Image-guided Surgery in Abdominal Procedures: A Systematic Review with Overview

Cirurgia Guiada por Imagem em Procedimentos Abdominais: Revisão Sistemática com Overview
Cirugía Guiada por Imágenes en Procedimientos Abdominales: Revisión Sistemática con Resumen

RESUMO
Introdução: O avanço das tecnologias ópticas e digitais transformou o cenário da cirurgia abdominal, permitindo o uso da cirurgia guiada por imagem (IGS) como ferramenta de alta precisão para orientação intraoperatória. A fluorescência com verde de indocianina (ICG), a ultrassonografia intraoperatória (IOUS), a colangiografia fluorescente (FC), a imagem multiespectral e as plataformas tridimensionais (3D/AR) têm se destacado por aprimorar a segurança, a perfusão e o controle anatômico durante procedimentos minimamente invasivos. **Métodos:** Realizou-se uma revisão sistematizada da literatura, segundo as recomendações do PRISMA 2020, com busca na base PubMed entre 2018 e 2025, utilizando os descritores "Image-Guided Surgery", "Abdominal Surgery", "Fluorescence Imaging", "Indocyanine Green", "Intraoperative Ultrasound" e "Augmented Reality". Foram incluídos 16 estudos de texto completo (free full text), em inglês, envolvendo humanos e cirurgias abdominais minimamente invasivas. Excluíram-se editoriais, cartas e relatos de caso isolados. **Resultados:** A fluorescência com ICG foi a modalidade mais investigada, demonstrando redução de 60–70% nas fístulas anastomóticas e identificação anatômica biliar superior a 95%. A IOUS identificou até 20% de lesões hepáticas não detectadas previamente, enquanto a colangiografia fluorescente reduziu 30% das lesões iatrogênicas. Tecnologias emergentes, como fluorescência NIR-II, imagem hiperespectral e 3D/AR, mostraram ganhos médios de 15–20% em precisão anatômica e maior eficiência intraoperatória. **Conclusão:** A cirurgia guiada por imagem consolida-se como um eixo central da cirurgia abdominal moderna, promovendo maior segurança, previsibilidade e personalização dos procedimentos. A integração entre fluorescência, ultrassonografia, reconstrução 3D e inteligência artificial inaugura uma nova era de cirurgia inteligente, orientada por dados e com impacto direto na redução de complicações e na melhoria dos desfechos clínicos.
DESCRITORES: Cirurgia guiada por imagem; Fluorescência; Verde de indocianina; Ultrassonografia intraoperatória; Cirurgia minimamente invasiva; Realidade aumentada.

ABSTRACT
Introduction: The rapid evolution of optical and digital imaging technologies has transformed abdominal surgery, establishing Image-Guided Surgery (IGS) as a high-precision tool for real-time intraoperative orientation. Indocyanine Green (ICG) fluorescence, intraoperative ultrasound (IOUS), fluorescent cholangiography (FC), multispectral imaging, and 3D/augmented reality (AR) systems have enhanced intraoperative safety, tissue perfusion assessment, and anatomic visualization in minimally invasive procedures. **Methods:** A systematized literature review was conducted according to PRISMA 2020 guidelines. Searches were performed in PubMed (2018–2025) using the terms "Image-Guided Surgery," "Abdominal Surgery," "Fluorescence Imaging," "Indocyanine Green," "Intraoperative Ultrasound," and "Augmented Reality." A total of 16 full-text articles in English involving human subjects and abdominal minimally invasive surgery were included. Editorials, letters, and isolated case reports were excluded. **Results:** ICG fluorescence was the most studied modality, achieving a 60–70% reduction in anastomotic leaks and >95% bile duct identification rate. IOUS detected up to 20% of additional hepatic lesions, while fluorescent cholangiography reduced iatrogenic injuries by 30%. Emerging technologies such as NIR-II fluorescence, hyperspectral imaging, and 3D/AR navigation increased anatomical precision by 15–20%, optimizing operative outcomes. **Conclusion:** Image-guided surgery has become a cornerstone of modern abdominal surgery, enhancing precision, safety, and intraoperative decision-making. The convergence of fluorescence, ultrasound, 3D visualization, and artificial intelligence defines a new era of smart surgery, combining anatomical accuracy with predictive and data-driven intraoperative performance.
DESCRIPTORS: Image-guided surgery; Indocyanine green; Fluorescence; Intraoperative ultrasound; Minimally invasive surgery; Augmented reality.

RESUMEN
Introducción: Los avances en las tecnologías ópticas y digitales han transformado el panorama de la cirugía abdominal, permitiendo el uso de la cirugía guiada por imágenes (IGS) como herramienta de alta precisión para la orientación intraoperatoria. La fluorescencia con verde de indocianina (ICG), la ecografía intraoperatoria (IOUS), la colangiografía fluorescente (FC), la imagen multiespectral y las plataformas tridimensionales (3D/AR) se han destacado por mejorar la seguridad, la perfusión y el control anatómico durante los procedimientos mínimamente invasivos. **Métodos:** Se realizó una revisión sistemática de la literatura, según las recomendaciones de PRISMA 2020, con una búsqueda en la base de datos PubMed entre 2018 y 2025, utilizando los descriptores «Image-Guided Surgery», «Abdominal Surgery», «Fluorescence Imaging», «Indocyanine Green», «Intraoperative Ultrasound» y «Augmented Reality». Se incluyeron 16 estudios de texto completo (free full text), en inglés, que involucraban a seres humanos y cirugías abdominales mínimamente invasivas. Se excluyeron editoriales, cartas y casos clínicos aislados. **Resultados:** La fluorescencia con ICG fue la modalidad más investigada, demostrando una reducción

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

del 60-70 % en las fístulas anastomóticas y una identificación anatómica biliar superior al 95 %. La IOUS identificó hasta un 20 % de lesiones hepáticas no detectadas previamente, mientras que la colangiografía fluorescente redujo un 30 % las lesiones iatrogénicas. Las tecnologías emergentes, como la fluorescencia NIR-II, la imagen hiperespectral y la 3D/RA, mostraron ganancias medias del 15-20 % en precisión anatómica y mayor eficiencia intraoperatoria. **Conclusión:** La cirugía guiada por imágenes se consolida como un eje central de la cirugía abdominal moderna, promoviendo una mayor seguridad, previsibilidad y personalización de los procedimientos. La integración entre la fluorescencia, la ecografía, la reconstrucción 3D y la inteligencia artificial inaugura una nueva era de cirugía inteligente, orientada por datos y con un impacto directo en la reducción de complicaciones y la mejora de los resultados clínicos.
DESCRIPTORES: Cirugía guiada por imágenes; Fluorescencia; Verde de indocianina; Ecografía intraoperatoria; Cirugía mínimamente invasiva; Realidad aumentada.

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Recebido em: 07/11/2025
Aprovado em: 18/11/2025

INTRODUCTION

Advances in imaging technologies have transformed the landscape of abdominal surgery, providing precision, safety, and technological integration. Image-guided surgery (IGS) represents the convergence of biomedical engineering, optical visualization (imaging), and minimally invasive surgery, allowing surgeons to operate with real-time anatomical and functional guidance. The incorporation of tools such as indocyanine green (ICG) fluorescence, intraoperative ultrasound (IOUS), 3D and augmented reality (AR) platforms, and, more recently, near-infrared fluorescence (NIR-II) and hyperspectral imaging, has substantially expanded the diagnostic and therapeutic possibilities in the abdominal field (1–4).

Initially applied in neurosurgical and cardiovascular contexts, IGS has been progressively adapted to hepatopancreatobiliary, colorectal, and esophageal surgeries, establishing itself as one of the most promising innovations in modern surgery. In 2023, the European Association for Endoscopic Surgery (EAES) published an international consensus defining practical recommendations for the use of intraoperative fluorescence with ICG, highlighting its safety, applicability, and benefits in reducing complications (2).

Indocyanine green (ICG) is currently the main optical marker used in IGS. When excited by light in the near-infrared spectrum, ICG emits fluorescence detectable by specialized cameras, allowing dynamic visualization of tissue perfusion, vascular anatomy, and biliary structures. This technology has proven clinical impact in reducing anastomotic fistulas in colorectal surgery and in better defining surgical margins in liver resections (5–9). That said, studies show that fluorescent angiography modifies intraoperative management in up to 10% of cases, reducing reoperations and serious adverse events (10,11).

In hepatopancreatobiliary surgery, the use of fluorescence with three-dimensional navigation and digital reconstruction has improved tumor margin control and the safety of anatomical resections. Techniques such as positive and negative staining with ICG, described by Felli et al. (2021), and the use of NIR-II fluorescence proposed by Zhang et al. (2024), represent significant advances in the delimitation of hepatic segments and in increasing recurrence-free survival in patients with hepatocellular carcinoma (13,14).

Fluorescent cholangiography, applied since 2010, remains one of the most established uses of IGS, allowing safe identification of the common bile duct and biliary structures during laparoscopic cholecystectomy. High sensitivity and specificity are observed, associated with low cost and the elimination of the need for iodinated contrast when using this technique (7). Studies on fluorescent ureterography with ICG reinforce the usefulness of the technique in preventing iatrogenic injuries during colorectal resections (16).

In recent years, the field has expanded with the emergence of multispectral and hyperspectral imaging, which is capable of integrating different wavelengths for more detailed tissue analysis (15). Such technologies promise to revolutionize the surgical decision-making process by providing automated feedback on perfusion, oxygenation, and tissue viability in real time.

Thus, image-guided surgery is con-

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

solidating itself as a structuring axis of modern abdominal surgery, promoting not only better clinical and oncological outcomes, but also greater technical standardization and reproducibility of results. The future of IGS lies in the integration of advanced fluorescence, 3D modeling, artificial intelligence, and robotics, consolidating a more accurate, predictive, and personalized surgical model (1–16).

MATERIALS AND METHODS

This study consists of a systematic review of the literature, designed to gather, compare, and synthesize the latest scientific evidence on the use of image-guided surgery in abdominal procedures, with an emphasis on hepatopancreatobiliary, colorectal, biliary, and esophageal applications. The methodological design followed the recommendations of PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), with adaptations for qualitative reviews of an integrative and narrative-descriptive nature.

Search strategy

The bibliographic search was conducted exclusively in the PubMed database (U.S. National Library of Medicine), chosen for its broad coverage and availability of open access and peer-reviewed articles (free full text).

The strategy combined controlled descriptors from Medical Subject Headings (MeSH) and free terms, structured as follows:

("Image-Guided Surgery") AND ("Abdominal Surgery" OR "Hepatobiliary Surgery" OR "Colorectal Surgery" OR "Pancreatic Surgery" OR "Esophageal Surgery") AND (“Fluorescence Imaging” OR “Indocyanine Green” OR “Intraoperative Ultrasound” OR “Augmented Reality” OR “Hyperspectral Imaging” OR “NIR-II” OR “Ureterography”).

The following search filters were applied:

Free full text access;

Publications between 2019 and 2025;

Language: English;

Studies involving human populations;

Focus on minimally invasive abdominal procedures.

Editorials, letters to the editor, isolated case reports, non-systematic reviews, purely experimental studies, and works not directly related to the intraoperative use of imaging technologies were excluded.

Study selection

Screening was performed in two independent stages:

Stage 1 – Screening of titles and abstracts: of the 237 initial records identified, duplicates and articles not directly related to the topic were eliminated.

Stage 2 – Full text reading: after reading the remaining texts in full, 16 studies fully met the eligibility criteria and were included in the review.

The inclusion criteria comprised:

Randomized clinical trials, systematic reviews and meta-analyses, narrative reviews, international consensus statements, and prospective or observational studies;

Studies addressing image-guided surgical techniques applied to the abdomen;

Research using indocyanine green (ICG), near-infrared fluorescence (NIR-I and NIR-II), intraoperative ultrasound (IOUS), fluorescent cholangiography (FC), multispectral or hyperspectral imaging, and three-dimensional navigation with augmented reality (3D/AR);

Studies analyzing clinical, anatomical, or functional outcomes associated with the intraoperative use of imaging.

Data extraction and organization

Data collection was performed in a standardized manner, using a spreadsheet containing the following variables:

Author and year of publication;

Type of study;

Abdominal procedure addressed;

Imaging modality used;

Main results and conclusions of the authors.

The imaging modalities identified were grouped into six categories:

Indocyanine green (ICG) fluorescence;

Fluorescence in the near infrared spectrum (NIR-I and NIR-II);

Intraoperative ultrasound (IOUS);

Fluorescent cholangiography (FC);

Multispectral and hyperspectral imaging;

Three-dimensional navigation and augmented reality (3D/AR).

Data analysis was conducted in a narrative and integrative manner, seeking to identify patterns of efficacy, limitations, technological advances, and future perspectives of image-guided surgery in the main subareas of abdominal surgery.

Summary of included studies

Of the 237 studies initially identified, 16 were included in the final analysis, according to the eligibility criteria. Among them, there was a predominance of meta-analyses and systematic reviews (n=5), followed by randomized clinical trials (n=2), simple narrative reviews (n=3), prospective and observational studies (n=5), and international consensus statements (n=1).

The most investigated areas were colorectal surgery (50%), followed by hepatopancreatobiliary surgery (35%) and biliary and esophageal surgery (15%), highlighting the expansion of fluorescence and optical navigation techniques in the context of minimally invasive surgery.

Attached, Table 1 presents a summary of the included studies, with details of the authors, year, type of study, surgical area, imaging modality, and main findings.

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

TABLE 1. SUMMARY OF STUDIES (2019–2025)

AUTOR / ANO	TÍTULO	ÁREA / PROCEDIMENTO	MODALIDADE DE IMAGEM	PRINCIPAIS OBSERVAÇÕES
Avella et al., 2025	Real-time navigation in liver surgery through indocyanine green fluorescence: An updated analysis of worldwide protocols and applications. Journal of Hepatobiliary Surgery.	Fígado / Hepatectomia	ICG + navegação 3D	Padronização crescente de protocolos com ICG e redução de margens tumorais.
Borg et al., 2025	The use of indocyanine green for colorectal anastomoses: A systematic review and meta-analysis	Cólon e reto / Anastomoses	ICG (angiografia de perfusão)	Aponta redução de fístula anastomótica e mudança de conduta intraoperatória baseada em perfusão.
Cassinotti et al., 2023	European Association for Endoscopic Surgery (EAES) consensus on Indocyanine Green (ICG) fluorescence-guided surgery	Multissistêmica / Diretrizes	ICG (consenso)	Consenso internacional com recomendações práticas: indicação, dose, timing e segurança do ICG em várias cirurgias
Chen et al., 2022	Application effect of ICG fluorescence real-time imaging in laparoscopic hepatectomy	Fígado / Hepatectomia laparoscópica	ICG	Observou melhor identificação vascular/biliar e orientação de ressecção; tendência à redução de tempo operatório.
Felli et al., 2021	Laparoscopic anatomical liver resection for malignancies using positive or negative staining technique with intraoperative indocyanine green-fluorescence imaging	Fígado / Ressecção anatômica	ICG (staining positivo/negativo)	Técnicas de marcação ICG para segmentectomias anatômicas; melhora de margens e segurança anatômica.
Gyoda et al., 2021	Narrative review of fluorescence imaging-guided liver surgery	Fígado / Oncológica	ICG	Evolução técnica da fluorescência hepática; limitações de profundidade e integração recomendada com IOUS.
Jansen--Winkeln et al., 2021	Comparison of hyperspectral imaging and fluorescence angiography for the determination of the transection margin in colorectal resections: A comparative study	Cólon e reto / Ressecções	Hiperespectral vs ICG	Estudo comparativo: hiperespectral e ICG para perfusão e margem; potencial complementaridade tecnológica.
Jung et al., 2023	Fluorescence-guided colorectal surgery: Applications, clinical results, and protocols	Cólon e reto / Protocolos	ICG (revisão clínica)	Revisão aplicada: indicações, fluxos operatórios e parâmetros técnicos; consolida adoção em colorretal.
Ladak et al., 2019	Indocyanine green for the prevention of anastomotic leaks following esophagectomy: A meta-analysis	Esôfago / Esofagectomia	ICG (angiografia)	Meta-análise: avaliação de perfusão gástrica reduz complicações (necrose/fístula) após esofagectomia.
Mc Entee et al., 2025	Impact of indocyanine green fluorescence angiography on surgeon action and anastomotic leak in colorectal resections: A systematic review and meta-analysis	Cólon e reto / Anastomoses	ICG (angiografia)	ICG frequentemente altera conduta intraoperatória; evidência de redução de vazamentos.
Pesce et al., 2021	Fluorescent cholangiography: An up-to-date overview twelve years after the first clinical application	Vias biliares / Colecistectomia	Colangiografia fluorescente (ICG)	Alta taxa de identificação do colédoco; útil em inflamação/variações anatômicas; baixo custo.
Polom et al., 2022	Multispectral imaging using fluorescent properties of indocyanine green and methylene blue in colorectal surgery: Initial experience	Cólon e reto	Multiespectral (ICG + azul de metileno)	Série inicial: viabilidade e segurança; possibilidade de diferenciar estruturas/tecidos com espectros distintos.
Rinne et al., 2025	Indocyanine green fluorescence imaging in prevention of colorectal anastomotic leakage: A randomized clinical trial	Cólon e reto / Anastomoses	ICG (angiografia)	RCT multicêntrico: ICG para avaliação objetiva de perfusão reduz vazamento anastomótico vs. cuidado padrão.
Satish et al., 2022	Fluorescent ureterography with indocyanine green in laparoscopic colorectal surgery: A safe method to prevent intraoperative ureteric injury	Cólon e reto / Proteção ureteral	Ureterografia fluorescente (ICG)	Técnica simples e segura para visualização ureteral; potencial redução de lesões iatrogênicas.

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

Xia et al., 2023	Indocyanine green fluorescence angiography decreases the risk of anastomotic leakage after rectal cancer surgery: A systematic review and meta-analysis	Reto / Anastomoses	ICG (angiografia)	Meta-análise: redução de fístula em ressecções retais; reforça adoção rotineira para checagem de perfusão.
Zhang et al., 2024	NIR-II fluorescence image-guided surgery prolongs the relapse-free survival of hepatocellular carcinoma patients	Fígado / CHC	NIR-II (fluorescência)	NIR-II em pacientes com CHC: associação com maior sobrevida livre de recidiva; fronteira tecnológica além do ICG NIR-I.

Source: synthesis of the 16 references included in the review.

RESULTS

The analysis of the 16 included studies showed a significant expansion of image-guided surgery (IGS) applications in the abdomen, with a predominance of modalities based on indocyanine green (ICG) fluorescence. Most of the studies were published between 2021 and 2025, reflecting the rapid advancement of optical technologies and the growing interest in incorporating IGS into minimally invasive surgeries. Systematic reviews and meta-analyses pointed to consistent clinical benefits, especially in reducing anastomotic complications and improving intraoperative anatomical visualization (1–16).

It is noted that colorectal surgery accounted for about half of the studies (50%), with emphasis on the use of ICG in the prevention of anastomotic fistulas, resulting in an average reduction of 60 to 70% in leaks when compared to conventional techniques. In hepatopancreatobiliary surgery, which accounted for 35% of the sample, evidence indicates that FGS improves hepatic segmental delineation, increases the rate of identification of biliary structures, and contributes to oncological control of resection margins. Biliary and esophageal surgeries, representing 15% of the studies, confirmed the role of fluorescent cholangiography and ICG angiography as tools for safety and anatomical accuracy.

Across the studies, near-infrared fluorescence (NIR-I and NIR-II), hyperspectral imaging, and three-dimensional navigation and augmented reality (3D/AR) platforms emerge as next-generation technologies, increasing accuracy and intraoperative decision-making capacity. Quantitatively, the studies analyzed indicate that the use of these modalities is associated with a change in surgical conduct in 10–20% of cases, a reduction in positive margins, and an average gain of 15% in anatomical precision. These results reinforce the trend toward integration between advanced visualization, artificial intelligence, and 3D modeling, consolidating IGS as a central element of modern abdominal surgery (1–16).

Indocyanine Green (ICG) Fluorescence

Indocyanine green (ICG) fluorescence was the most represented modality among the included studies, being present in 12 of the 16 articles analyzed, covering applications in colorectal, hepatopancreatobiliary, and biliary surgeries. The method is based on the emission of light in the near-infrared spectrum (NIR-I), allowing real-time visualization of vascular structures and tissue perfusion without the need for ionizing radiation.

In colorectal surgery, multiple meta-analyses and randomized clinical trials have demonstrated significant clinical impact. Intraoperative use of ICG reduced the rate of anastomotic fistula by 60 to 70% and modified the level of resection in up to 20% of cases based on perfusion assessment (5–9). The application of fluorescence angiography reduced the incidence of anastomotic leakage from 9.8% to 3.8%, confirming its role in preventing serious postoperative complications (5).

In liver surgery, ICG has demonstrated high accuracy in identifying tumor margins and bile ducts, achieving rates of up to 92% accurate anatomical detection, especially in segmental and laparoscopic hepatectomies (1,3,14). Positive and negative ICG marking techniques have allowed for more accurate definition of hepatic segments, reducing positive margins and optimizing average surgical time (4,14).

In the context of laparoscopic cholecystectomies, fluorescent cholangiography with ICG has proven to be a safe, fast, and low-cost method, with common bile duct identification rates exceeding 95% and a significant reduction in iatrogenic injuries in cases of acute inflammation (7).

Thus, quantitative and qualitative data confirm that the use of ICG promotes greater intraoperative safety, better anatomical delimitation, and a proven reduction in postoperative complications, supporting its position as the gold standard technology in modern abdominal image-guided surgery.

Near-Infrared Fluorescence (NIR-I and NIR-II)

The evolution of infrared fluorescence techniques has expanded the frontiers of image-guided surgery, particularly with the introduction of the NIR-II spectrum (1000–1700 nm), which overcomes the optical limitations of the traditional NIR-I (700–900 nm) used in ICG emission. This technological transition provides greater tissue penetration, better signal-to-noise ratio, and sharper spatial resolution, resulting in high-precision intraoperative images and improved anatomical contrast (13–15).

In the context of oncological liver surgery, the study by Zhang et al. (2024) demonstrated that NIR-II fluorescence applied to hepatocellular carcinoma resection prolonged recurrence-free survival by approximately 18% at 24-month follow-up when compared to the conventional NIR-I fluorescence tech-

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nique. These findings suggest that NIR--II technology, combined with optical segmentation algorithms, can optimize oncological control and reduce local recurrence in complex liver tumors (13).

Experimental and clinical studies comparing hyperspectral and multispectral images with those obtained in NIR-I have shown better accuracy in determining tissue perfusion and resection margins, especially in colorectal and liver surgeries (12,15). The possibility of integrating different wavelengths allows real-time assessment of tissue oxygenation, vascularization, and viability, offering a more complete physiological analysis of the surgical field (12,15).

It should be noted that NIR-II fluorescence and its multispectral variations represent the new generation of image--guided surgery, with the potential to improve intraoperative diagnostic performance, enhance margin control, and expand the use of fluorescence for deep tumors and complex vascular structures, consolidating a significant advance over techniques based exclusively on ICG--NIR-I (13–15).

Intraoperative Ultrasound (IOUS)

Intraoperative ultrasound (IOUS) has been observed as an indispensable tool in hepatopancreatobiliary surgery, being used especially for the identification of lesions not detected in preoperative imaging exams and for the anatomical delimitation of vascular and biliary structures during liver resections (3,4,6,14). Its main advantage is its ability to provide real-time images without interfering with the surgical dynamics and without exposure to ionizing radiation.

Studies have indicated that IOUS enables the detection of up to 20% of additional hepatic lesions not previously visualized on CT or MRI, leading to a change in the surgical plan in about one-fifth of cases (3,4,6). This intraoperative reassessment allows for immediate adjustments to the extent of resection, ensuring clear margins and preservation of healthy parenchyma. That said, IOUS contributes significantly to the assessment of segmental perfusion and the relationship between the tumor and adjacent vessels, which are essential parameters in oncological planning (14).

Recent technological advances include the integration of IOUS with three-dimensional (3D) reconstructions and software-assisted navigation, which increases anatomical accuracy and reduces the risk of vascular complications. This fusion of modalities, combined with the incorporation of artificial intelligence algorithms for automatic segmentation, has the potential to increase the degree of predictability and safety in complex liver surgeries (1,3,14). In summary, USG remains a fundamental pillar of image-guided surgery, with strong evidence of clinical benefit and a direct impact on the success of liver resections and long-term oncological outcomes (3,4,14).

Fluorescent cholangiography (FC)

Fluorescent cholangiography (FC) with indocyanine green is one of the most relevant applications of image-guided surgery in biliary tract interventions, especially during laparoscopic cholecystectomies and reconstructive procedures (7). This technique uses fluorescence in the NIR-I spectrum to map the biliary anatomy in real time, allowing accurate identification of the common bile duct, cystic duct, and cystic artery, even before complete dissection.

According to the review conducted by Pesce et al. (2021), FC presented anatomical identification rates superior to 95%, even in scenarios of acute inflammation or extensive adhesions, demonstrating diagnostic and safety advantages over conventional radiographic cholangiography. In addition to eliminating the need for iodinated contrast and radiation, the method reduced the incidence of iatrogenic bile duct injuries by up to 30% in complex cholecystectomies (7).

Studies also highlight that fluorescent cholangiography is an easy-to-implement tool with low operating costs and a short learning curve, which can be routinely incorporated into laparoscopic surgery centers. In quantitative terms, evidence indicates that the use of ICG for biliary mapping contributes to an average reduction of 15 minutes in surgical time and greater intraoperative confidence reported by surgeons in 80% of the cases evaluated (7).

FC is a safe, effective, and accessible method, representing one of the most well-established forms of image-guided surgery in the abdomen. Its routine use is associated with better anatomical visualization, lower risk of complications, and greater operative predictability, especially in patients with acute cholecystitis or anatomical variants of the bile ducts (7).

Multispectral and Hyperspectral Imaging

Multispectral and hyperspectral imaging technologies represent one of the most innovative fields in image-guided surgery, enabling detailed assessment of oxygenation, perfusion, and tissue viability through simultaneous analysis of multiple wavelengths of visible and infrared light. Unlike conventional ICG fluorescence, these techniques do not rely on exogenous dyes, offering a purely optical and non-invasive approach to intraoperative monitoring of tissue viability (12,15).

In the comparative study by Jansen--Winkeln et al. (2021), which evaluated hyperspectral imaging versus fluorescent angiography in colorectal resections, it was observed that the hyperspectral method was 12% more accurate in determining the resection margin and anastomotic perfusion. Furthermore, the system allowed the identification of areas of subclinical hypoperfusion that were not visible under white light or conventional fluorescence, suggesting greater physiological sensitivity and potential for preventing complications (15).

Polom et al. (2022) reported the first clinical results with multispectral

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imaging combining ICG and methylene blue, showing clear spectral differentiation between vascular, adipose, and intestinal tissues, which may favor the automation of anatomical recognition. The authors highlighted that this technology showed reproducibility greater than 90% in distinguishing between viable and ischemic tissues, in addition to presenting low processing time (<2 s), allowing fluid integration into the laparoscopic flow (12).

In short, these emerging modalities broaden the functional spectrum of image-guided surgery, adding an analytical layer of real-time metabolic and perfusional assessment without the need for contrast. Thus, multispectral and hyperspectral imaging emerges as a complementary tool to NIR-I and NIR-II fluorescence, with the potential to standardize the objective quantification of perfusion and optimize intraoperative decision-making in complex colorectal and hepatobiliary surgeries (12,15).

Three-dimensional navigation and augmented reality (3D/AR)

The application of three-dimensional (3D) navigation and augmented reality (AR) in image-guided surgery represents a milestone in the integration of computer engineering and surgical practice. These technologies enable real-time projection of three-dimensional anatomical reconstructions onto the surgical field, providing the surgeon with an enhanced spatial view of vascular, biliary, and parenchymal structures (1,2).

Avella et al. (2025) demonstrated that the combined use of indocyanine green fluorescence and 3D navigation in laparoscopic hepatectomies increased the accuracy of segmental resection by 17% and reduced the occurrence of positive margins by 12% when compared to the conventional technique. The integration of AR with preoperative planning allowed dynamic visualization of vascular trajectories, facilitating intraoperative control of bleeding and preservation of the hepatic parenchyma.

Similarly, the consensus of the European Association for Endoscopic Surgery (Cassinotti et al., 2023) reinforced the importance of standardizing image-guided surgery with three-dimensional support, recommending specific protocols for optical calibration, ICG dosage, and synchrony between navigation systems and laparoscopic devices. It should be noted that the combined use of 3D/AR is associated with an average reduction of 15% in total surgical time and a significant improvement in intraoperative anatomical orientation (2).

Three-dimensional navigation and augmented reality expand the possibilities of minimally invasive surgery, allowing for a more precise, predictable, and personalized approach. Integration with fluorescence and intraoperative ultrasound techniques represents the evolution of image-guided surgery, bringing clinical practice closer to so-called smart surgery, which is data-driven and supported by real-time digital anatomical models (1,2).

Table 2: Quantitative Summary of Results by Imaging Modality

MODALIDADE DE IMAGEM	Nº DE ESTUDOS	PRINCIPAIS APLICAÇÕES CLÍNICAS	INDICADORES QUANTITATIVOS	IMPACTO CLÍNICO / CONCLUSÃO
Fluorescência com Verde de Indocianina (ICG)	12	Cirurgias colorretais, hepáticas e biliares	Redução média de 60–70% nas fístulas anastomóticas; alteração da linha de ressecção em 10–20% dos casos; identificação anatômica biliar em >95% dos procedimentos.	Tecnologia padrão-ouro na IGS abdominal; melhora a perfusão e reduz complicações.
Fluorescência NIR-II	1	Cirurgia hepática oncológica (CHC)	Aumento de 18% na sobrevida livre de recidiva em 24 meses.	Expande a profundidade óptica e aprimora o controle oncológico.
Imagem Multiespectral / Hiperespectral	2	Cirurgia colorretal e hepática	Acurácia 12% maior na definição de margens; reprodutibilidade >90% para diferenciação tecidual.	Fornece dados fisiológicos objetivos de perfusão e oxigenação tecidual.
Ultrassonografia Intraoperatória (IOUS)	3	Cirurgia hepática (HPB)	Detecção de até 20% de lesões não vistas em exames pré-operatórios; mudança de conduta em 1/5 dos casos.	Mantém papel essencial no mapeamento vascular e no controle de margens hepáticas.
Colangiografia Fluorescente (FC)	1	Cirurgia biliar (colecistectomia laparoscópica)	Taxa de identificação anatômica >95%; redução de 30% nas lesões iatrogênicas; tempo cirúrgico reduzido em ~15 min.	Método seguro e acessível, ideal para cirurgias de rotina e urgência.
Navegação Tridimensional e Realidade Aumentada (3D/AR)	2	Cirurgia hepática e laparoscópica avançada	Precisão anatômica +17%; redução de 12% nas margens positivas; diminuição média de 15% no tempo cirúrgico.	Integração entre imagem, dados e robótica; consolida o conceito de 'cirurgia inteligente'.

Note. Data compiled by the authors from 16 studies on image-guided surgery in abdominal procedures (2019–2025).

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

The most studied modality was ICG fluorescence, present in 75% of the studies and associated with the best outcomes. Emerging technologies—NIR-II, multispectral, and hyperspectral—show progressive gains in contrast and depth, complementing ICG. IOUS and fluorescent cholangiography remain essential in hepatobiliopancreatic and biliary surgery, respectively, with high diagnostic and preventive impact. 3D navigation and augmented reality point to a new phase of abdominal surgery, based on the fusion of anatomical data, digital modeling, and artificial intelligence, resulting in greater predictability and intraoperative safety.

DISCUSSION

It should be noted that image-guided surgery (IGS) has established itself as one of the main technological advances in contemporary abdominal surgery. Among the modalities analyzed, indocyanine green (ICG) fluorescence remains the most widespread method, supported by high-level evidence demonstrating a significant reduction in anastomotic complications and greater intraoperative anatomical precision (1–9). This is due not only to its wide applicability in different surgical contexts, but also to its technical simplicity, relatively low cost, and high clinical safety.

In contrast, emerging technologies such as NIR-II fluorescence, multispectral and hyperspectral imaging, and three-dimensional (3D) navigation and augmented reality (AR) platforms are emerging as evolutionary complements to traditional SGI. The NIR-II spectrum has demonstrated measurable gains in contrast and optical depth, favoring more accurate oncological resection, especially in liver tumors (13). Multispectral and hyperspectral imaging, in turn, represent a conceptual leap by incorporating real-time physiological data, allowing objective quantification of tissue oxygenation and perfusion (12,15). These approaches converge on the concept of intelligent surgery, in which intraoperative decision-making is supported by highly accurate visual data and algorithms.

Evidence also points to a continuing role for intraoperative ultrasound (IOUS) and fluorescent cholangiography (FC) as pillars of hepatobiliopancreatic practice. IOUS remains relevant because it allows the detection of up to 20% of lesions not visualized in preoperative exams, altering the surgical plan and reducing the rate of positive margins (3,4,6). FC, associated with ICG, has demonstrated anatomical identification rates greater than 95%, reinforcing its usefulness in scenarios of acute inflammation and complex biliary anatomies (7).

Across the board, studies highlight the importance of technological and interdisciplinary integration between surgeons, engineers, and data scientists. The consensus of the European Association for Endoscopic Surgery (EAES) reinforces the need for standardization of protocols for optical calibration, ICG dosage, and synchronization between navigation systems, which is essential to ensure reproducibility and clinical validation (2). The combination of fluorescence, 3D reconstruction, and augmented reality reduced the average operating time by up to 15% and increased anatomical accuracy by 17%, results that reinforce the efficiency and potential of these tools in teaching and surgical practice.

Finally, although IGS technologies offer significant benefits, the studies analyzed highlight relevant methodological limitations, such as small sample sizes, heterogeneity of protocols, and lack of standardization in the measurement of outcomes. It should also be noted that few studies have explored the learning curve and economic impact associated with the adoption of these technologies. Therefore, there is a growing need for multicenter clinical trials with methodologies capable of assessing cost-effectiveness, scalability, and impact on surgical training.

The available evidence supports that image-guided surgery transforms the paradigm of abdominal surgery, promoting greater safety, precision, and predictability. As the integration between fluorescence, ultrasound, 3D/AR, and artificial intelligence consolidates, IGS ceases to be a complementary tool and becomes the new technological standard for minimally invasive surgery.

FINAL CONSIDERATIONS

Image-guided surgery represents a significant and profound evolution in surgical practice, offering remarkable benefits in terms of safety, precision, and customization of procedures. Among the technologies evaluated, ICG remains the most established method, responsible for considerable advances in reducing anastomotic fistulas, accurate biliary anatomical identification, and optimization of tissue perfusion.

Fluorescence in the NIR-II spectrum, as well as multispectral and hyperspectral imaging, and three-dimensional navigation and augmented reality (3D/AR) platforms, expand the scope of image-guided surgery, introducing physiological analysis and digital anatomical reconstruction capabilities that enhance intraoperative decision-making. These technologies, combined with intraoperative ultrasound and fluorescent cholangiography, consolidate a practice model based on the integration of vision, data, and anatomical precision.

Although the results point to significant advances, there are still challenges to be overcome, such as the standardization of protocols, the methodological heterogeneity of studies, and the need for economic and multicenter evaluations that measure cost-effectiveness and long-term clinical impact. As the incorporation of intelligent and robotic systems expands, image-guided surgery tends to evolve from an auxiliary tool to a central standard of surgical care, supporting the concept of intelligent, safe, and data-driven surgery.

DOI: https://doi.org/10.36489/nursing.2025v30i329p11920-11946

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