



REVIEW ARTICLE

# Quantification of indocyanine green fluorescence angiography in colorectal surgery: a systematic review of the literature

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## Abstract

**Background** Indocyanine green fluorescence angiography (ICGFA) during colorectal surgery associates with reduced post-operative anastomotic complication rates. Because its interpretation is subjective, quantification has been proposed to address inter-user variability. This study reviews the published literature regarding ICGFA quantification during colorectal surgery with a focus on impactful clinical deployment.

**Methods** A systematic review was performed of English language publications regarding clinical studies of ICGFA quantification in colorectal surgery in PubMed, Scopus, Web of Science and Cochrane Library on 29th August 2024, updated to 18th November 2024, following PRISMA guidelines. Newcastle Ottawa scale (NOS) was used to assess quality.

**Results** A total of 1428 studies were screened with 22 studies (1469 patients) selected. There was significant heterogeneity of ICGFA methodology, quantification methods and parameter selection and only three studies were NOS “high” quality. Extracorporeal application was most common. Four studies (154 patients) conducted real-time ICGFA analyses (others were post hoc) and four utilised artificial intelligence methods. Eleven studies only included patients undergoing left-sided resection (six focusing specifically on rectal resections). Only one study employed the quantification method to guide intra-operative decision-making regarding colonic transection. Twenty-six different perfusion parameters were assessed, with time from injection to visible fluorescence and maximum intensity the most commonly (but not only) correlated parameters regarding anastomotic complication ( $n=18$ ). Other grounding correlates were tissue oxygenation ( $n=3$ , two with hyper-spectral imagery), metabolites ( $n=2$ ) and surgeon interpretation ( $n=5$ ).

**Conclusion** Quantification of the ICGFA signal for colorectal surgery is feasible but has so far seen limited academic advancement beyond feasibility.

**Keywords** Colorectal surgery · Near infrared laparoscopy · Indocyanine green · Fluorescence angiography · Quantification

Colorectal surgery remains the mainstay of treatment for both benign and malignant colorectal disease. One of its most critical complications is anastomotic leakage (AL), with recent randomised controlled trials (RCTs) reporting an incidence of up to 23% following anterior resection of the rectum [1–4]. AL is associated with increased secondary complications, mortality, hospital length of stay and costs and poorer oncological outcomes [5–11].

Alongside many risk factors for AL following colorectal resectional surgery such as smoking, male gender, obesity, age, diabetes, neoadjuvant therapy, tumour location [12–15], ensuring appropriate perfusion of the anastomosis is a key step in mitigating AL [16]. Traditionally, surgeons have assessed bowel perfusion using various parameters such as palpable pulsation of the mesentery, colonic discolouration and active bleeding at the resection margin [12], however, these factors have been found to be subjective and unreliable [17].

Recent large scale RCTs are now concluding that indocyanine green fluorescence angiography (ICGFA) provides a rapid and reliable intra-operatively bowel perfusion assessment [3, 18–23] by presenting near-infrared (NIR) imagery for the surgeon to interpret, that may become a new standard

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of care for restorative colorectal surgery. However potential barriers to its widespread adoption remain including its subjective nature, with significant inter-user variability [24–26] evident, and associated learning curve. Computer vision methods of ICGFA quantification have been proposed as a means of adding robustness to the technique and so it is now timely to consider their merit in overcoming interpretation issues in the near-term and so be part of any technology roll-out. Here we review the state of the art via published literature regarding ICGFA signal quantification in colorectal surgery with a focus on impactful clinical deployment.

## Methods

### Search strategy

This review did not meet the criteria for a systematic review as per Prospero criteria as there was no unifying, single, primary outcome [27] and so a systematic literature search was carried out according to PRISMA-Search checklist guidelines and recommendations [28]. PubMed, Scopus, Web of Science and Cochrane Collaboration database were searched for relevant publications initially from inception to 29th August 2024 and then updated to 18th November 2024 using the following Medical Subject Heading (MESH) search terms: “colorectal” (includes “colon” and “rectum”), “bowel”, “anastomosis”, “anastomotic leak”, “outcome”, “perfusion”, “assessment”, “evaluation”, “fluorescence”, “angiography”, “indocyanine green”, “quantification”, “computation”. All terms were “exploded” to include sub-headings and the truncation symbol (\*) used as appropriate. The Boolean operator “OR” was used within concepts, whilst “AND” was used to link concepts. Titles and abstracts were then screened by two reviewers (PMcE and AS). Additionally, reference lists in relevant publications and Google Scholar were screened for other relevant publications.

### Study selection

For inclusion in analysis, studies had to meet the following criteria:

- Publication of a clinical study in patients undergoing colorectal surgery for benign or malignant disease
- ICGFA use for assessment of bowel perfusion
- A method to quantify the fluorescence imagery
- Full text available in English

Studies were excluded if any of the following criteria were met:

- No human patients (e.g. animal studies)
- Publication types such as systematic reviews, meta-analyses, guidelines, conference abstracts.

### Outcome of interest

The studies included were compared based on the methodology used, the ICG dosage, the NIR camera system and the quantification software. Types of operations performed and timing of ICG administration were recorded. Measured parameters, endpoints of the studies, the rate of change of mind based on fluorescence imaging and the anastomotic complication rates were summarised.

### Data extraction

The selection process was assisted by an online tool (Rayyan®) [29]. Two reviewers (PMcE and AS) independently examined studies according to the predefined strategy and criteria. Each extracted and recorded separately the title and publication details in addition to population characteristics. Databases were reviewed and compared at the end of the reviewing process to limit selection bias, remove duplicates and a third reviewer (PB) was used to clarify any disputes.

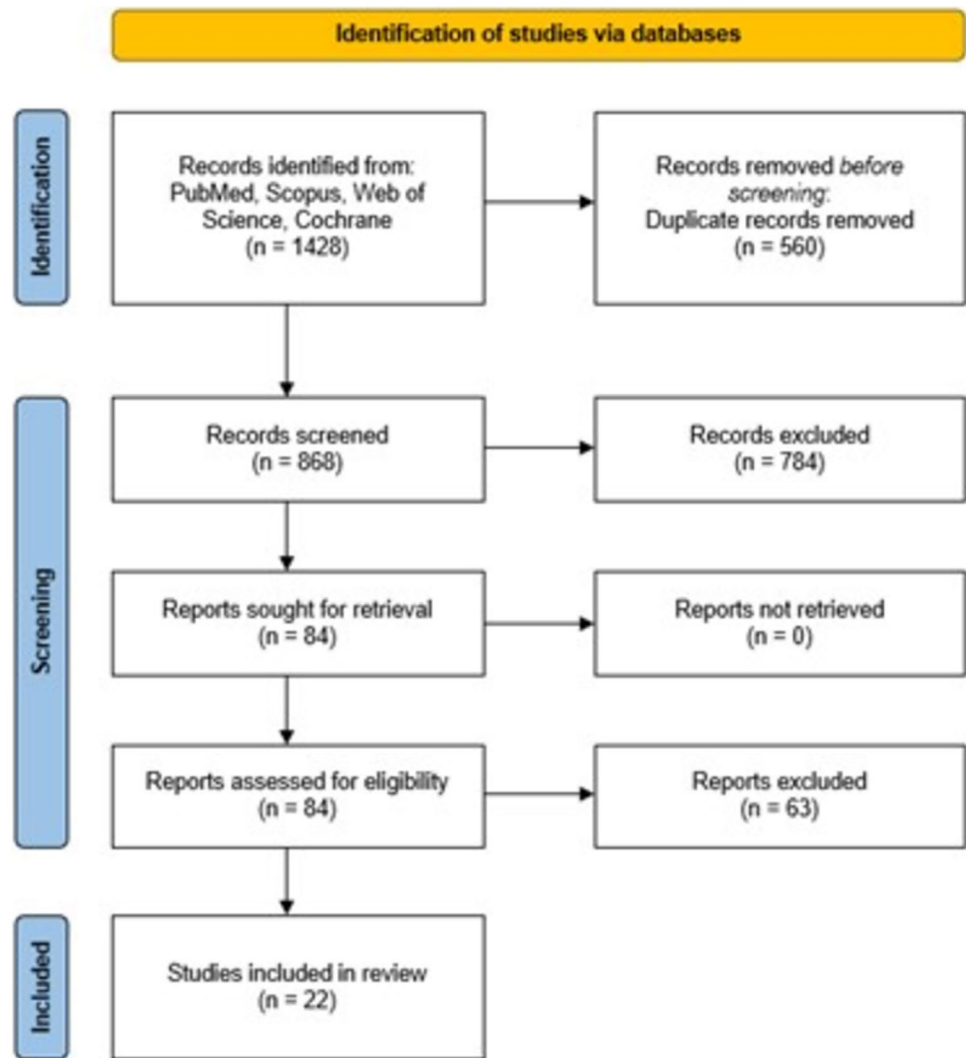
### Quality assessment

The quality assessment was performed by two authors (PMcE and AS) independently. Studies were assessed using the Newcastle Ottawa Scale (NOS) [30]. In the case of any disputes, a third author (PB) was consulted to clarify. Traffic light plots to present NOS assessments were created using the “robvis” package in RStudio 2023.12.0 [31].

## Results

### Study characteristics

The initial search yielded a total of 1428 studies, of which 84 met the criteria for full review, with 22 being finally included in this study as depicted in the PRISMA flow diagram (Fig. 1). All these studies were published after 2010, with fifteen (68.1%) being published from 2020 onwards. Together, the 22 studies included quantitative ICGFA analysis data from a total of 1469 patients, with the number of patients in each study ranging from 4 to 301. In four studies (154 patients) real-time analysis of the fluorescence signal was performed with the remainder (1315 patients) utilising post hoc video recording analysis (Table 1) [12, 32–52]. The senior corresponding author was a surgeon in twenty-one studies with the other one being coordinated by a scientist

**Fig. 1** PRISMA flowchart of study selection

[44]. NOS evaluated 16 studies as moderate quality with three each being high and low quality. (Fig. 2).

### ICG protocol, visualisation and software

Most ( $n = 20$ ) studies assessed ICGFA of the colonic segment intended for anastomosis prior to anastomotic formation, with one other study assessing ICGFA both before and after [12], and one after only anastomosis [37]. Eleven studies included only patients undergoing left-sided resection, with six of these focusing specifically on rectal resections (576 patients). One of the included rectal-only studies assessed only the distal rectal stump after resection of the specimen [49]. The remaining eleven studies included patients undergoing resectional surgery for a variety of benign and malignant pathologies throughout the colon, rectum and small bowel. The dose of ICG given varied significantly also. Eight of the studies administered a weight-dependent dose of ICG, with ten studies using a

fixed dose regimen (four studies did not report dosing). Various camera systems were used with manufacturers including Stryker [32, 34, 42, 43, 49–52], Karl Storz [33, 37, 40, 47], Novadaq [35, 38], Hamamatsu Photonics [36], Pulsion Medical System [12], Quest Medical Imaging [39, 41], Olympus [44, 48], Medtronic [45], Intuitive [46, 48] and Arthrex [52]. Thirteen studies performed extra-corporeal ICG assessment of the region of interest, whilst two studies performed intra-corporeal assessment, with six studies using a mixture (one study did not report this). Of the six studies examining rectal resections only, two each performed ICGFA assessment extra-corporeally, intra-corporeally or as a mixture. Eighteen of the studies reported an image capture protocol, with twelve reporting a specified length of time, ten reporting a fixed distance between the camera and the tissue of interest and five reporting turning off the background lights for extracorporeal assessment. ICGFA signal quantification was carried out using a variety of commercially available [36, 37, 49] or bespoke

**Table 1** Study and patient characteristics. NR not recorded

Publication	Patient number	Study period	Operations	Analysis	Senior author
Park et al. (2020)	65	August 2018–May 2019	Anterior resection/low anterior resection	Post hoc	Surgeon
Son et al. (2019)	86	July 2015–December 2017	Anterior resection/low anterior resection	Post hoc	Surgeon
Son et al. (2023) + Hyperspectral Imaging	68	January 2021–December 2022	Sigmoid/rectal resection	Real-time	Surgeon
Protyniak et al. (2015)	77	June 2013–June 2014	Multiple sites within colon and rectum	Post hoc	Surgeon
Wada et al. (2017)	112	August 2013–April 2016	Left-sided colorectal resections	Post hoc	Surgeon
Hayami et al. (2019)	22	December 2014–September 2015	Multiple sites within colon and rectum	Post hoc	Surgeon
Kudszus et al. (2010)	201	2003–2008	Multiple sites within colon and rectum	Post hoc	Surgeon
Bornstein et al. (2018)	49	NR	Multiple sites within small bowel, colon and rectum	Post hoc	Surgeon
Faber et al. (2023)	20	NR	Multiple sites within colon and rectum	Post hoc	Surgeon
D'Urso et al. (2021)	22	January 2017–November 2018	Left-sided colorectal resections	Real-time	Surgeon
Meijer et al. (2021)	4	NR	Varied operations with mesenteric resection	Post hoc	Surgeon
Dalli et al. (2024)	23	NR	Multiple sites within colon and rectum	Post hoc	Surgeon
Adams et al. (2024)	89	August 2021–June 2022	Multiple sites within colon and rectum	Post hoc	Surgeon
Arpaia et al. (2022)	11	NR	Multiple sites within colon and rectum	Real-time	Scientist
Gomez-Rosado et al. (2022)	70	July 2020–February 2021	Multiple sites within colon and rectum	Post hoc	Surgeon
Kim et al. (2017)	310	2013–2016	Low and ultra-low anterior resections	Post hoc	Surgeon
Aiba et al. (2021)	110	September 2017–January 2020	Multiple sites within colon and rectum	Post hoc	Surgeon
Han et al. (2022)	22	February 2020–July 2020	Left-sided colorectal resections	Post hoc	Surgeon
Iwamoto et al. (2020)	25	July 2016–June 2017	Anterior resection	Post hoc	Surgeon
Egi et al. (2022)	12	January 2021–March 2021	Left-sided colorectal resections	Post hoc	Surgeon
Soares et al. (2022)	18	May 2019–November 2019	Multiple sites within colon and rectum	Post hoc	Surgeon
Singaravelu et al. (2024)	53	NR	Multiple sites within colon and rectum	Real-time	Surgeon

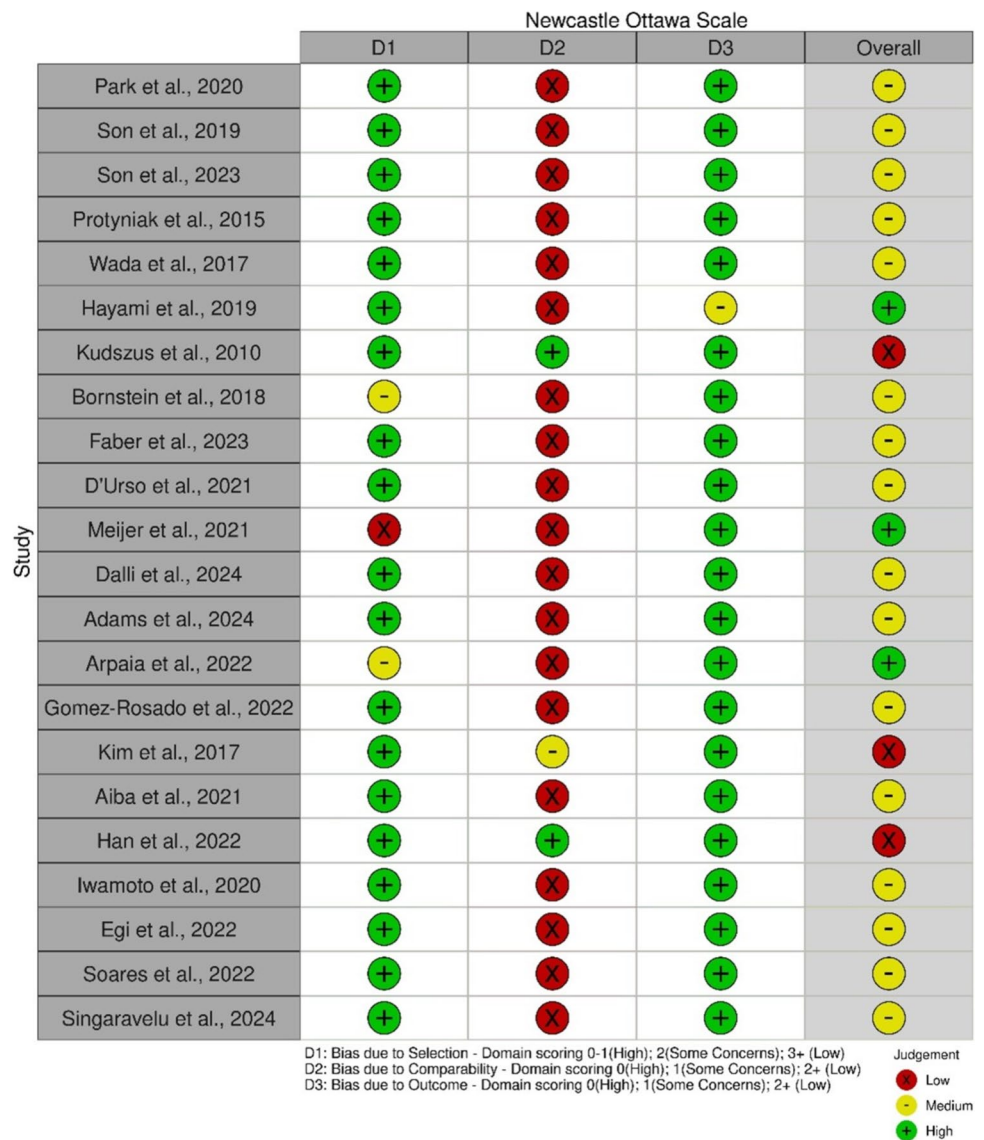
[32, 38, 42, 52] software, however none of the latter seem to have been made available yet online for use by others (Table 2).

### Perfusion parameters

In total, in included studies, 26 different perfusion parameters were defined and used being broadly categorisable into intensity, inflow and outflow milestones (see Table 2 and Fig. 3 for details).

### Intensity

Maximum fluorescence intensity ( $F_{\max}$ ) was the second most frequently assessed parameter ( $n = 13$ ). Other intensity parameters included half of the maximum intensity and the fluorescence intensity drop at 50 and 100 s after maximum intensity ( $n = 1$  each).

**Fig. 2** Traffic light plot for Newcastle Ottawa Score results

## Inflow

Time to reach maximum intensity from the beginning of visible fluorescence ( $T_{\max}$ ) was the most frequently assessed parameter ( $n = 15$ ). Time to reach half of maximum intensity from the beginning of visible fluorescence ( $T_{1/2\max}$ ) and time from injection to visible fluorescence ( $T_0$ ) were also included in many studies ( $n = 8$  and  $7$ , respectively). Some of the calculated inflow parameters included time ratio ( $T_{1/2\max}/T_{\max}$ ), relative slope ( $F_{\max}/T_{\max}$ ), time from injection to reach maximum intensity ( $T_0 + T_{\max}$ ), maximum inflow slope (ingress slope), maximum inflow slope in percentage per second (normalised slope), rate of change and duration (timing) of the overall intensity curve, slope at ten seconds after visible fluorescence ( $RS_{10s}$ ).

## Outflow

Only three of the included studies assessed parameters occurring after maximum fluorescence intensity. These were the maximum outflow slope (egress slope), area under the curve (AUC) in percentage after 30/60/120/180 s from  $T_{\max}$  ( $AUC_{30/60/120/180}$ ), overall downslope, downslope at 50/100 s, centre of mass, the fluorescence difference between maximum intensity and intensity at a sharp drop then gentle decrease ( $F_{\text{plateau}}$ ), the time after maximum intensity  $F_{\text{plateau}}$  occurs ( $T_{\text{plateau}}$ ) and the decreased fluorescence slope ( $F_{\text{plateau}}$  divided by  $T_{\text{plateau}}$ ).

**Table 2** ICG protocol, visualisation, software and perfusion parameters

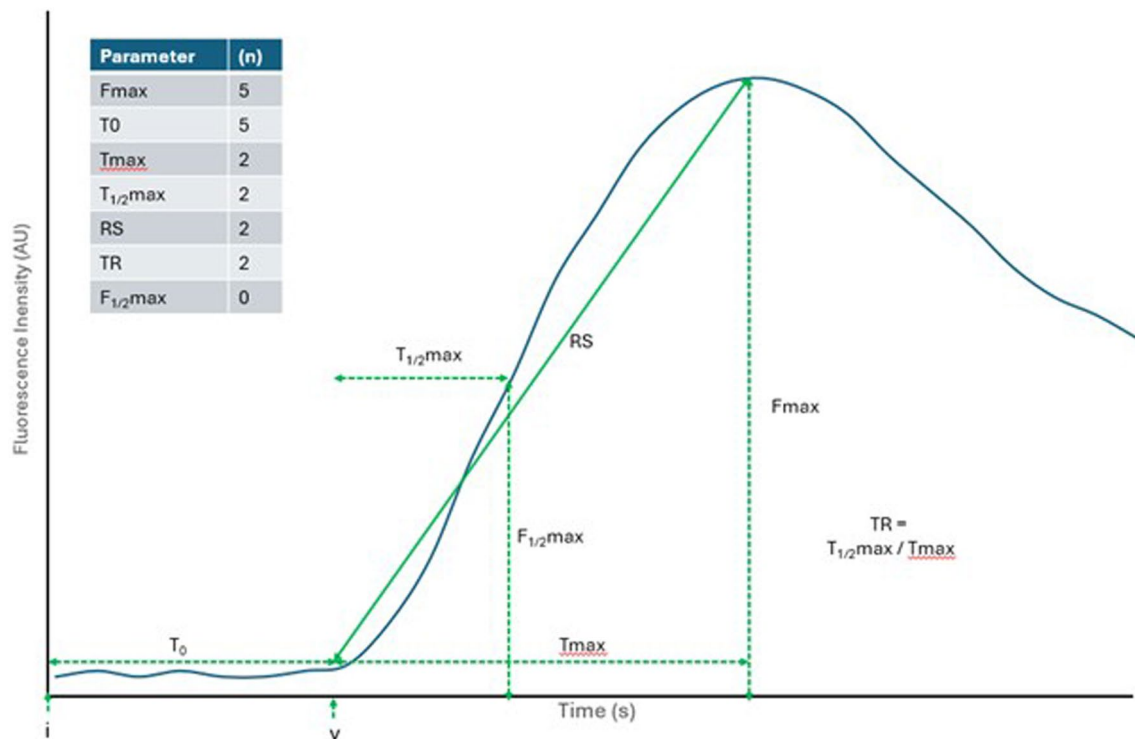
Paper	Timing (relative to anastomosis)	Dosage	Camera system	Intra- or extra-corporeal ICG assessment	Image capture Protocol	Quantification system	Parameters used
Park et al. (2020)	Prior	0.2 mg/kg	1588 AIM, Stryker	Mixed	Camera 6–8 cm from tissue, for 2 min after injection	MATLAB 2019, Math-Works	$T_{max}$ , $T_{1/2max}$ , TR, $F_{max}$ , RS
Son et al. (2019)	Prior	0.25 mg/kg	IMAGE1 S, Karl Storz	Mixed	For 2 min after injection, up to 5 min if poor perfusion	Tracker 4.97, Douglas Brown, Open Source	$T_{max}$ , $T_{1/2max}$ , TR, $F_{max}$ , RS
Son et al. (2023)	Prior	0.2 mg/kg	1588 AIM, Stryker	All extra-corporeal	Camera 4–5 cm from tissue, lights off, for 2 min after injection	ICG Analyzer Program 8.0, Pusan National University	$T_{max}$ , $T_{1/2max}$ , TR, $F_{max}$ , RS
Protyniak et al. (2015)	Prior	NR	SPY Elite Imaging System, Novadaq	Mixed	For 60 s after visible fluorescence	SPY-Q, Stryker	$T_{max}$
Wada et al. (2017)	Prior	5 mg	PDE-neo System, Hamamatsu Photonics	All extra-corporeal	Camera 15 cm from tissue, lights off	ROIs, Hamamatsu Photonics	$T_{max}$ , $T_{1/2max}$ , $F_{max}$ , RS
Hayami et al. (2019)	Post	5 mg	D-light P system, Karl Storz	All extra-corporeal	Camera 20 cm from tissue, for 5 min after injection	ROIs, Hamamatsu Photonics	$T_0$ , $T_{max}$ , $T_{1/2max}$ , $F_{max}$ , RS
Kudszus et al. (2010)	Pre and post	0.2–0.5 mg/kg	IC-View, Pulsion Medical System	All extra-corporeal	Tripod-mounted camera, lights off, loop of small intestine as reference	IC-Calc®	NR
Bornstein et al. (2018)	Prior	NR	SPY Elite Imaging System, Novadaq	All extra-corporeal	For 113–128 s after injection	Modified Comprehensive Angiographic and Perfusion Analysis platform	$F_{max}$ and 'Timing'
Faber et al. (2023)	Prior	5 mg	Quest Spectrum 2.0, Quest Medical Imaging	All extra-corporeal	Camera 30 cm above tissue, for 5 min after injection, 90 degrees to tissue, standardised camera settings	Quest Research Framework, Quest Medical Imaging	$T_{max}$ , $F_{max}$ , Ingress Slope, RS, Normalised Slope, Egress Slope, AUC 30/60/120/180s
D'Urso et al. (2021)	Prior	0.2 mg/kg	D-light P system, Karl Storz	All extra-corporeal	NR	Fluorescence-based enhanced reality (FLER)	$T_{max}$
Meijer et al. (2021)	N/A	5 mg	Quest Spectrum, Quest Medical Imaging	All extra-corporeal	NR	Mevislab, MeVis Medical Solutions AG	$T_{max}$ , $T_{1/2max}$ , TR, $F_{max}$ , $F_{1/2max}$ , RS, RS10s
Dalli et al. (2024)	Prior	0.1 mg/kg	Pinpoint, Stryker	Mixed	4 min from visible fluorescence	IBM Tracker + MATLAB	$T_0$ , $T_{max}$ , $T_{1/2max}$ , TR, $F_{max}$ , $F_{50s}$ , $F_{100s}$ , Downslope <sub>50s</sub> , Downslope <sub>100s</sub> , COM

**Table 2** (continued)

Paper	Timing (relative to anastomosis)	Dosage	Camera system	Intra- or extra-corporeal ICG assessment	Image capture Protocol	Quantification system	Parameters used
Adams et al. (2024)	Prior	NR	SPY-PHI QP, Stryker	All extra-corporeal	2 min from visible fluorescence, bowel 10 cm proximal to resection margin as reference	SPY-PHI QP, Stryker	$T_{\max}$ , $F_{\max}$
Arpaia et al. (2022)	Prior	NR	Visera Elite, Olympus	NR	NR	Minimum Output Sum of Squared Error (MOSSE) tracker. Python 2.7—TensorFlow, Keras, OpenCV	NR
Gomez-Rosado et al. (2022)	Prior	7.5 mg	VisionSense VS Iridium, Medtronic	Mixed	Camera 15 cm from tissue, standardised camera lens, lights off	Elevation IR, Medtronic	$T_0$ , $T_{\max}$ , $T_{\max} + T_0$ , $F_{\max}$ , $F_{\max \text{ROI}}$ , RS
Kim et al. (2017)	Prior	10 mg	Da Vinci Firefly, Intuitive	All extra-corporeal	According to manufacturer's instructions	Color Standards, Micro-soft PowerPoint	$T_{\text{Omesocolon}}$ , $T_{\text{Ocolon}}$ , $F_{\max}$ (grades 1–5)
Aiba et al. (2021)	Prior	0.1 mg/kg	OPAL1, Karl Storz	All extra-corporeal	Camera 5 cm above tissue, lights off	NA	$T_0$
Han et al. (2022)	Prior	7.5 mg	Visera Elite, Olympus or Da Vinci Firefly, Intuitive	All intra-corporeal	2 min after visible fluorescence, injection at start of case for baseline	HSL Video Analyzer, Dr. Park's Software Lab	$T_{\max}$ , $T_{1/2\max}$ , TR, $F_{\min}$ , $F_{\max}$ , RS, $T_{\text{plateau}}$ , $F_{\text{plateau}}$ , Slope <sub>plateau</sub>
Iwamoto et al. (2020)	Prior	7.5 mg	Pinpoint, Stryker	All intra-corporeal	Camera 5 cm from tissue, for 5 min after injection	ROIs, Hamamatsu Photonics	$T_0$ , $T_{\max}$
Egi et al. (2022)	Prior	5 mg	Pinpoint, Stryker	All extra-corporeal	NR	NA	$T_0$
Soares et al. (2022)	Prior	10 mg	Pinpoint, Stryker	All extra-corporeal	Tripod-mounted camera	NR	$F_{\max}$
Singaravelu et al. (2024)	Prior	0.1 mg/kg	Pinpoint/Stryker 1688, Styker and Synergy Vision, Arthrex	Mixed	90 s after ICG injection with indication of actual transection site	MATLAB R2024a, MathWorks	$T_{\max}$ , $T_{1/2\max}$ , $F_{\max}$ , RS

NR not recorded, TR time ratio, RS relative slope, AI artificial intelligence, T0 time to visible fluorescence, AUC area under curve, COM centre of mass





**Fig. 3** Schematic representation of the most commonly utilised perfusion parameters. AU arbitrary units, s seconds, i time of ICG injection, v time of first visible fluorescence, T0 time from ICG injection to first visible fluorescence, Fmax maximum intensity, Tmax time to reach maximum intensity from beginning of visible fluorescence,

F1/2max half maximum intensity, T1/2max time to reach half maximum intensity from beginning of visible fluorescence, TR time ratio, (n) number of studies where parameter was statistically significantly correlated to endpoint

### Artificial intelligence (AI) models

Four studies used AI. Park et al. [32] developed an unsupervised machine learning model using a self-organizing map (SOM) network to predict the risk of anastomotic complications focussing only on rectal resections. This model was trained on 50 patient videos and tested on 15. The training dataset included 10,000 ICG curves extracted from 200 different locations within the fluorescence videos. The average intensity value was calculated from each region of interest for 40 s (at 30 frames/second). SOM clustering of the training data resulted in 25 ICG curve patterns and each pattern was risk-labelled (safe/intermediate/dangerous).

Dalli et al. [42] developed a patient calibrated quantitative ICGFA bowel transection recommender. Initially, a reference ICGFA curve was obtained from a 4-min ICGFA video recorded from the colon before any tissue dissection occurred. Subsequently, a second ICG dose was administered to obtain a determinative ICGFA curve following dissection and vessel ligation. The ICGFA imagery was tracked and quantified, producing ICG curves which underwent smoothing and normalisation. The reference curve was then scaled and shifted to match the determinative curve and if narrower or wider than the determinative curve, brisker or

slower perfusion was inferred, respectively. A determinative curve with  $\geq 85\%$  match to the reference curve indicated sufficient perfusion. Consequently, the most distal region of interest, characterised by sufficient perfusion in the determinative ICGFA imagery, was defined and recommended as a safe transection site. The model was trained on 14 patient videos and validated on 9 patient videos.

Arpaia et al. [44] developed a machine learning model using the Feed Forward Neural Network algorithm (*Adam* optimizer, *cross-entropy* loss function) to classify whether perfusion was adequate or inadequate. In this, a region of interest (rectangle) was selected and divided into 20 vertical slices, and a histogram of the green band was generated. A fast-tracking algorithm was used to track these selected regions. The feature vector (20 vertical elements) was classified as either adequate or inadequate perfusion, with the correctness confirmed by the operating surgeons. The model was trained on eleven patient videos.

Singaravelu et al. [52] developed a deep learning bi-directional long short-term memory model to predict where an experienced ICGFA user would place the surgical stapler based on their interpretation of the imagery. ICGFA video frames underwent stabilisation and tracking. Training involved the selection of four lines of different lengths and



positions across the fluorescent-nonfluorescent boundary of the region of interest, with the extraction of fluorescence parameters from multiple regions centred on each line. The site of stapling selected by the operating surgeon was then labelled “expert”, with the perfused side labelled “good” and the non-perfused side labelled “poor”. This model was trained on 25 patient videos and tested on 28.

## Clinical deployment and correlation

### Clinical deployment

In only one of the included studies were the perfusion parameters and quantification method actually used intra-operatively. Son et al. [34] ( $n=68$ ) developed a protocol based on tissue oxygen saturation ( $\text{StO}_2$ ) and  $T_{1/2\text{max}}$  with which they decided whether or not to change the intended transection line to a more proximal segment (this occurred in 6/68 cases). Three other studies performed real-time analysis of the ICGFA signal, but the operating surgeon was blinded to the interpretation of the quantification method in these cases. D’Urso et al. [40] ( $n=22$ ) used fluorescence-based enhanced reality (FLER) to superimpose the virtual perfusion cartography onto the bowel to display perfusion values with the aim of correlating this to intestinal lactates and mitochondrial respiration. Arpaia et al. [44] carried out real-time testing of their AI model in an unspecified number of cases with the aim of correlating to surgical classification of the region’s perfusion as adequate or inadequate. Singaravelu et al. [52] carried out real-time testing of their AI model with the aim of correlating to surgeon selection of the transection point. In the remaining studies, analysis of the ICGFA signal was conducted after the operation and so all intra-operative decisions made were based on the independent ICGFA interpretation of surgeon.

### Anastomotic complications

The most common outcome of interest in the studies was anastomotic complication rate, with eighteen studies reporting this and eleven of these assessing for correlation between perfusion parameters and anastomotic complication. Of the 26 parameters assessed, six were found to correlate with anastomotic complication rate.  $T_0$  and  $F_{\text{max}}$  were the most common ( $n=4$ ), with slope ( $n=2$ ), TR ( $n=2$ ),  $T_{1/2\text{max}}$  ( $n=1$ ) and  $T_{\text{max}}$  ( $n=1$ ) also found to correlate. The AI model generated by Park et al. [32] was more predictive of anastomotic complication than the perfusion parameters assessed (AUC 0.842 AI vs 0.734 TR and 0.750  $T_{1/2\text{max}}$ ). Adams et al. [43] reported no correlation between the studied parameters and anastomotic complication, whilst Protyniak et al. [35], Faber et al. [39] and Meijer et al. [41] reported their study

numbers as being too small to assess for correlation. When comparing studies with intra-corporeal ICGFA assessment versus extra-corporeal assessment, the study findings were similar. Han et al. [48] (intra-corporeal) reported  $F_{\text{max}}$  was lower in the AL group, in keeping the findings of Wada et al. [36] and Kim et al. [46] (extra-corporeal). Iwamoto et al. [49] (intra-corporeal) assessed the rectal stump after transection and found  $T_0$  was higher in the AL group, in keeping with the findings of Aiba et al. [47] and Hayami et al. [37] (extra-corporeal).

Five of the six studies focussing on rectal resections assessed for parameter correlation with anastomotic complication. In these,  $T_0$ ,  $F_{\text{max}}$  and TR were most found to correlate ( $n=2$ ), with  $T_{1/2\text{max}}$  also correlating in one study [34].

### Tissue oxygen saturation

Three studies [34, 50, 51] assessed for correlation between perfusion parameters and tissue oxygen saturation and in these,  $T_{1/2\text{max}}$ ,  $T_{\text{max}}$ ,  $T_0$  and  $F_{\text{max}}$  (all  $n=1$ ) were found to correlate with the former two correlating in one study specifically including rectal resections. Two of the studies utilised a hyperspectral imaging camera to assess tissue oxygen saturation [34, 51] and the third study utilised near-infrared spectroscopy [50].

### Metabolic markers

D’Urso et al. [40] reported that  $T_{\text{max}}$  correlated with both capillary lactates and mitochondrial respiration. Dalli et al. [42] reported correlation of lactate ratio with both downslope and  $F_{\text{max}}$ , however the generated model did not correlate.

### Surgeon interpretation

Whilst thirteen studies reported the rate with which the surgeon changed the surgical plan with ICGFA, only one correlated this with measured parameters. Adams et al. [43] reported that in cases where the surgeon changed the surgical plan, the  $F_{\text{max}}$  was significantly lower and  $T_{\text{max}}$  significantly higher than in cases with no change. The AI model generated by Arpaia et al. [44] reported a prediction accuracy of 99.9% when comparing the perfusion of the selected region of interest versus surgeon classification as adequate or inadequate. Three studies assessed whether the quantification method matched the transection point selected by the operating surgeon. Bornstein et al. [38] reported disparity between their system and the selected transection point in 11 of 72 cases, whilst Dalli et al. [42] found their system matched the selected transection point in 10 of 11 bowel segments (9 patients). Singaravelu et al. [52] reported 85% accuracy at pixel level versus expert surgeon interpretation in the overall

**Table 3** Clinical endpoints and results

Paper	Change of mind	Anastomotic complication (AC)	Other	Results
Park et al. (2020)	3/50 training, 3/15 testing based on surgeon	3/50 leak, 1/50 stricture in training, 0 complications in testing		ROC curves of $T_{1/2max}$ , TR and AI model predictive of anastomotic complication risk by hypoperfusion ( $p$ 0.034, 0.006 and $<0.001$ , respectively) TR $>0.6$ associated with anastomotic complication ( $p=0.002$ )
Son et al. (2019)	7/86 based on surgeon	6/86 anastomotic complications		$T_{1/2max} \leq 10$ s associated with $StO_2 \geq 60\%$ ( $p<0.01$ ). $T_{max} \leq 30$ s associated with $StO_2 \geq 60\%$ ( $p0.01$ )
Son et al. (2023)	6/68 based on readings	5/68 anastomotic complication 1/6 in change group	Hyperspectral Imaging using TIVITA Tissue System to measure $StO_2$	Too small to assess for correlation
Protyniak et al. (2015)	4/77 based on surgeon	2/77 leaks		$F_{max} < 52AU$ 100% sensitive, 92.5% specific, 38.5% PPV, 100% NPV for prediction of AL.
Wada et al. (2017)	18/112 based on surgeon	5/112 leaks		Slope $< 2.1AU/sec$ 100% sensitive, 75.7% specific, 16.1% PPV, 100% NPV for prediction of AL
Hayami et al. (2019)	1/22 based on surgeon	3/22 leaks		$T_0$ significantly higher in AL group ( $P<0.001$ )
Kudszus et al. (2010)	28/201 based on surgeon	7/201 leaks		NR
Bornstein et al. (2018)	NR	NR	Disparity between system and surgeon selection of transection point	11/72 disparity, 6/11 disparity of both perfusion and timing, 5/11 had single disparity
Faber et al. (2023)	4/20 based on surgeon	4/20 leaks	Perfusion patterns 1, 2 and 3	Too small to assess for correlation
D'Urso et al. (2021)	3/22 based on surgeon	5/22 leaks	Capillary lactates and mitochondrial respiration	$T_{max}$ significantly higher at proximal resection site in AL group ( $p=0.01$ )
Meijer et al. (2021)	1/4 based on surgeon	1/4 leaks		Too small to assess for correlation
Dalli et al. (2024)	NR	1/23 leaks	Surgeon selection of transection point and mean lactate concentrations	19 segments for development, 11 segments for validation. Region of interest-based recommendation matched surgeon selection in 10 of 11 cases in validation series. Moderate negative correlation with downslope and lactate ratio ( $p<0.001$ ). Moderate negative correlation with $F_{max}$ and lactate ratio ( $p<0.001$ )
Adams et al. (2024)	7/89 based on surgeon	9/85 leaks	Surgeon preserves bowel (accepted perfusion, AP) or clinical decision to resect back to healthy margin (rejected perfusion, RP)	No correlation with parameters and anastomotic leak. $F_{max}$ lower in RP group ( $p=0.03$ ). $T_{max}$ higher in RP group ( $p<0.01$ )
Arpaia et al. (2022)	NR	NR		Prediction accuracy of 99.9% to assess if the quality of perfusion is adequate or inadequate
Gomez-Rosado et al. (2022)	16/69 based on surgeon	9/69 leaks		$F_{max}$ significantly lower in AL group ( $p=0.03$ ). Slope significantly lower in AL group ( $p=0.03$ )
Kim et al. (2017)	NR	2/310 leaks, 11/310 strictures		$T_0$ significantly higher in stricture group ( $p=0.01$ ). $F_{max}$ significantly lower in stricture group ( $p0.002$ )

**Table 3** (continued)

Paper	Change of mind	Anastomotic complication (AC)	Other	Results
Aiba et al. (2021)	2/110 based on surgeon	6/110 leaks	66 in marginal flow group, 44 in direct flow group	$T_0$ significantly higher in AL in marginal flow group ( $p = 0.046$ )
Han et al. (2022)	NR	2/22 leaks	High and low ligation of the inferior mesenteric artery, 11 in each group	$F_{max}$ significantly lower in overall AL group ( $p = 0.012$ )
Iwamoto et al. ((2020)	NR	6/25 leaks	INVOS, Medtronic to measure $StO_2$	$T_0$ significantly higher in AL group ( $p = 0.03$ )
Egi et al. ((2022)	NR	0/12	Multispectral imaging using SpectroCam, Ocean	Strong correlation with $T_0$ and $StO_2$ ( $p = 0.017$ )
Soares et al. ((2022)	NR	NR	Insight to measure $StO_2$	Strong correlation between $F_{max}$ and $StO_2$ ( $p < 0.001$ )
Singaravvelu et al. ((2024)	3/53	NR	Surgeon selection of transection point	Deep learning model 85% accurate at pixel level versus surgeon selection

NR not reported, ROC receiver operating characteristic, AI artificial intelligence, TR time ratio,  $StO_2$  tissue oxygen saturation, AU arbitrary units, PPV positive prediction value, NPV negative prediction value

set of 28 unseen cases and 89% accurate for the 15 real-time testing cases. Kudszus et al. [12] did not report any correlation of perfusion parameters and outcomes (Table 3).

## Discussion

RCTs and meta-analyses report benefit of ICGFA in colorectal surgery amongst regular users, without the need for quantification methods, in relation to post-operative AL rates [3, 19–23]. With widespread availability of NIR-capable platforms, the use of ICGFA for perfusion assessment during colorectal surgery may so become standard of care as professional society guidelines assimilate such level 1 evidence irrespective of individual unit perception [53]. Potential barriers to broad ICGFA implementation include the associated learning curve [24–26], along with a lack of standardised training pathways and any associated cognitive load with adding a step into already complex procedures [54] as well as need to document correct interpretation. Real-time quantification of the ICGFA signal has been proposed as a method to offset these issues, especially for new adopters [55].

This review clarifies the current state of the published art regarding quantification with a focus on useful clinical deployment. Overall, experience remains at developmental stage with significant heterogeneity of study quality, methodology and results. Whilst all the studies use a commercially available NIR-capable platform, the outputs from these platforms are variable (and all perform variable signal processing in doing so) and so each quantification method has been tailored to individual imagers. Even in studies utilising the same imaging platform, different computational approaches mean discrepancies in ICGFA quantification that limit generalisability [56]. Furthermore, whilst fluorescence signal intensity varies significantly with factors such as camera lens configuration (0 degrees versus 30 degrees) and distance from as well as position of target (i.e. central or peripheral placement in the field of view [57]), only some studies standardise set-up protocols (although some work suggests standardisation may worsen signal computational inference [58]). Reflective perhaps of variance in clinical practice [59], significant heterogeneity is also observed regarding ICG dosing.

Whilst experiences to date demonstrate that quantification of the ICGFA signal is feasible, there is still uncertainty as to its value and purpose, and there remains no fully validated system. Only a minority of studies focus on rectal resections which is where the main (and perhaps only) benefit of ICGFA is supported by clinical trialling [21]. Anastomotic complication was the endpoint most commonly assessed with half of studies attempting to correlate the quantified parameters with this, with others targeting alternative surrogates such as tissue oxygen

saturation (despite this itself being in need of clinical validation<sup>1</sup> [34], and measurement standardisation), metabolic markers or novel imaging methods such as hyperspectral imaging [60]. Perhaps more meaningful and more achievable for clinical validation (given that ICGFA is now known to associate with reduced AL rates when used by ICGFA-experienced surgeons) are the quantitative methods grounded in representing expert interpretation.

Another issue with ICGFA quantification may be the focus on seemingly separate fluorescence parameters although these are naturally interrelated as a time series. Whilst appearing distinct metrics for characterising fluorescence behaviour, they reflect connected dynamic, physical processes and their measurement may change with altering measurement conditions. AI methods [34, 42, 44, 52] may provide better analytics for this and its use seems likely to increase in this field and indeed others [61, 62]. Although uncommon as an endpoint as yet, ICGFA interpretation seems apposite for AI systems as the foundational phenomena are understandable even if the specifics of deep learning methods that exploit them may not be.

Aside from uncertainty of quantification method of best fit, there are other challenges to developing clinical commercial systems. Whilst it does appear that small datasets are sufficient to create and train quantification models, for validation and testing larger volumes of patient data from diverse populations is necessary, and there is no existing assessable warehouse of annotated imagery. Whilst individual units may hold some libraries, current data protection regulations make sharing this data with third parties challenging, meaning development studies need to perform their own prospective validations, including in different centres. Furthermore, there is concern at regulatory level about the level of decision support provided as this has liability impact. This concern could possibly be minimised utilising the quantitative method grounded in expert surgeon interpretation as it could, if proven to be validated in clinical studies, provide the user with the information of how an experienced ICGFA user would interpret the imagery [63]. Lastly, the optimum method for initial deployment is uncertain as introduction of algorithms into imager camera heads or towers may impact existing regulatory approvals, and so any new potential systems need deployment in a separable device as seen currently often in endoscopic polyp identification methods [64, 65]. These factors may account for why ICGFA quantification is still predominantly in the development phase (only four studies in this review have managed to perform real-time quantification of the ICGFA signal with only one of these using the quantification to inform intra-operative surgical decision making) in contrast to the use of ICGFA which has progressed to the point of seven published RCTs

comparing the use of ICGFA to non-use [1–4, 18, 23, 66], with others now completing enrolment/analysis [67–69].

In terms of study limitations, as discussed above, the biggest issue is the variability in study type which limited formal aggregation and meta-analysis. It is possible of course too that commercial entities developing systems are progressing without academic disclosure of their method and efforts.

## Conclusion

This review demonstrates that quantification of the ICGFA signal during colorectal surgery appears confined to academic explorations and the absence of deployed methods that would enable methodologically appropriate clinical trialling highlights a critical gap in the current clinical literature. ICGFA can be used reliably with experience by observation alone, computational methods may usefully aim to replicate this evaluation by representing experience user interpretation rather than aiming to simply provide further ungrounded data for additional interpretation.

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## References

- Gach T, Bogacki P, Orzeszko Z, Markowska B, Krzak JM, Szura M et al (2023) Fluorescent ICG angiography in laparoscopic rectal resection—a randomized controlled trial Preliminary report. *Wideochir Inne Tech Maloinwazyjne* 18(3):410–417
- Eltaweel M, Mohamadain A (2024) The value of intraoperative indocyanine green angiography to assess anastomotic perfusion and leakage in patients undergoing laparoscopic colorectal resection: a randomized controlled clinical trial. *Al-Azhar Int Med J* 5:10
- Watanabe J, Takemasa I, Kotake M, Noura S, Kimura K, Suwa H et al (2023) Blood perfusion assessment by indocyanine green fluorescence imaging for minimally invasive rectal cancer surgery (Essential trial): a randomized clinical trial. *Ann Surg* 278(4):e688–e694
- Jafari MD, Pigazzi A, McLemore EC, Mutch MG, Haas E, Rasheid SH et al (2021) Perfusion assessment in left-sided/low anterior resection (PILLAR III): a randomized, controlled, parallel, multicenter study assessing perfusion outcomes with PINPOINT near-infrared fluorescence imaging in low anterior resection. *Dis Colon Rectum* 64(8):995–1002
- Vallance A, Wexner S, Berho M, Cahill R, Coleman M, Haboubi N et al (2017) A collaborative review of the current concepts and challenges of anastomotic leaks in colorectal surgery. *Colorectal Dis* 19(1):O1–o12
- Mualla NM, Hussain MR, Akrmah M, Malik P, Bashir S, Lin JJ (2021) The impact of postoperative complications on long-term oncological outcomes following curative resection of colorectal cancer (Stage I–III): a systematic review and meta-analysis. *Cureus* 13(1):e12837
- Law WL, Choi HK, Lee YM, Ho JW (2007) The impact of postoperative complications on long-term outcomes following curative resection for colorectal cancer. *Ann Surg Oncol* 14(9):2559–2566
- Ptok H, Marusch F, Meyer F, Schubert D, Gastinger I, Lippert H (2007) Impact of anastomotic leakage on oncological outcome after rectal cancer resection. *Br J Surg* 94(12):1548–1554
- Kingham TP, Pachter HL (2009) Colonic anastomotic leak: risk factors, diagnosis, and treatment. *J Am Coll Surg* 208(2):269–278
- Asari SA, Cho MS, Kim NK (2015) Safe anastomosis in laparoscopic and robotic low anterior resection for rectal cancer: a narrative review and outcomes study from an expert tertiary center. *Eur J Surg Oncol* 41(2):175–185
- Buchs NC, Gervaz P, Secic M, Bucher P, Mugnier-Konrad B, Morel P (2008) Incidence, consequences, and risk factors for anastomotic dehiscence after colorectal surgery: a prospective monocentric study. *Int J Colorectal Dis* 23(3):265–270
- Kudszus S, Roesel C, Schachtrupp A, Höer JJ (2010) Intraoperative laser fluorescence angiography in colorectal surgery: a noninvasive analysis to reduce the rate of anastomotic leakage. *Langenbecks Arch Surg* 395(8):1025–1030
- Tan DJH, Yaow CYL, Mok HT, Ng CH, Tai CH, Tham HY et al (2021) The influence of diabetes on postoperative complications following colorectal surgery. *Tech Coloproctol* 25(3):267–278
- Choi HK, Law WL, Ho JW (2006) Leakage after resection and intraperitoneal anastomosis for colorectal malignancy: analysis of risk factors. *Dis Colon Rectum* 49(11):1719–1725
- McDermott FD, Heeney A, Kelly ME, Steele RJ, Carlson GL, Winter DC (2015) Systematic review of preoperative, intraoperative and postoperative risk factors for colorectal anastomotic leaks. *Br J Surg* 102(5):462–479
- Zarnescu EC, Zarnescu NO, Costea R (2021) Updates of risk factors for anastomotic leakage after colorectal surgery. *Diagnostics (Basel)* 11(12):2382
- Karliczek A, Harlaar NJ, Zeebregts CJ, Wiggers T, Baas PC, van Dam GM (2009) Surgeons lack predictive accuracy for anastomotic leakage in gastrointestinal surgery. *Int J Colorectal Dis* 24(5):569–576
- Faber RA, Meijer RPJ, Droogh DHM, Jongbloed JJ, Bijlstra OD, Boersma F et al (2024) Indocyanine green near-infrared fluorescence bowel perfusion assessment to prevent anastomotic leakage in minimally invasive colorectal surgery (AVOID): a multicentre, randomised, controlled, phase 3 trial. *Lancet Gastroenterol Hepatol*. [https://doi.org/10.1016/S2468-1253\(24\)00198-5](https://doi.org/10.1016/S2468-1253(24)00198-5)
- Verhoeff K, Mocanu V, Fang B, Dang J, Kung JY, Switzer NJ et al (2022) Are we overestimating the effect of indocyanine green on leaks following colorectal surgery: a systematic review and meta-analysis. *Innovations Surg Intervent Med* 2022(2):1–14
- Emile SH, Khan SM, Wexner SD (2022) Impact of change in the surgical plan based on indocyanine green fluorescence angiography on the rates of colorectal anastomotic leak: a systematic review and meta-analysis. *Surg Endosc* 36(4):2245–2257
- Lucarini A, Guida AM, Orville M, Panis Y (2024) Indocyanine green fluorescence angiography could reduce the risk of anastomotic leakage in rectal cancer surgery: a systematic review and meta-analysis of randomized controlled trials. *Colorectal Dis* 26:408–416
- McEntee PD, Singaravelu A, Boland PA, Moynihan A, Creavin B, Cahill RA (2025) Impact of indocyanine green fluorescence angiography on surgeon action and anastomotic leak in colorectal resections. A systematic review and meta-analysis. *Surg Endosc*. <https://doi.org/10.1007/s00464-025-11582-y>
- Alekseev M, Rybakov E, Shelygin Y, Chernyshov S, Zarodnyuk I (2020) A study investigating the perfusion of colorectal anastomoses using fluorescence angiography: results of the FLAG randomized trial. *Colorectal Dis* 22(9):1147–1153
- Hardy NP, Dalli J, Khan MF, Andrejevic P, Neary PM, Cahill RA (2021) Inter-user variation in the interpretation of near infrared perfusion imaging using indocyanine green in colorectal surgery. *Surg Endosc* 35(12):7074–7081
- Larsen PO, Nerup N, Andersen J, Dohrn N, Klein MF, Brisling S et al (2023) Anastomotic perfusion assessment with indocyanine green in robot-assisted low-anterior resection, a multicenter study of interobserver variation. *Surg Endosc* 37(5):3602–3609
- Hardy NP, Joosten JJ, Dalli J, Hompes R, Cahill RA, van Berge Henegouwen MI (2022) Evaluation of inter-user variability in indocyanine green fluorescence angiography to assess gastric conduit perfusion in esophageal cancer surgery. *Dis Esophagus*. <https://doi.org/10.1093/dote/doac016>
- PROSPERO. Guidance notes for registering a systematic review protocol with PROSPERO2016. Available from: <https://www.crd.york.ac.uk/prosperto/documents/Registering%20a%20review%20on%20PROSPERO.pdf>
- Rethlefsen ML, Kirtley S, Waffenschmidt S, Ayala AP, Moher D, Page MJ, Koffel JB (2021) PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews. *Syst Rev* 10(1):39
- Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A (2016) Rayyan—a web and mobile app for systematic reviews. *Syst Rev* 5(1):210
- Wells GA SB, O'Connell D, Peterson J, Welch V, Losos M, Tugwell P (2000) The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Available



- from: [https://www.ohri.ca/programs/clinical\\_epidemiology/oxford.asp](https://www.ohri.ca/programs/clinical_epidemiology/oxford.asp)
31. McGuinness LA, Higgins JPT (2021) Risk-of-bias VISualization (robvis): an R package and Shiny web app for visualizing risk-of-bias assessments. *Res Synth Methods* 12(1):55–61
  32. Park SH, Park HM, Baek KR, Ahn HM, Lee IY, Son GM (2020) Artificial intelligence based real-time microcirculation analysis system for laparoscopic colorectal surgery. *World J Gastroenterol* 26(44):6945–6962
  33. Son GM, Kwon MS, Kim Y, Kim J, Kim SH, Lee JW (2019) Quantitative analysis of colon perfusion pattern using indocyanine green (ICG) angiography in laparoscopic colorectal surgery. *Surg Endosc* 33(5):1640–1649
  34. Son GM, Nazir AM, Yun MS, Lee IY, Im SB, Kwak JY et al (2023) The safe values of quantitative perfusion parameters of ICG angiography based on tissue oxygenation of hyperspectral imaging for laparoscopic colorectal surgery: a prospective observational study. *Biomedicines* 11(7):2029
  35. Protyniak B, Dinallo AM, Boyan WP Jr, Dressner RM, Arvanitis ML (2015) Intraoperative indocyanine green fluorescence angiography—an objective evaluation of anastomotic perfusion in colorectal surgery. *Am Surg* 81(6):580–584
  36. Wada T, Kawada K, Takahashi R, Yoshitomi M, Hida K, Hasegawa S, Sakai Y (2017) ICG fluorescence imaging for quantitative evaluation of colonic perfusion in laparoscopic colorectal surgery. *Surg Endosc* 31(10):4184–4193
  37. Hayami S, Matsuda K, Iwamoto H, Ueno M, Kawai M, Hirono S et al (2019) Visualization and quantification of anastomotic perfusion in colorectal surgery using near-infrared fluorescence. *Tech Coloproctol* 23(10):973–980
  38. Bornstein JE, Munger JA, Deliz JR, Mui A, Chen CS, Kim S et al (2018) Assessment of Bowel end perfusion after mesenteric division: eye versus SPY. *J Surg Res* 232:179–185
  39. Faber RA, Tange FP, Galema HA, Zwaan TC, Holman FA, Peeters K et al (2023) Quantification of indocyanine green near-infrared fluorescence bowel perfusion assessment in colorectal surgery. *Surg Endosc* 37(9):6824–6833
  40. D’Urso A, Agnus V, Barberio M, Seeliger B, Marchegiani F, Charles AL et al (2021) Computer-assisted quantification and visualization of bowel perfusion using fluorescence-based enhanced reality in left-sided colonic resections. *Surg Endosc* 35(8):4321–4331
  41. Meijer RPJ, van Manen L, Hartgrink HH, Burggraaf J, Gioux S, Vahrmeijer AL, Mieog JSD (2021) Quantitative dynamic near-infrared fluorescence imaging using indocyanine green for analysis of bowel perfusion after mesenteric resection. *J Biomed Opt*. <https://doi.org/10.1117/1.JBO.26.6.060501>
  42. Dalli J, Epperlein JP, Hardy NP, Khan MF, Mac Aonghusa P, Cahill RA (2024) Clinical and computational development of a patient-calibrated ICGFA bowel transection recommender. *Surg Endosc* 38(6):3212–3222
  43. Adams ED, Salem JF, Burch MA, Fleshner PR, Zaghiyan KN (2024) Blinded intraoperative quantitative indocyanine green metrics associate with intestinal margin acceptance in colorectal surgery. *Dis Colon Rectum* 67(4):549–557
  44. Arpaia P, Bracale U, Corcione F, De Benedetto E, Di Bernardo A, Di Capua V et al (2022) Assessment of blood perfusion quality in laparoscopic colorectal surgery by means of machine learning. *Sci Rep* 12(1):14682
  45. Gomez-Rosado JC, Valdes-Hernandez J, Cintas-Catena J, Cano-Matias A, Perez-Sanchez A, Del Rio-Lafuente FJ et al (2022) Feasibility of quantitative analysis of colonic perfusion using indocyanine green to prevent anastomotic leak in colorectal surgery. *Surg Endosc* 36(2):1688–1695
  46. Kim JC, Lee JL, Park SH (2017) Interpretative guidelines and possible indications for indocyanine green fluorescence imaging in robot-assisted sphincter-saving operations. *Dis Colon Rectum* 60(4):376–384
  47. Aiba T, Uehara K, Ogura A, Tanaka A, Yonekawa Y, Hattori N et al (2021) The significance of the time to arterial perfusion in intraoperative ICG angiography during colorectal surgery. *Surg Endosc* 35(12):7227–7235
  48. Han SR, Lee CS, Bae JH, Lee HJ, Yoon MR, Al-Sawat A et al (2022) Quantitative evaluation of colon perfusion after high versus low ligation in rectal surgery by indocyanine green: a pilot study. *Surg Endosc* 36(5):3511–3519
  49. Iwamoto H, Matsuda K, Hayami S, Tamura K, Mitani Y, Mizumoto Y et al (2020) Quantitative indocyanine green fluorescence imaging used to predict anastomotic leakage focused on rectal stump during laparoscopic anterior resection. *J Laparoendosc Adv Surg Tech A* 30(5):542–546
  50. Egi H, Ohnishi K, Akita S, Sugishita H, Ogi Y, Yoshida M et al (2022) The arrival time of indocyanine green in tissues can be a quantitative index because of its correlation with tissue oxygen saturation: a clinical pilot study. *Asian J Endosc Surg* 15(2):432–436
  51. Soares AS, Bano S, Clancy NT, Stoyanov D, Lovat LB, Chand M (2022) Multisensor perfusion assessment cohort study: preliminary evidence toward a standardized assessment of indocyanine green fluorescence in colorectal surgery. *Surgery* 172(1):69–73
  52. Singaravelu A, Mc Entee PD, Hardy NP, Khan MF, Mulsow J, Shields C, Cahill RA (2024) Clinical evaluation of real-time artificial intelligence provision of expert representation in indocyanine green fluorescence angiography during colorectal resections. *Int J Surg* 110(12):8246–8249
  53. Flores-Rodríguez E, Garrido-López L, Sánchez-Santos R, Cano-Valderrama O, Rodríguez-Fernández L, Nogueira-Sixto M et al (2023) Is ICG essential in all colorectal surgery? A 3-year experience in a single center: a cohort study. *Int J Colorectal Dis* 38(1):67
  54. Cassinotti E, Al-Taher M, Antoniou SA, Arezzo A, Baldari L, Boni L et al (2023) European association for endoscopic surgery (EAES) consensus on indocyanine green (ICG) fluorescence-guided surgery. *Surg Endosc* 37(3):1629–1648
  55. Dalli J, Shanahan S, Hardy NP, Chand M, Hompes R, Jayne D et al (2022) Deconstructing mastery in colorectal fluorescence angiography interpretation. *Surg Endosc* 36(12):8764–8773
  56. Nijssen DJ, Joosten JJ, Osterkamp J, van den Elzen RM, de Bruin DM, Svendsen MBS et al (2024) Quantification of fluorescence angiography for visceral perfusion assessment: measuring agreement between two software algorithms. *Surg Endosc* 38(5):2805–2816
  57. Dalli J, Jindal A, Gallagher G, Epperlein JP, Hardy NP, Malallah R et al (2023) Evaluating clinical near-infrared surgical camera systems with a view to optimizing operator and computational signal analysis. *J Biomed Opt* 28(3):035002
  58. Dalli J, Joosten JJ, Jindal A, Hardy NP, Camilleri-Brennan J, Andrejevic P et al (2023) Impact of standardising indocyanine green fluorescence angiography technique for visual and quantitative interpretation on interuser variability in colorectal surgery. *Surg Endosc*. <https://doi.org/10.1007/s00464-023-10564-2>
  59. Wexner S, Abu-Gazala M, Boni L, Buxey K, Cahill R, Carus T et al (2022) Use of fluorescence imaging and indocyanine green during colorectal surgery: results of an intercontinental Delphi survey. *Surgery* 172(6):S38–S45
  60. Jansen-Winkel B, Germann I, Köhler H, Mehdorn M, Maktabi M, Sucher R et al (2021) Comparison of hyperspectral imaging and fluorescence angiography for the determination of the transection margin in colorectal resections—a comparative study. *Int J Colorectal Dis* 36(2):283–291

61. Varghese C, Harrison EM, O'Grady G, Topol EJ (2024) Artificial intelligence in surgery. *Nat Med* 30(5):1257–1268
62. Joshi G, Jain A, Araveeti SR, Adhikari S, Garg H, Bhandari M (2024) FDA-approved artificial intelligence and machine learning (AI/ML)-enabled medical devices: an updated landscape. *Electronics* 13(3):498
63. Cahill RA (2024) Cognitive vision: AI automation of the surgical eye in fluorescence angiography—correspondence. *Int J Surg* 110(8):5218–5219
64. Repici A, Badalamenti M, Maselli R, Correale L, Radaelli F, Rondonotti E et al (2020) Efficacy of real-time computer-aided detection of colorectal neoplasia in a randomized trial. *Gastroenterology* 159(2):512–20.e7
65. Hassan C, Balsamo G, Lorenzetti R, Zullo A, Antonelli G (2022) Artificial intelligence allows leaving-in-situ colorectal polyps. *Clin Gastroenterol Hepatol* 20(11):2505–13.e4
66. De Nardi P, Elmore U, Maggi G, Maggiore R, Boni L, Cassinotti E et al (2020) Intraoperative angiography with indocyanine green to assess anastomosis perfusion in patients undergoing laparoscopic colorectal resection: results of a multicenter randomized controlled trial. *Surg Endosc* 34(1):53–60
67. Armstrong G, Croft J, Corrigan N, Brown JM, Goh V, Quirke P et al (2018) IntAct: intra-operative fluorescence angiography to prevent anastomotic leak in rectal cancer surgery: a randomized controlled trial. *Colorectal Dis* 20(8):O226–O234
68. Kossi J. Indocyanine green fluorescence imaging in prevention of colorectal anastomotic leakage (ICG-COLORAL) NCT03602677 Available from: <https://clinicaltrials.gov/study/NCT03602677>
69. Sun L, Gao J, Wu G, Meng C, Yang Z, Wei P et al (2024) Perfusion outcomes with near-infrared indocyanine green imaging system in laparoscopic total mesorectal excision for mid-rectal or low-rectal cancer (POSTER): a study protocol. *BMJ Open* 14(5):e079858

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