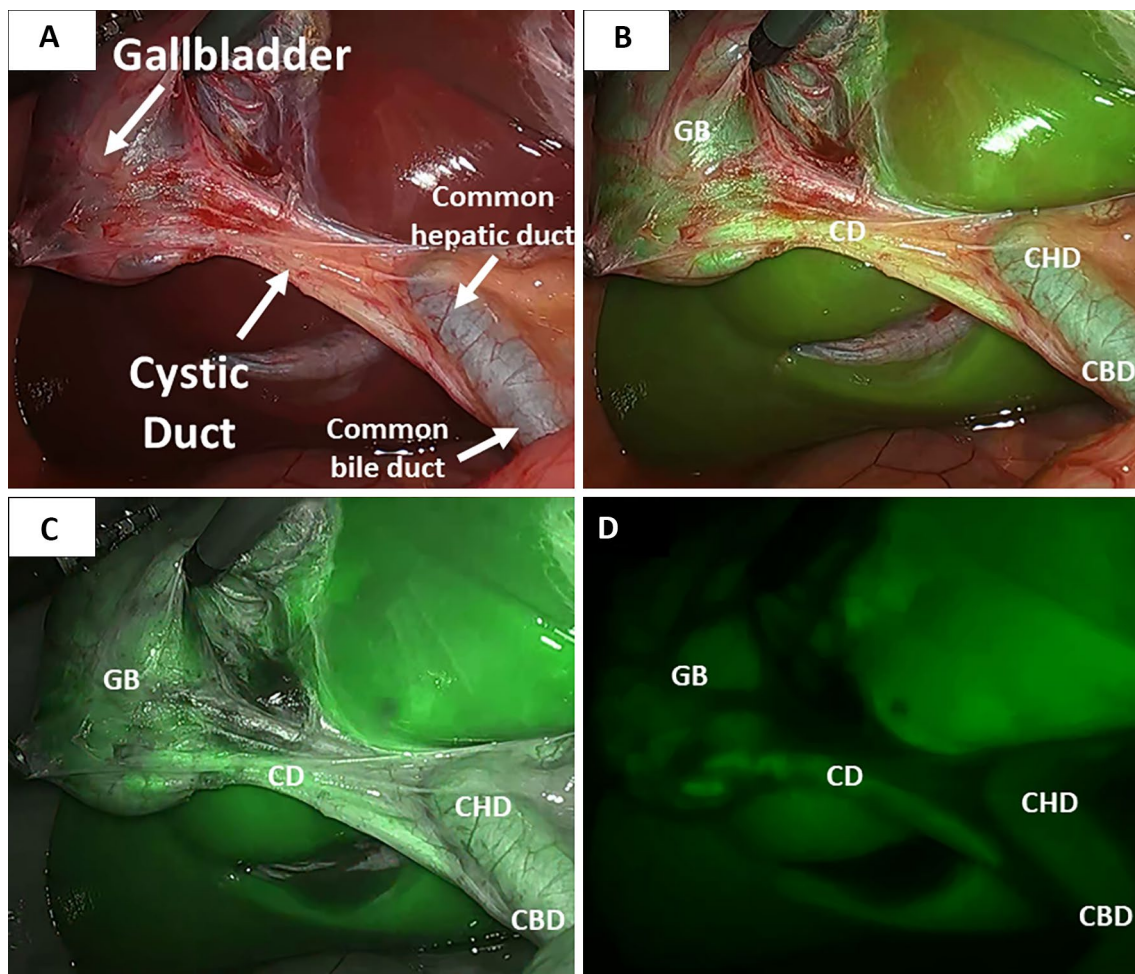
Fig. 4 Lap chole ICG

proprietary systems and methods applied to the LSCI signals in this device were designed to mitigate known motion artifact limitations and optimize blood flow and perfusion visualization.

Ancillary laparoscopic camera systems are routinely used in RAS procedures including for direct visualization during port placements. Usability and human factor scores demonstrate minimal disruption to RAS workflow in the concomitant use of LSCI for augmented advanced visualization technology during RAS procedures. Picture-in-picture ancillary laparoscopic displays on the robotic platform screen posed minimal inconvenience to operating surgeons and team at the time of tissue perfusion assessment. This device's ability to combine LSCI and ICG imaging and perform perfusion detection similarly well in RAS compared to laparoscopic surgery, holds promise for potential future applications across new surgical approaches, such as endoluminal/endoscopic surgery or incorporation into robotic systems. Interestingly, a robotic platform may be ideal to address certain limitations of LSCI technology, such as motion artifact, by eliminating camera tremor and instability [22].

Finally, since the objective of this novel clinical device trial was safety and feasibility, limitations include small sample size, cohort selection, and generalizability. The lack of device- and surgery-related adverse events identified in this study by post-operative day 28 is likely a consequence of the small sample sizes of each procedure performed in this pivotal study. Larger clinical trials focused on specific procedures involving intestinal anastomoses are currently underway to better understand the impact of combined ICG/LSCI technology on anastomotic leaks. Moreover, our study's patient population had a higher proportion of females and patients with lower BMIs in both RAS and laparoscopic groups, as well as older patients in the RAS group compared to other published cohorts of RAS vs. Laparoscopic approaches in colorectal and bariatric surgery [32–34]. However, the differences in patient demographics between RAS and Laparoscopic groups were not significant. In addition, the study was not powered or designed to determine

Table 3 Usability and utility of ActivSight™ combined LSCI and ICG NIR fluorescence technology device by robotic-assisted surgery (RAS) vs. laparoscopic surgery, as determined by end-user human factor testing on Likert Scale (scale 1–5 where 1 is dissatisfied and 5 is satisfied)

	RAS ($n=40$)		Laparoscopic ($n=27$)		p value
	Mean	SD	Mean	SD	
Setting up	**4.2**	**1.0**	**4.1**	**1.0**	0.70
Ease of set up	4.2	0.9	4.4	0.9	
Ease of activation	4.2	1.0	3.9	1.1	
Form factor	**3.9**	**0.9**	**3.7**	**1.1**	**0.02***
Size	3.7	1.0	3.4	1.2	
Weight	4.0	0.9	3.4	1.2	
Shape	3.7	0.9	3.4	1.2	
Color of adapter	4.5	0.8	4.6	0.8	
Handling	3.9	0.7	3.6	1.0	
Display	**4.1**	**0.7**	**4.1**	**1.0**	0.92
Brightness	4.3	0.6	4.3	0.8	
Specificity	3.9	0.8	3.9	1.2	
Resolution	4.0	0.8	4.1	0.9	
Augmentation	4.1	0.8	3.9	1.1	
Does device LSCI show perfusion? (% yes)	**97.5%**		**100.0%**		0.32

Bold values indicate category mean/SD for the components of each category

*$p < .05$ for statistical significance

the efficacy in perfusion detection between LSCI and ICG fluorescence imaging since this was a pilot safety and feasibility trial.

In conclusion, these results demonstrate the safety, usability, and utility of a dual mode LSCI and ICG device that combines the benefits of both LSCI and ICG NIR fluorescence imaging for real-time intraoperative augmented visualization in RAS and laparoscopic surgery.

Declarations

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