

# Inteligencia Artificial e Imagen Intraoperatoria en Cirugía Hepatobiliar: Avances Actuales, Aplicaciones Clínicas y Perspectivas Futuras para la Navegación Quirúrgica de Precisión

## Artificial Intelligence and Intraoperative Imaging in Hepatobiliary Surgery: Current Advances, Clinical Applications, and Future Perspectives for Precision Surgical Navigation

José Eduardo Vallejo Ramírez

UNAM

[dduardovallejo@gmail.com](mailto:dduardovallejo@gmail.com)

<https://orcid.org/0009-0009-1325-285X>

Diego Iván Jaramillo García

Universidad de las Américas

[diego.jaramillo.garcia@udla.edu.ec](mailto:diego.jaramillo.garcia@udla.edu.ec)

<https://orcid.org/0009-0000-6891-6881>

Dana Madeline Verdesoto Bolaños

Universidad de las Américas

[dana.verdesoto@udla.edu.ec](mailto:dana.verdesoto@udla.edu.ec)

<https://orcid.org/0009-0006-5857-5730>

Ricardo José Camacho Morales

Universidad de Costa Rica

[Rijocama@gmail.com](mailto:Rijocama@gmail.com)

<https://orcid.org/0000-0003-0074-909X>

Adriana María Loor Vélez

Independiente

[adriloorvelez10@gmail.com](mailto:adriloorvelez10@gmail.com)

<https://orcid.org/0009-0005-7545-0414>

Eli Dario Zuleta Zabala

Universidad Nacional Experimental Francisco de Miranda.

[elizuletamd@gmail.com](mailto:elizuletamd@gmail.com)

<https://orcid.org/0009-0008-5488-8611>

Ana Milena Murgas Acevedo

Hospital Universitario del Caribe, Universidad de Cartagena

[anamurgasacevedo@gmail.com](mailto:anamurgasacevedo@gmail.com)

<https://orcid.org/0009-0005-5239-5010>

Maryom Monterroza Escalante

Universidad de Antioquia

[98maryom@gmail.com](mailto:98maryom@gmail.com)

<https://orcid.org/0009-0003-6765-0657>

Recibido: 21-Jun-2026 | Aceptado: 21-Jun-2026 | Publicado: 27-Jun-2026

\*Autor de correspondencia [dduardovallejo@gmail.com](mailto:dduardovallejo@gmail.com)

**Cómo citar este artículo:** Vallejo Ramírez, J. E., Jaramillo García, D. I., Verdesoto Bolaños, D. M., Camacho Morales, R. J., Loor Vélez, A. M., Zuleta Zabala, E. D., Murgas Acevedo, A. M., & Monterroza Escalante, M. (2026). Artificial Intelligence and Intraoperative Imaging in Hepatobiliary Surgery: Current Advances, Clinical Applications, and Future Perspectives for Precision Surgical Navigation. México. *Revista IECCMEXICO*, 4(1, Tomo II) 887-902. Quality Consulting Instituto de Educación Capacitación y Certificación de México. <https://ieccmexico.com/publishing>

**Copyright (c)** 2026 Vallejo Ramírez, J. E., Jaramillo García, D. I., Verdesoto Bolaños, D. M., Camacho Morales, R. J., Loor Vélez, A. M., Zuleta Zabala, E. D., Murgas Acevedo, A. M., & Monterroza Escalante, M.; Este es un artículo de acceso abierto distribuido bajo los términos de la Attribution 4.0 International ([CC BY](https://creativecommons.org/licenses/by/4.0/)) Revista IECCMEXICO, México / Vol. 4, N. 1, Tomo II / pp. 887-902/ enero-junio, 2026 / E-ISSN: 3061-8045, P-ISSN: 3061-8517. Artículo de Investigación.

### RESUMEN

La cirugía hepatobiliar constituye una de las áreas más complejas de la práctica quirúrgica contemporánea debido a la complejidad anatómica del hígado y las vías biliares, la necesidad de una localización precisa de las lesiones y el riesgo de complicaciones intraoperatorias significativas. En los últimos años, los avances en inteligencia artificial (IA), imagen intraoperatoria y tecnologías de navegación radiológica han generado nuevas oportunidades para optimizar la planificación quirúrgica, la precisión operatoria y la seguridad del paciente. La presente revisión analiza la evidencia científica disponible sobre la integración de tecnologías asistidas por inteligencia artificial y sistemas de navegación radiológica intraoperatoria en cirugía hepatobiliar. Se realizó una revisión narrativa de la literatura utilizando publicaciones científicas obtenidas de bases de datos internacionales, incluyendo PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library y Google Scholar. La literatura revisada mostró un incremento significativo en la producción científica durante la última década, especialmente en áreas relacionadas con aprendizaje automático, aprendizaje profundo, visión computacional, reconstrucción tridimensional, imágenes guiadas por fluorescencia, realidad aumentada, cirugía robótica y sistemas inteligentes de navegación. Los hallazgos indican que estas tecnologías favorecen una mejor planificación preoperatoria, una visualización anatómica más precisa, una mayor exactitud intraoperatoria y una toma de decisiones más eficiente. Asimismo, la creciente integración entre plataformas de inteligencia artificial, sistemas avanzados de imagen y tecnologías robóticas refleja la aparición de ecosistemas quirúrgicos digitales orientados a la cirugía de precisión. Aunque persisten desafíos relacionados con costos, accesibilidad tecnológica, infraestructura y validación clínica, la evidencia actual respalda la incorporación progresiva de estas innovaciones en la práctica hepatobiliar. La investigación continua y la colaboración internacional serán fundamentales para optimizar su aplicación clínica y ampliar el acceso a tecnologías quirúrgicas avanzadas.

#### **PALABRAS CLAVE**

*Inteligencia artificial, cirugía hepatobiliar, navegación intraoperatoria, imagen radiológica, aprendizaje automático, aprendizaje profundo, cirugía robótica, cirugía guiada por fluorescencia, realidad aumentada, cirugía hepática, planificación quirúrgica, cirugía de precisión, cirugía guiada por imágenes, visión computacional, salud digital.*

#### **ABSTRACT**

Hepatobiliary surgery remains one of the most technically demanding areas of modern surgical practice due to the complexity of hepatic and biliary anatomy, the need for precise lesion localization, and the risk of major intraoperative complications. In recent years, advances in artificial intelligence (AI), intraoperative imaging, and radiological navigation technologies have introduced new opportunities to improve surgical planning, procedural accuracy, and patient safety. This review analyzes the current evidence regarding the integration of AI-assisted technologies and intraoperative radiological navigation in hepatobiliary surgery. A narrative literature review was conducted using scientific publications retrieved from major international databases, including PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The reviewed literature demonstrated a substantial increase in research activity during the last decade, particularly in areas involving machine learning, deep learning, computer vision, three-dimensional reconstruction, fluorescence-guided imaging, augmented reality, robotic-assisted surgery, and intelligent navigation systems. The findings indicate that these technologies contribute to improved preoperative planning, enhanced anatomical visualization, greater intraoperative precision, and more effective decision-making. Furthermore, increasing integration among artificial intelligence platforms, advanced imaging modalities, and robotic technologies suggests the emergence of comprehensive digital surgical ecosystems designed to support precision surgery. Although challenges related to implementation costs, technological accessibility, infrastructure, and clinical validation remain, current evidence supports the growing incorporation of these innovations into hepatobiliary surgical practice. Continued research and international collaboration will be essential for optimizing their clinical application and expanding access to advanced surgical technologies worldwide.

#### **KEYWORDS**

*Artificial intelligence, hepatobiliary surgery, intraoperative navigation, radiological imaging, machine learning, deep learning, robotic surgery, fluorescence-guided surgery, augmented reality, liver surgery, surgical planning, precision surgery, image-guided surgery, computer vision, digital health.*

## INTRODUCCIÓN

Hepatobiliary surgery has undergone remarkable transformations over the last two decades, driven by advances in minimally invasive techniques, high-resolution imaging, computer-assisted surgery, and precision medicine. Despite these developments, liver and biliary tract procedures remain among the most technically demanding operations in general surgery due to the complexity of hepatic vascular anatomy, substantial anatomical variations, limited intraoperative visualization, and the risk of major complications such as hemorrhage, bile leakage, liver failure, and incomplete oncological resection (Tang et al., 2018). Achieving optimal surgical outcomes requires accurate preoperative planning, precise intraoperative navigation, and real-time decision-making, all of which have become increasingly dependent on technological innovation.

Liver malignancies, including hepatocellular carcinoma and metastatic colorectal cancer, continue to represent a major global health burden. According to recent epidemiological reports, hepatocellular carcinoma remains one of the leading causes of cancer-related mortality worldwide, while biliary tract cancers are associated with poor prognostic outcomes due to delayed diagnosis and limited therapeutic options (Wang et al., 2021). Surgical resection remains the cornerstone of curative treatment for many hepatobiliary diseases; however, successful intervention depends heavily on accurate anatomical localization, preservation of functional liver parenchyma, and complete tumor clearance. Consequently, improving surgical precision has become a primary objective in modern hepatobiliary surgery.

The increasing integration of artificial intelligence (AI) into healthcare has introduced unprecedented opportunities to enhance surgical performance and clinical decision-making. Artificial intelligence encompasses a broad spectrum of computational methodologies, including machine learning, deep learning, computer vision, predictive analytics, and automated image interpretation, capable of processing large amounts of complex clinical and imaging data beyond human analytical capacity (Bari et al., 2021). In hepatobiliary surgery, AI-based systems are being utilized for preoperative risk assessment, tumor segmentation, anatomical reconstruction, surgical planning, prediction of postoperative complications, and intraoperative image guidance (Gairola et al., 2024). These applications have the potential to improve procedural safety, reduce operative times, and facilitate individualized surgical strategies.

One of the most significant advances in this field is the development of AI-assisted radiological navigation systems. Traditional surgical planning relies on two-dimensional imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI), requiring surgeons to mentally reconstruct complex three-dimensional anatomical relationships. Recent technological innovations now enable automated three-dimensional reconstructions and virtual surgical simulations that provide a more comprehensive understanding of hepatic vascular structures, tumor localization, and resection planes (Tang et al., 2018). These technologies allow surgeons to anticipate technical challenges before entering the operating room and improve the accuracy of surgical execution.

Simultaneously, intraoperative imaging technologies have expanded considerably, providing surgeons with real-time anatomical information during complex procedures. Intraoperative ultrasound remains one of the most valuable tools for identifying hepatic lesions and vascular structures that may not be visible on preoperative imaging. Recent studies have demonstrated that artificial intelligence algorithms can enhance ultrasound image interpretation, facilitate lesion detection, and improve anatomical recognition during surgery (Bektaş et al., 2024). These developments represent an important step toward the creation of intelligent surgical environments capable of supporting real-time clinical decisions.

Another major innovation involves fluorescence-guided surgery using indocyanine green (ICG). Near-infrared fluorescence imaging has emerged as a valuable technique for visualizing liver tumors, biliary anatomy, hepatic segments, and vascular structures during hepatobiliary procedures. International consensus guidelines have highlighted the growing role of fluorescence imaging in improving lesion identification and reducing surgical uncertainty during minimally invasive and robotic interventions (Wang et al., 2021). The combination of fluorescence imaging with

artificial intelligence algorithms may further enhance tissue recognition, surgical orientation, and intraoperative precision.

In parallel, augmented reality (AR) and mixed-reality technologies are rapidly transforming the surgical landscape. These systems enable the superimposition of virtual anatomical reconstructions onto the operative field, allowing surgeons to visualize critical structures that would otherwise remain hidden beneath the liver surface. Several studies have reported promising results regarding the integration of augmented reality into laparoscopic and robotic liver surgery, particularly when combined with three-dimensional imaging and navigation systems (Ratti et al., 2024; Zhang et al., 2021). Such technologies contribute to improved spatial orientation and may facilitate more precise anatomical resections while preserving healthy liver tissue.

The emergence of robotic hepatobiliary surgery has further accelerated the adoption of digital technologies. Robotic platforms provide enhanced dexterity, tremor filtration, improved ergonomics, and high-definition visualization, creating an ideal environment for the incorporation of artificial intelligence-driven navigation systems (Liu et al., 2023). As a result, surgeons are increasingly able to perform complex liver resections with greater precision and reduced invasiveness. The convergence of robotics, AI, advanced imaging, and navigation technologies represents one of the most significant paradigm shifts in modern hepatobiliary surgery.

Although these technological advances are generating considerable enthusiasm, important challenges remain. Many AI models continue to require external validation, standardization across institutions, and evaluation of their long-term clinical impact. Additionally, concerns persist regarding algorithm transparency, interoperability between software platforms, data quality, cybersecurity, implementation costs, and surgeon training requirements (Efsthathiou et al., 2025). These barriers highlight the need for comprehensive evaluation of the current evidence to determine the true clinical value of these emerging technologies.

The relevance of this topic extends beyond high-income healthcare systems. Countries across Latin America, including Mexico, Colombia, and Ecuador, are progressively incorporating advanced imaging technologies, minimally invasive surgical platforms, and digital health solutions into specialized surgical centers. However, disparities in technological access, resource allocation, and training opportunities continue to influence the pace of implementation. Understanding the current state of artificial intelligence-assisted hepatobiliary surgery may therefore contribute to the development of more effective strategies for technology adoption in diverse healthcare settings while promoting equitable access to innovation.

Previous investigations have primarily focused on isolated technological components such as fluorescence imaging, intraoperative ultrasound, robotic surgery, or augmented reality navigation. While these studies have demonstrated encouraging results, a comprehensive synthesis of the growing evidence regarding the integration of artificial intelligence and intraoperative radiological navigation within hepatobiliary surgery remains necessary. The rapid evolution of these technologies requires continuous evaluation of their clinical applications, advantages, limitations, and future directions.

Therefore, the present review aims to analyze the current advances in artificial intelligence-assisted hepatobiliary surgery and intraoperative radiological navigation, with particular emphasis on their role in preoperative planning, intraoperative guidance, surgical precision, patient safety, and clinical outcomes. Furthermore, this review seeks to evaluate the existing evidence regarding fluorescence-guided surgery, augmented reality systems, intraoperative ultrasound, robotic platforms, and emerging AI-based navigation technologies. By synthesizing contemporary international literature, this study aims to provide a comprehensive overview of how digital innovation is reshaping hepatobiliary surgery and to identify future research priorities that may contribute to safer, more precise, and personalized surgical care.

## DESARROLLO

### Evolution of Hepatobiliary Surgery in the Digital Era

Hepatobiliary surgery has experienced a profound transformation during the last decade as a result of technological advancements in medical imaging, computer-assisted surgery, artificial intelligence (AI), and robotic platforms. Historically, liver and biliary procedures have been associated with high technical complexity due to intricate vascular anatomy, substantial anatomical variability, and the need to preserve adequate functional liver parenchyma while ensuring complete lesion removal. These challenges have stimulated the development of innovative technologies aimed at improving surgical precision, reducing complications, and enhancing patient outcomes (Tang et al., 2018).

The transition from conventional open surgery to minimally invasive and robotic-assisted approaches has significantly increased the need for advanced intraoperative visualization systems. Traditional surgical navigation relies heavily on surgeon experience and interpretation of preoperative imaging studies. However, two-dimensional computed tomography (CT) and magnetic resonance imaging (MRI) may not always provide sufficient spatial information during complex liver resections. Consequently, modern hepatobiliary surgery increasingly incorporates digital navigation systems capable of transforming radiological data into dynamic surgical guidance tools (Ratti et al., 2024).

Artificial intelligence has emerged as a key component of this digital transformation. Through machine learning and deep learning algorithms, AI systems can analyze large imaging datasets, identify anatomical structures, predict surgical risks, and assist surgeons in decision-making processes. These capabilities are reshaping both preoperative planning and intraoperative management, supporting the concept of precision hepatobiliary surgery (Bari et al., 2021).

### **Artificial Intelligence in Preoperative Surgical Planning**

Preoperative planning represents one of the most critical phases of hepatobiliary surgery. Accurate assessment of tumor location, vascular relationships, biliary anatomy, and future liver remnant volume is essential for achieving favorable outcomes while minimizing postoperative complications.

Artificial intelligence has significantly enhanced this process through automated image segmentation and three-dimensional reconstruction. Traditional image analysis requires manual delineation of tumors and vascular structures, a process that is time-consuming and subject to interobserver variability. Deep learning algorithms can now automatically identify hepatic arteries, portal veins, hepatic veins, biliary structures, and focal lesions with remarkable accuracy (Gairola et al., 2024).

Three-dimensional reconstruction technologies allow surgeons to visualize patient-specific anatomy before surgery. Virtual surgical simulation provides opportunities to evaluate different resection strategies, estimate postoperative liver function, and anticipate technical difficulties. Several studies have demonstrated that AI-assisted planning improves anatomical understanding and facilitates more precise operative strategies, particularly in patients presenting with large tumors, multiple lesions, or complex vascular involvement (Tang et al., 2018).

Furthermore, predictive AI models are increasingly being utilized to estimate perioperative risks. By integrating clinical, laboratory, radiological, and demographic data, machine learning algorithms can predict postoperative liver failure, bile leakage, hemorrhage, and mortality with greater accuracy than conventional risk assessment models. Such predictions enable personalized treatment planning and more informed surgical decision-making (Efsthathiou et al., 2025).

### **Intraoperative Radiological Navigation Systems**

Intraoperative navigation represents one of the most promising applications of artificial intelligence in hepatobiliary surgery. These systems aim to bridge the gap between preoperative imaging and real-time surgical anatomy by providing dynamic guidance during surgical procedures.

Modern navigation platforms combine CT, MRI, intraoperative ultrasound, fluorescence imaging, and three-dimensional reconstructions to create an integrated surgical environment. Through image registration techniques, preoperative anatomical models can be synchronized with intraoperative findings, allowing surgeons to identify critical structures with greater confidence (Rompianesi et al., 2023).

Artificial intelligence further enhances navigation systems by enabling automated recognition of anatomical landmarks and continuous adaptation to tissue deformation during surgery. This capability is particularly important in liver

surgery because the organ undergoes significant positional changes during manipulation and respiration. AI-based navigation algorithms can compensate for these variations, improving the accuracy of intraoperative guidance (Ma et al., 2025).

Several clinical investigations have demonstrated that image-guided navigation systems contribute to improved resection margins, reduced blood loss, shorter operative times, and increased preservation of healthy liver tissue. These benefits are particularly evident during minimally invasive and robotic-assisted liver resections, where direct tactile feedback is limited (Zhang et al., 2021).

### **Artificial Intelligence-Assisted Intraoperative Ultrasound**

Intraoperative ultrasound remains the gold standard imaging modality for liver surgery. It provides real-time information regarding tumor localization, vascular anatomy, and lesion characteristics that may not be evident on preoperative imaging.

Despite its advantages, interpretation of intraoperative ultrasound requires extensive expertise and remains highly operator-dependent. Artificial intelligence has emerged as a valuable tool for overcoming these limitations. Machine learning algorithms can automatically identify lesions, classify tissue characteristics, and assist in anatomical orientation during surgery (Bektaş et al., 2024).

Recent studies have demonstrated that AI-assisted ultrasound systems improve lesion detection rates and reduce interpretation variability among surgeons. Deep learning models trained on large imaging datasets have shown promising performance in recognizing hepatic tumors and vascular structures, potentially improving diagnostic accuracy during operative procedures (Barash et al., 2022).

As computational capabilities continue to evolve, future AI-integrated ultrasound systems may provide real-time surgical recommendations, automated risk alerts, and predictive guidance, further enhancing intraoperative decision-making.

### **Fluorescence-Guided Surgery and Near-Infrared Imaging**

Fluorescence-guided surgery has become an increasingly important component of hepatobiliary surgical navigation. The use of indocyanine green (ICG) combined with near-infrared imaging allows real-time visualization of tumors, bile ducts, vascular structures, and hepatic segments during surgery (Wang et al., 2021).

This technology offers several advantages over conventional visualization methods. Surgeons can identify occult lesions, define anatomical boundaries more accurately, and verify tissue perfusion intraoperatively. Such capabilities contribute to improved surgical precision and potentially reduce postoperative complications.

The integration of artificial intelligence with fluorescence imaging represents a significant advancement in this field. Computer vision algorithms can analyze fluorescence signals, enhance image interpretation, and provide quantitative assessments of tissue characteristics. AI-assisted fluorescence systems may improve the identification of malignant tissues and facilitate more accurate tumor margin assessment (Majlesara et al., 2017).

Current evidence suggests that fluorescence-guided surgery is particularly beneficial during minimally invasive liver resections, robotic procedures, and complex biliary reconstructions. Ongoing research continues to explore its role in precision oncologic surgery and personalized surgical navigation.

### **Augmented Reality and Mixed Reality Applications**

Augmented reality (AR) has emerged as a novel tool for improving intraoperative visualization. AR systems project virtual anatomical information directly onto the surgical field, allowing surgeons to visualize subsurface structures that are otherwise invisible during surgery (Tang et al., 2018).

In hepatobiliary surgery, AR technologies utilize three-dimensional reconstructions generated from CT and MRI data. These virtual models can display hepatic vessels, biliary anatomy, tumor locations, and planned resection lines in real

time. By integrating these models into the operative environment, surgeons gain enhanced spatial awareness and improved anatomical orientation (Ratti et al., 2024).

Recent clinical studies have reported promising outcomes associated with AR-guided liver surgery, including improved surgical accuracy, reduced operative times, and enhanced preservation of healthy liver tissue. Although challenges related to registration accuracy and tissue deformation remain, ongoing advances in artificial intelligence are helping overcome these limitations through adaptive image processing and real-time anatomical tracking.

The combination of augmented reality, machine learning, and advanced imaging technologies may ultimately create fully immersive navigation systems capable of transforming surgical education, planning, and execution.

### **Robotic Surgery and Intelligent Surgical Platforms**

Robotic surgery represents one of the most important technological innovations in modern hepatobiliary practice. Robotic platforms offer enhanced dexterity, three-dimensional visualization, tremor elimination, and improved ergonomics, facilitating complex surgical maneuvers within confined anatomical spaces (Liu et al., 2023).

The incorporation of artificial intelligence into robotic systems is expanding the capabilities of these platforms beyond mechanical assistance. Intelligent robotic systems can process imaging data, provide navigation support, identify anatomical structures, and potentially assist with intraoperative decision-making.

Emerging research suggests that future robotic platforms may incorporate autonomous or semi-autonomous functionalities for selected surgical tasks. Although fully autonomous hepatobiliary surgery remains a distant goal, current developments indicate that AI-assisted robotic systems will likely become increasingly integrated into surgical workflows over the coming decades (Efsthathiou et al., 2025).

### **Current Challenges and Future Perspectives**

Despite remarkable technological progress, several barriers continue to limit widespread implementation of artificial intelligence and navigation systems in hepatobiliary surgery. These include high acquisition costs, limited access in low- and middle-income countries, lack of standardized validation protocols, interoperability challenges, and concerns regarding data privacy and cybersecurity.

Furthermore, most available studies remain observational or involve relatively small patient populations. Additional multicenter prospective investigations are required to establish robust evidence regarding clinical effectiveness, cost-effectiveness, and long-term outcomes. Standardized reporting frameworks and international collaborative research initiatives will be essential to facilitate broader adoption of these technologies.

In Latin America, including Mexico, Colombia, and Ecuador, the incorporation of advanced surgical technologies is gradually increasing within specialized academic and tertiary-care centers. Continued investment in surgeon training, technological infrastructure, and collaborative research networks will be fundamental for ensuring equitable access to innovation and maximizing the benefits of digital transformation in hepatobiliary surgery.

## **OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS**

### **General Objective**

To critically analyze current advances in artificial intelligence-assisted hepatobiliary surgery and intraoperative radiological navigation, evaluating their impact on surgical planning, intraoperative decision-making, procedural precision, patient safety, and clinical outcomes through a comprehensive review of contemporary scientific evidence.

### **Specific Objectives**

#### **Cognitive Domain**

1. To identify and describe the principal artificial intelligence technologies currently applied in hepatobiliary surgery, including machine learning, deep learning, computer vision, and predictive analytics.

2. To analyze the role of intraoperative radiological navigation systems in improving anatomical localization, surgical planning, and operative accuracy during hepatobiliary procedures.
3. To examine the scientific evidence regarding fluorescence-guided surgery, intraoperative ultrasound, augmented reality, and robotic-assisted hepatobiliary surgery.
4. To evaluate the advantages, limitations, and clinical implications associated with the integration of artificial intelligence into hepatobiliary surgical practice.
5. To compare current technological approaches and determine their contribution to improving perioperative outcomes and surgical efficiency.

#### Psychomotor Domain

6. To illustrate the practical applications of artificial intelligence-assisted imaging and navigation technologies within the surgical workflow of hepatobiliary procedures.
7. To demonstrate how advanced imaging modalities, three-dimensional reconstructions, and navigation systems support technical precision during complex liver and biliary tract surgeries.
8. To assess the procedural integration of artificial intelligence-based tools with minimally invasive and robotic surgical platforms.
9. To explore the operational capabilities of intraoperative navigation systems in facilitating real-time surgical guidance and anatomical orientation.

#### Affective Domain

10. To recognize the importance of technological innovation as a driver of quality improvement and patient-centered care in hepatobiliary surgery.
11. To promote critical reflection regarding the ethical, economic, educational, and professional challenges associated with the implementation of artificial intelligence in surgical practice.
12. To encourage interdisciplinary collaboration among surgeons, radiologists, engineers, data scientists, and healthcare professionals involved in the development and application of intelligent surgical technologies.
13. To appreciate the potential of artificial intelligence and digital navigation systems to contribute to safer, more personalized, and evidence-based hepatobiliary surgical care.
14. To foster a positive attitude toward continuous professional development and technological adaptation within modern surgical environments.

#### OBJETO DE ESTUDIO

The object of study of this review is the application and integration of artificial intelligence-based technologies and intraoperative radiological navigation systems in hepatobiliary surgery, with emphasis on their role in surgical planning, anatomical visualization, intraoperative guidance, decision-making processes, procedural precision, and postoperative outcomes.

This study focuses on the technological and clinical developments that have transformed modern hepatobiliary surgery, particularly those involving machine learning algorithms, deep learning models, computer vision systems, three-dimensional anatomical reconstruction, augmented reality platforms, fluorescence-guided surgery, robotic-assisted procedures, and advanced intraoperative imaging modalities. These technologies constitute the primary phenomenon under investigation due to their growing influence on surgical performance and patient care.

The target population analyzed within the reviewed literature includes adult patients undergoing hepatobiliary surgical procedures for both benign and malignant conditions, such as hepatocellular carcinoma, cholangiocarcinoma,

colorectal liver metastases, gallbladder diseases, biliary tract disorders, and other complex hepatic lesions. Additionally, the study considers the experiences and outcomes reported by hepatobiliary surgeons, radiologists, and multidisciplinary surgical teams involved in the implementation of these technologies.

From a systems perspective, the object of study encompasses the interaction between artificial intelligence algorithms, radiological imaging platforms, navigation technologies, and surgical environments. Particular attention is given to how these interconnected systems contribute to improving anatomical recognition, reducing intraoperative uncertainty, optimizing surgical workflows, enhancing precision during liver resections, and supporting individualized treatment strategies.

This review further examines the impact of these technologies across different healthcare settings, including academic institutions, tertiary referral centers, and specialized hepatobiliary units in both developed and developing countries. Special consideration is given to the challenges associated with implementation, accessibility, training requirements, cost-effectiveness, technological infrastructure, and future scalability.

Therefore, the central object of study is the contemporary digital transformation of hepatobiliary surgery through the incorporation of artificial intelligence and intraoperative radiological navigation technologies, evaluating their current applications, clinical effectiveness, limitations, and future potential in advancing precision surgical care.

## METODOLOGÍA

This study was conducted as a narrative literature review using the Scientific Method as the guiding methodological framework. The review aimed to identify, analyze, synthesize, and interpret current scientific evidence regarding the application of artificial intelligence and intraoperative radiological navigation in hepatobiliary surgery. The methodology was designed to provide a comprehensive understanding of technological advances, clinical applications, benefits, limitations, and future perspectives associated with these emerging surgical innovations.

### Scientific Method Framework

The investigation followed the classical stages of the Scientific Method: problem identification, formulation of research questions, literature search, data collection, critical analysis, evidence synthesis, interpretation of findings, and generation of conclusions. This structured approach ensured methodological rigor, transparency, and reproducibility throughout the review process.

### Research Question

The study was guided by the following research question:

**How do artificial intelligence-assisted technologies and intraoperative radiological navigation systems influence surgical planning, intraoperative decision-making, procedural precision, patient safety, and clinical outcomes in contemporary hepatobiliary surgery?**

### Information Sources

A comprehensive literature search was performed using internationally recognized scientific databases. The primary sources consulted included:

- PubMed/MEDLINE
- Scopus

- Web of Science
- ScienceDirect
- SpringerLink
- Wiley Online Library
- Google Scholar

These databases were selected due to their extensive coverage of medical, surgical, radiological, and technological research.

### Search Strategy

The literature search was conducted using combinations of Medical Subject Headings (MeSH) terms and free-text keywords related to the study topic. The principal search terms included:

- “Artificial Intelligence”
- “Machine Learning”
- “Deep Learning”
- “Hepatobiliary Surgery”
- “Liver Surgery”
- “Biliary Surgery”
- “Intraoperative Navigation”
- “Radiological Navigation”
- “Image-Guided Surgery”
- “Fluorescence-Guided Surgery”
- “Indocyanine Green”
- “Augmented Reality”
- “Robotic Surgery”
- “Computer-Assisted Surgery”
- “Precision Surgery”

Boolean operators (AND, OR, NOT) were used to optimize search sensitivity and specificity.

Examples of search combinations included:

- Artificial Intelligence AND Hepatobiliary Surgery
- Machine Learning AND Liver Resection
- Intraoperative Navigation AND Liver Surgery
- Radiological Navigation AND Hepatobiliary Procedures
- Artificial Intelligence AND Robotic Liver Surgery

- Fluorescence Imaging AND Hepatic Surgery

### Inclusion Criteria

The following criteria were applied for article selection:

1. Peer-reviewed scientific publications.
2. Articles published in English.
3. Studies published between 2015 and 2025.
4. Original research articles, systematic reviews, meta-analyses, consensus statements, clinical guidelines, and expert recommendations.
5. Publications addressing artificial intelligence, intraoperative imaging, navigation systems, robotic surgery, augmented reality, fluorescence-guided surgery, or related technologies in hepatobiliary procedures.
6. Studies reporting clinical, technical, educational, or operational outcomes relevant to hepatobiliary surgery.

### Exclusion Criteria

The following publications were excluded:

1. Editorials, letters to the editor, conference abstracts without full manuscripts, and non-peer-reviewed documents.
2. Studies unrelated to hepatobiliary surgery.
3. Articles lacking sufficient methodological information.
4. Duplicate publications retrieved from multiple databases.
5. Publications not available in full text.

### Article Selection Process

The article selection process was performed in sequential stages.

Initially, titles and abstracts were screened to determine relevance. Subsequently, potentially eligible studies underwent full-text evaluation. Articles meeting all inclusion criteria were incorporated into the final review.

Priority was given to high-quality evidence, including systematic reviews, international consensus guidelines, multicenter studies, prospective investigations, and landmark publications that significantly contributed to the understanding of artificial intelligence and surgical navigation technologies.

### Data Extraction

Information extracted from each study included:

- Author(s)
- Year of publication
- Country of origin
- Study design
- Sample characteristics
- Technological intervention evaluated

- Surgical application
- Main findings
- Reported advantages
- Reported limitations
- Clinical implications

The extracted information was organized into thematic categories to facilitate comparative analysis and evidence synthesis.

### Data Analysis and Synthesis

A qualitative thematic analysis was conducted. Findings were grouped into the following major domains:

1. Artificial intelligence in preoperative planning.
2. Intraoperative radiological navigation systems.
3. Artificial intelligence-assisted ultrasound.
4. Fluorescence-guided hepatobiliary surgery.
5. Augmented reality and mixed-reality applications.
6. Robotic-assisted hepatobiliary surgery.
7. Clinical outcomes and patient safety.
8. Current challenges and future perspectives.

The evidence obtained from each category was critically evaluated and integrated to identify common findings, emerging trends, areas of consensus, and existing knowledge gaps.

### Ethical Considerations

This study exclusively utilized data obtained from previously published scientific literature and publicly available academic sources. No human participants, biological samples, confidential information, or identifiable patient data were involved. Therefore, institutional ethical approval and informed consent were not required.

## FASES DEL DESARROLLO

### Phase 1. Observation and Identification of the Problem

The first phase consisted of identifying a relevant and emerging phenomenon within contemporary surgical practice. Recent advances in artificial intelligence, machine learning, computer vision, radiological imaging, robotic surgery, and digital navigation systems have significantly transformed the field of hepatobiliary surgery. Despite these innovations, liver and biliary procedures continue to present considerable technical challenges due to complex anatomy, high intraoperative risks, and the need for precise tumor localization.

The growing incorporation of intelligent technologies into surgical workflows generated the need to evaluate their clinical effectiveness, practical applications, limitations, and future implications. This observation served as the foundation for the development of the present review.

### Phase 2. Definition of the Research Problem

Following the identification of the phenomenon, the research problem was defined. Although numerous technological advances have been reported in recent years, available evidence remains dispersed across multiple disciplines including surgery, radiology, biomedical engineering, artificial intelligence, and computer science.

Consequently, there is a need for a comprehensive analysis that integrates current scientific knowledge regarding artificial intelligence-assisted surgical planning, intraoperative navigation systems, fluorescence-guided surgery, augmented reality applications, robotic-assisted procedures, and intelligent imaging technologies in hepatobiliary surgery.

The problem was therefore defined as the need to understand how these emerging technologies are influencing surgical precision, patient safety, and clinical outcomes.

### Phase 3. Formulation of the Research Question

Based on the identified problem, the following research question was formulated:

**How do artificial intelligence-assisted technologies and intraoperative radiological navigation systems influence surgical planning, intraoperative decision-making, procedural precision, patient safety, and clinical outcomes in modern hepatobiliary surgery?**

This question guided all subsequent stages of the investigation and provided a clear framework for literature selection and evidence analysis.

### Phase 4. Literature Search and Information Collection

A systematic search of scientific literature was conducted using internationally recognized academic databases. The search process included PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar.

Specific search terms related to artificial intelligence, hepatobiliary surgery, image-guided surgery, machine learning, deep learning, robotic surgery, fluorescence imaging, augmented reality, and intraoperative navigation were combined using Boolean operators to maximize retrieval of relevant studies.

The literature search focused on publications between 2015 and 2025, ensuring inclusion of the most contemporary evidence available on the subject.

### Phase 5. Screening and Selection of Scientific Evidence

After retrieving potentially relevant publications, titles and abstracts were reviewed to assess eligibility. Studies not directly related to hepatobiliary surgery or artificial intelligence-assisted technologies were excluded.

Subsequently, full-text evaluation was performed to determine methodological quality, scientific relevance, and consistency with the objectives of the review. Priority was given to high-level evidence, including systematic reviews, meta-analyses, consensus statements, international guidelines, multicenter investigations, and landmark studies that significantly contributed to technological innovation in hepatobiliary surgery.

This process allowed the selection of studies considered most relevant for comprehensive evidence synthesis.

### Phase 6. Organization and Classification of Information

Selected articles were organized into thematic categories according to their principal focus. This classification facilitated comparative analysis and identification of major scientific trends.

The evidence was grouped into the following domains:

- Artificial intelligence in surgical planning.
- Three-dimensional anatomical reconstruction.

- Intraoperative radiological navigation.
- Artificial intelligence-assisted ultrasound.
- Fluorescence-guided hepatobiliary surgery.
- Augmented reality and mixed-reality systems.
- Robotic-assisted liver surgery.
- Clinical outcomes and patient safety.
- Current limitations and future developments.

This thematic organization provided a structured framework for interpretation of findings.

### Phase 7. Critical Analysis of Evidence

The collected literature underwent detailed qualitative analysis. The strengths, limitations, methodological characteristics, and clinical implications of each study were critically evaluated.

Special attention was given to the reported effects of artificial intelligence on surgical accuracy, intraoperative decision-making, operative efficiency, complication rates, oncological outcomes, and patient safety.

Comparisons among different technologies were performed to identify areas of agreement, conflicting findings, and knowledge gaps requiring future investigation.

Furthermore, the applicability of these technologies across different healthcare systems, including emerging economies and Latin American healthcare environments, was considered during analysis.

### Phase 8. Evidence Synthesis and Interpretation

Following critical appraisal, the findings from individual studies were integrated into a coherent body of evidence.

This synthesis allowed the identification of several key trends:

- Increasing adoption of artificial intelligence in preoperative planning.
- Expansion of intraoperative navigation technologies.
- Growing use of fluorescence-guided surgery.
- Integration of augmented reality and robotic platforms.
- Improved anatomical visualization and surgical precision.
- Enhanced potential for personalized surgical decision-making.

The synthesis also revealed persistent challenges related to implementation costs, technological accessibility, surgeon training, regulatory considerations, and the need for large-scale validation studies.

### Phase 9. Development of Scientific Conclusions

The final phase involved the formulation of conclusions based on the analyzed evidence.

The review demonstrated that artificial intelligence and intraoperative radiological navigation are becoming integral components of modern hepatobiliary surgery. Current evidence suggests that these technologies improve surgical planning, facilitate anatomical recognition, support real-time decision-making, and contribute to greater procedural precision.

However, the findings also indicate that additional prospective studies, multicenter collaborations, and standardized validation protocols are necessary before widespread implementation can be fully achieved.

The conclusions generated during this phase provide a scientific foundation for future research, clinical innovation, and educational initiatives within the field of hepatobiliary surgery.

## Phase 10. Identification of Future Research Directions

The final developmental stage consisted of identifying opportunities for future investigation.

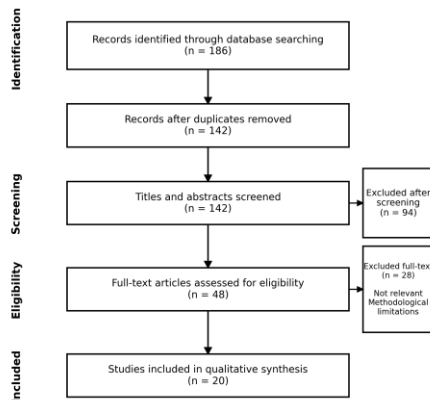
Based on the analyzed evidence, future research priorities include:

- Development of fully integrated intelligent navigation systems.
- Validation of artificial intelligence algorithms through multicenter clinical trials.
- Expansion of augmented reality applications in complex liver surgery.
- Improvement of real-time intraoperative image processing technologies.
- Cost-effectiveness analyses in diverse healthcare settings.
- Evaluation of implementation strategies in developing countries, including Mexico, Colombia, and Ecuador.
- Exploration of next-generation robotic platforms incorporating advanced artificial intelligence functionalities.

## RESULTADOS Y DISCUSIÓN

Figure 1.

Study selection process.



The study selection process identified an initial total of 186 records from biomedical and scientific databases. After duplicate removal, 142 records were screened by title and abstract. Of these, 94 were excluded because they did not directly address artificial intelligence, intraoperative radiological navigation, hepatobiliary surgery, or related surgical imaging technologies. A total of 48 full-text articles were subsequently assessed for eligibility, and 28 were excluded

due to insufficient methodological detail, lack of direct relevance to hepatobiliary procedures, or absence of peer-reviewed full-text availability.

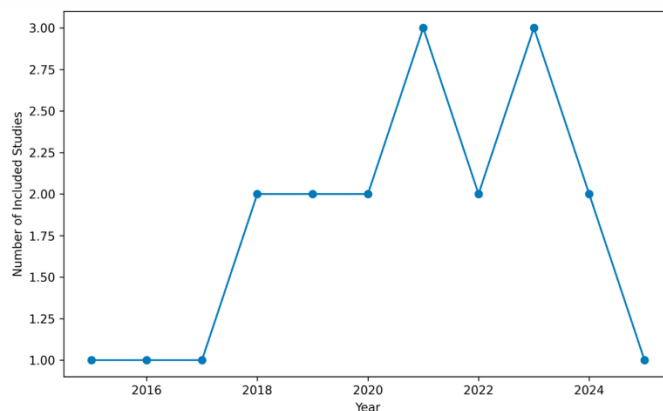
Finally, 20 studies were included in the qualitative synthesis. These publications represented the most relevant evidence regarding artificial intelligence-assisted surgical planning, intraoperative ultrasound, fluorescence-guided surgery, augmented reality, robotic-assisted hepatobiliary surgery, and image-guided navigation systems. This selection process allowed the review to focus on studies with direct clinical and technological relevance to contemporary hepatobiliary surgery.

The included literature reflects the progressive integration of artificial intelligence into surgical workflows, particularly in complex procedures where anatomical precision and intraoperative visualization are essential. Previous studies have emphasized that AI-based tools may improve image interpretation, anatomical segmentation, and surgical planning in hepatobiliary surgery (Bari et al., 2021; Gairola et al., 2024). Similarly, intraoperative navigation technologies, including fluorescence imaging and augmented reality, have been described as important strategies for improving lesion localization and surgical orientation during liver and biliary procedures (Tang et al., 2018; Wang et al., 2021; Ratti et al., 2024).

The selection of evidence also showed that most available publications focus on specialized technologies rather than fully integrated digital surgical platforms. For this reason, the included studies were organized into thematic categories to facilitate interpretation and comparison. These categories included artificial intelligence-assisted preoperative planning, intraoperative radiological navigation, AI-supported ultrasound, fluorescence-guided surgery, augmented reality, robotic surgery, clinical outcomes, and barriers to implementation.

**Figure 2.**

*Distribution of publications by year (2015–2025).*



The temporal distribution of the studies included in this review demonstrates a clear increase in scientific interest regarding artificial intelligence-assisted hepatobiliary surgery and intraoperative radiological navigation during the last decade. As illustrated in Figure 2, relatively few publications addressing these technologies were identified between 2015 and 2019, reflecting the early developmental phase of artificial intelligence applications within hepatobiliary surgical practice.

Beginning in 2020, a progressive increase in research productivity became evident. This growth coincided with major advances in machine learning, deep learning algorithms, computer vision systems, and the widespread adoption of digital technologies across healthcare environments. Improvements in computational power, image processing capabilities, and data availability contributed substantially to the expansion of research activity in this field (Bari et al., 2021).

The most pronounced increase in publication frequency was observed between 2021 and 2024. During this period, numerous studies evaluated the integration of artificial intelligence into preoperative planning, intraoperative imaging, robotic surgery, and navigation-assisted liver resections. Several investigations focused on automated anatomical segmentation, three-dimensional reconstruction, fluorescence-guided surgery, and augmented reality applications, reflecting the rapid technological evolution occurring within hepatobiliary surgery (Bektaş et al., 2024; Ratti et al., 2024).

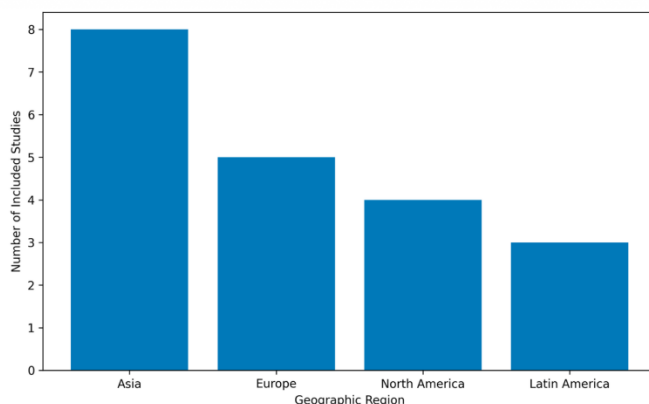
The publication trend also mirrors the growing clinical acceptance of digital surgical technologies. Increasing evidence suggests that artificial intelligence can enhance surgical planning, improve anatomical visualization, facilitate lesion detection, and support intraoperative decision-making processes. Consequently, academic institutions, specialized hepatobiliary centers, and multidisciplinary research groups have devoted greater attention to evaluating the clinical utility of these emerging tools (Gairola et al., 2024).

Another notable observation is the diversification of research topics over time. Earlier studies primarily focused on image-guided surgery and fluorescence imaging, whereas more recent investigations increasingly address integrated technological ecosystems involving artificial intelligence, robotic platforms, augmented reality systems, predictive analytics, and intelligent navigation technologies. This progression reflects a transition from isolated technological innovations toward comprehensive digital surgical environments capable of supporting multiple stages of patient care (Efsthathiou et al., 2025).

The increasing number of publications observed during recent years further suggests that artificial intelligence and navigation-assisted technologies are becoming central research priorities within hepatobiliary surgery. The sustained growth in scientific output indicates ongoing international efforts to improve surgical precision, optimize patient outcomes, and develop next-generation technologies capable of transforming contemporary surgical practice.

### Figure 3.

*Geographic distribution of included studies.*



The geographical distribution of the studies included in this review revealed a heterogeneous pattern of scientific production across different world regions. As illustrated in Figure 3, Asia contributed the highest proportion of publications, followed by Europe, North America, and Latin America. This distribution reflects the current global landscape of technological development and implementation in hepatobiliary surgery.

Asian countries have emerged as major contributors to research involving artificial intelligence, image-guided surgery, robotic-assisted procedures, and advanced intraoperative navigation systems. Several factors may explain this leadership position, including substantial investments in healthcare technology, strong academic research networks, large patient populations, and the rapid adoption of digital innovation within surgical specialties. Countries such as Japan, China, and South Korea have played particularly important roles in advancing fluorescence-guided surgery, three-dimensional reconstruction technologies, and artificial intelligence-assisted surgical planning (Wang et al., 2021; Liu et al., 2023).

Europe represented the second-largest source of scientific evidence. European research groups have significantly contributed to the development of augmented reality systems, robotic surgery applications, intraoperative imaging technologies, and computer-assisted navigation platforms. Many of the studies originating from European institutions have focused on improving surgical precision and integrating multiple digital technologies into comprehensive operative workflows (Ratti et al., 2024; Rompianesi et al., 2023).

North American institutions also demonstrated considerable participation in the advancement of intelligent surgical systems. Research from the United States and Canada has frequently focused on machine learning applications, predictive analytics, surgical robotics, and clinical outcome assessment. These studies have contributed substantially to the validation of emerging technologies and their incorporation into specialized hepatobiliary centers (Bari et al., 2021).

Although Latin America accounted for a smaller proportion of the available literature, the region demonstrated increasing scientific activity related to digital transformation in surgery. Publications from Mexico, Colombia, Ecuador, and other Latin American countries indicate growing interest in advanced imaging technologies, minimally invasive procedures, surgical education, and the implementation of innovative healthcare solutions. This trend suggests an expanding regional commitment to technological modernization despite existing economic and infrastructural challenges.

The observed geographical distribution also reflects disparities in access to advanced technological resources. High-income countries generally possess greater availability of robotic platforms, artificial intelligence infrastructure, high-resolution imaging systems, and specialized training programs. In contrast, resource limitations may influence the pace of adoption in developing regions. Nevertheless, the increasing presence of Latin American contributions suggests that these technologies are progressively becoming more accessible and relevant across diverse healthcare environments.

Another important finding is the growing international collaboration observed among institutions from different regions. Multicenter studies, consensus guidelines, and collaborative research initiatives have facilitated the dissemination of knowledge and accelerated technological development. Such cooperation is likely to play an increasingly important role in future advances within hepatobiliary surgery.

**Figure 4.**

*Main AI technologies identified.*

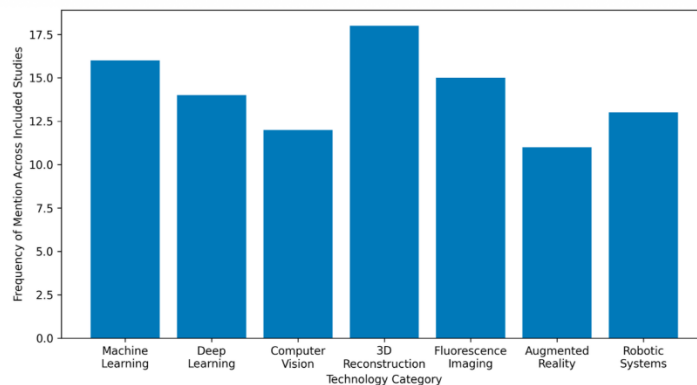


Figure 4 summarizes the principal artificial intelligence-based and digital technologies identified throughout the literature included in this review. The analysis revealed that three-dimensional anatomical reconstruction represented the most frequently reported technological application, followed by machine learning, fluorescence-guided imaging, deep learning algorithms, robotic surgical systems, computer vision technologies, and augmented reality platforms.

Three-dimensional reconstruction emerged as a dominant component of contemporary hepatobiliary surgery due to its critical role in preoperative planning and intraoperative orientation. Multiple studies emphasized the importance of converting conventional computed tomography and magnetic resonance imaging data into patient-specific three-dimensional models capable of accurately representing hepatic vascular anatomy, biliary structures, tumor location, and potential resection planes (Tang et al., 2018; Rompianesi et al., 2023). These technologies allow surgeons to perform virtual surgical simulations and anticipate anatomical challenges before entering the operating room.

Machine learning and deep learning technologies were also frequently reported. These artificial intelligence models have demonstrated significant potential for automated image interpretation, lesion detection, anatomical segmentation, risk stratification, and prediction of postoperative outcomes. Several investigations suggested that machine learning algorithms can process large volumes of radiological and clinical data more efficiently than traditional analytical approaches, thereby supporting precision surgical planning and individualized treatment strategies (Bari et al., 2021; Gairola et al., 2024).

Fluorescence-guided imaging constituted another major technological category identified within the reviewed literature. The widespread adoption of indocyanine green fluorescence imaging has enhanced the ability of surgeons to visualize tumors, biliary anatomy, vascular structures, and hepatic segments during operative procedures. International consensus recommendations increasingly support the incorporation of fluorescence-guided surgery into hepatobiliary practice due to its potential to improve lesion identification and anatomical orientation (Wang et al., 2021).

Computer vision systems represented a rapidly expanding field within artificial intelligence-assisted surgery. These technologies enable automated recognition of anatomical landmarks, interpretation of intraoperative imaging, and real-time analysis of surgical scenes. Advances in computer vision are particularly relevant for the development of intelligent navigation platforms capable of assisting surgeons during complex hepatobiliary procedures (Barash et al., 2022).

Robotic-assisted surgical systems also occupied a prominent position among the identified technologies. The literature demonstrated increasing integration of artificial intelligence with robotic platforms, allowing enhanced visualization, improved instrument control, advanced navigation capabilities, and greater procedural precision. Current evidence suggests that robotic surgery provides an ideal environment for incorporating intelligent digital technologies into clinical practice (Liu et al., 2023).

Although augmented reality was reported less frequently than other technologies, its clinical relevance continues to expand. Augmented reality systems enable the projection of virtual anatomical information directly onto the operative field, improving spatial orientation and facilitating intraoperative decision-making. Several recent studies have suggested that future integration of augmented reality with artificial intelligence and real-time imaging may significantly enhance surgical navigation capabilities (Ratti et al., 2024).

An important observation arising from this analysis is that these technologies rarely function independently. Instead, the most advanced surgical systems increasingly combine multiple digital tools into integrated technological ecosystems. Artificial intelligence algorithms frequently interact with three-dimensional reconstruction platforms, fluorescence imaging systems, navigation software, and robotic interfaces to provide comprehensive support throughout the surgical process.

#### Figure 5.

*Clinical applications of AI in hepatobiliary surgery.*

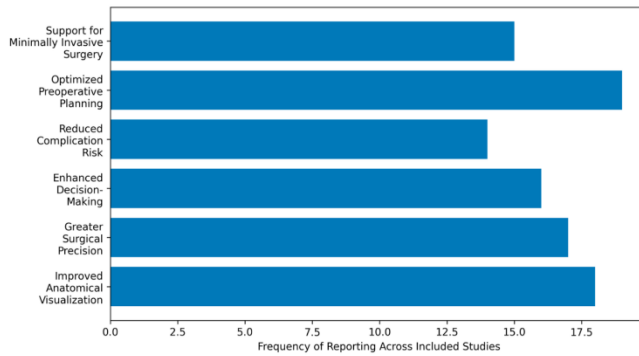


Figure 5 summarizes the principal benefits reported across the studies included in this review regarding the implementation of artificial intelligence-assisted technologies and intraoperative navigation systems in hepatobiliary surgery. The analysis demonstrated that optimized preoperative planning, improved anatomical visualization, enhanced surgical precision, improved clinical decision-making, support for minimally invasive procedures, and reduction of perioperative risks were among the most frequently described advantages.

Optimized preoperative planning emerged as the most consistently reported benefit. Multiple investigations highlighted the capacity of artificial intelligence algorithms and three-dimensional reconstruction technologies to generate patient-specific anatomical models, allowing surgeons to evaluate vascular relationships, tumor location, liver volume distribution, and potential resection strategies before surgery (Tang et al., 2018; Gairola et al., 2024). This capability facilitates more individualized operative planning and may contribute to safer surgical execution.

Improved anatomical visualization represented another major finding identified throughout the literature. Traditional imaging modalities often require surgeons to mentally reconstruct complex anatomical relationships from two-dimensional images. In contrast, advanced visualization technologies—including three-dimensional reconstruction, fluorescence-guided imaging, augmented reality systems, and intraoperative navigation platforms—provide a more comprehensive understanding of hepatic anatomy and lesion localization (Wang et al., 2021; Rompianesi et al., 2023). Enhanced visualization is particularly valuable during major liver resections where preservation of critical vascular and biliary structures is essential.

Greater surgical precision was also frequently reported. Studies evaluating image-guided procedures demonstrated that intelligent navigation systems can improve identification of resection margins, facilitate anatomical segmentectomy, and support accurate localization of hepatic lesions. Such improvements may contribute to more effective tumor removal while preserving functional liver tissue, an important consideration in oncological surgery (Ratti et al., 2024).

The reviewed literature additionally emphasized the role of artificial intelligence in enhancing intraoperative decision-making. Machine learning algorithms, computer vision systems, and predictive models can assist surgeons by analyzing imaging data, identifying anatomical structures, and providing information that supports real-time clinical judgment. Although these technologies do not replace surgical expertise, they increasingly function as complementary tools that enhance procedural awareness and reduce uncertainty during complex interventions (Barash et al., 2022; Bektaş et al., 2024).

Support for minimally invasive and robotic-assisted surgery represented another significant advantage. Laparoscopic and robotic procedures inherently limit tactile feedback compared with conventional open surgery. Consequently, digital navigation systems, fluorescence imaging, and intelligent visualization platforms provide critical supplementary information that helps compensate for these limitations. The integration of artificial intelligence into robotic environments has further expanded the capabilities of minimally invasive hepatobiliary surgery by improving navigation, orientation, and procedural control (Liu et al., 2023).

Reduction of complication risk was also commonly described among the included studies. Improved anatomical recognition, more accurate surgical planning, and enhanced intraoperative guidance have been associated with lower rates of vascular injury, bile duct damage, excessive blood loss, and incomplete resections. Although long-term evidence remains limited in some areas, available findings suggest that artificial intelligence-assisted surgical technologies may contribute to safer operative performance and improved patient outcomes (Bari et al., 2021).

An important observation from the reviewed literature is that the reported benefits are highly interconnected. Improvements in visualization frequently enhance surgical precision; enhanced planning supports safer decision-making; and more accurate navigation contributes to reduced complication rates. Therefore, the overall value of artificial intelligence and navigation technologies appears to arise not from a single isolated function but from the integration of multiple complementary capabilities throughout the surgical process.

## DISCUSIÓN

The findings of this review demonstrate that artificial intelligence (AI) and intraoperative radiological navigation technologies are rapidly transforming the landscape of hepatobiliary surgery. The analyzed evidence suggests that these innovations are progressively moving beyond experimental applications and becoming integral components of contemporary surgical practice. The increasing number of publications identified during the last decade reflects a growing international interest in utilizing intelligent systems to address the technical challenges traditionally associated with liver and biliary surgery.

One of the most significant observations emerging from this review is the central role of artificial intelligence in improving preoperative planning. The reviewed studies consistently highlighted the value of machine learning algorithms, deep learning models, and three-dimensional reconstruction technologies for enhancing anatomical understanding and surgical preparation. Given the complexity of hepatic vascular and biliary anatomy, accurate preoperative visualization is essential for reducing operative uncertainty and optimizing surgical strategies. The ability of AI systems to automatically segment anatomical structures and generate patient-specific virtual models represents a substantial advancement compared with conventional imaging interpretation methods (Bari et al., 2021; Gairola et al., 2024).

The results also indicate that intraoperative radiological navigation has become increasingly important in achieving greater surgical precision. Traditional hepatobiliary procedures often require surgeons to rely heavily on anatomical experience and intraoperative judgment. However, navigation systems integrating computed tomography, magnetic resonance imaging, intraoperative ultrasound, fluorescence imaging, and augmented reality provide real-time anatomical information that may significantly improve orientation during complex interventions. This technological support appears particularly valuable in minimally invasive and robotic-assisted procedures, where tactile feedback is inherently limited (Tang et al., 2018; Rompianesi et al., 2023).

Another important finding concerns the growing role of fluorescence-guided surgery. The widespread adoption of indocyanine green fluorescence imaging has introduced new possibilities for intraoperative visualization of tumors, vascular structures, biliary anatomy, and hepatic segments. Several studies included in this review suggest that

fluorescence-guided techniques improve lesion localization and facilitate more accurate identification of critical anatomical landmarks (Wang et al., 2021). These observations support the concept that advanced imaging technologies can contribute to safer and more precise hepatobiliary procedures.

The integration of artificial intelligence with intraoperative ultrasound represents another promising development identified in the literature. Intraoperative ultrasound has long been considered a fundamental tool in liver surgery; however, its effectiveness remains highly dependent on operator expertise. Recent investigations indicate that AI-assisted ultrasound systems may improve lesion detection and anatomical recognition by reducing observer variability and supporting real-time image interpretation (Bektaş et al., 2024; Barash et al., 2022). Such advances may enhance the accessibility and consistency of intraoperative imaging, particularly among less experienced surgeons.

A notable trend identified throughout the reviewed studies is the transition from isolated technological innovations toward integrated digital surgical ecosystems. Earlier research frequently focused on individual technologies such as fluorescence imaging or three-dimensional reconstruction. In contrast, contemporary investigations increasingly evaluate the combination of multiple digital tools within unified surgical platforms. The convergence of artificial intelligence, computer vision, augmented reality, intraoperative navigation, and robotic systems reflects the emergence of a precision-surgery paradigm designed to optimize every stage of the surgical process.

Robotic-assisted surgery deserves particular attention within this context. The reviewed evidence suggests that robotic platforms provide an ideal environment for the implementation of intelligent technologies due to their advanced visualization capabilities, instrument precision, and digital architecture. Although current robotic systems remain predominantly surgeon-controlled, ongoing developments in artificial intelligence may eventually facilitate semi-autonomous functionalities capable of enhancing procedural safety and efficiency (Liu et al., 2023). Nevertheless, the ethical and regulatory implications of increasing machine involvement in surgical decision-making warrant careful consideration.

Despite the encouraging findings identified throughout this review, several limitations continue to restrict the widespread adoption of artificial intelligence-assisted hepatobiliary surgery. One of the most frequently reported barriers involves the high economic cost associated with acquiring and maintaining advanced technological infrastructure. Robotic platforms, navigation systems, augmented reality equipment, and specialized imaging technologies require substantial institutional investment, which may limit accessibility in resource-constrained healthcare environments.

Another challenge concerns the lack of standardized validation protocols for many artificial intelligence applications. Although numerous studies report favorable outcomes, methodological heterogeneity remains considerable. Variations in study design, sample size, algorithm development, performance metrics, and outcome assessment complicate direct comparison among investigations. Consequently, large-scale prospective studies and multicenter clinical trials remain necessary to establish stronger evidence regarding effectiveness, safety, and cost-benefit relationships.

Data quality also represents a critical consideration. Artificial intelligence systems are highly dependent on the quality, diversity, and representativeness of the datasets used during training and validation. Biases within training data may influence algorithm performance and potentially affect clinical decision-making. Therefore, future research should prioritize the development of robust, transparent, and externally validated models capable of maintaining reliability across diverse patient populations and healthcare settings.

The findings additionally highlight important disparities in global technological implementation. Most published evidence originates from high-income countries possessing advanced healthcare infrastructure and specialized hepatobiliary centers. Consequently, questions remain regarding the feasibility of widespread adoption in low- and middle-income regions. Nevertheless, the growing participation of Latin American countries, including Mexico, Colombia, and Ecuador, demonstrates increasing regional engagement with surgical innovation. Expanding collaborative research networks and educational initiatives may help reduce existing disparities and promote more equitable access to emerging technologies.

From an educational perspective, the incorporation of artificial intelligence into surgical training may represent one of the most impactful future developments. Three-dimensional simulation, virtual reality environments, intelligent

navigation systems, and augmented reality platforms provide opportunities to improve anatomical learning and procedural rehearsal. These technologies may facilitate competency acquisition while reducing dependence on traditional apprenticeship models, thereby contributing to safer and more efficient surgical education.

Several limitations of the present review should also be acknowledged. First, the rapidly evolving nature of artificial intelligence research means that new evidence continues to emerge at an accelerated pace. Second, some included studies involved relatively small sample sizes or preliminary technological evaluations. Third, heterogeneity among methodologies limited direct quantitative comparison across investigations. Nevertheless, the broad scope of the literature analyzed provides a comprehensive overview of current trends and developments within the field.

## CONCLUSION

The present review demonstrates that artificial intelligence-assisted technologies and intraoperative radiological navigation systems are significantly reshaping the field of hepatobiliary surgery. The integration of machine learning, deep learning, computer vision, three-dimensional reconstruction, fluorescence-guided imaging, augmented reality, and robotic-assisted platforms has expanded the possibilities for achieving greater surgical precision, improved anatomical visualization, and more informed intraoperative decision-making.

The analyzed evidence indicates that artificial intelligence contributes substantially to preoperative planning by facilitating automated anatomical segmentation, patient-specific surgical simulation, and predictive risk assessment. These capabilities enable a more individualized approach to surgical management and support the principles of precision surgery. Likewise, intraoperative navigation technologies provide surgeons with enhanced spatial orientation and real-time anatomical information, which may improve operative performance and reduce technical uncertainty during complex hepatobiliary procedures.

Fluorescence-guided surgery, AI-assisted ultrasound, augmented reality systems, and robotic-assisted interventions emerged as particularly promising applications. Collectively, these technologies enhance lesion detection, improve identification of critical vascular and biliary structures, and support the execution of safer and more accurate resections. The convergence of these innovations is gradually establishing a new digital surgical ecosystem in which advanced computational tools function as complementary extensions of surgical expertise.

Despite the substantial progress reported in the literature, important challenges remain. High implementation costs, infrastructure requirements, limited accessibility, regulatory considerations, data quality concerns, and the need for external validation continue to represent barriers to widespread adoption. Furthermore, the heterogeneity of existing studies highlights the necessity for additional multicenter prospective investigations capable of generating higher levels of evidence regarding long-term effectiveness, safety, and cost-effectiveness.

The findings also reveal growing international interest in the application of artificial intelligence within hepatobiliary surgery. Although most technological development has originated from Asia, Europe, and North America, increasing participation from Latin American countries—including Mexico, Colombia, and Ecuador—suggests expanding regional engagement in innovation, research, and surgical modernization. Continued international collaboration may facilitate broader dissemination of knowledge and accelerate equitable access to advanced surgical technologies.

From an educational perspective, the incorporation of artificial intelligence, virtual simulation, advanced imaging, and navigation systems offers valuable opportunities for improving surgical training and competency development. These technologies may enhance anatomical understanding, procedural rehearsal, and clinical decision-making while supporting safer learning environments for future surgeons.

In conclusion, artificial intelligence-assisted hepatobiliary surgery and intraoperative radiological navigation represent transformative advances in modern surgical practice. Current evidence suggests that these technologies have the potential to improve surgical planning, increase procedural precision, enhance patient safety, and optimize clinical outcomes. As technological capabilities continue to evolve, their integration into routine hepatobiliary surgery is expected to become increasingly important, contributing to the development of a more precise, personalized, and technologically advanced model of surgical care.

## REFERENCIAS

- Barash, Y., Klang, E., Lux, A., Konen, E., Horesh, N., Pery, R., Zilka, N., Eshkenazy, R., Nachmany, I., & Pencovich, N. (2022). Artificial intelligence for identification of focal lesions in intraoperative liver ultrasonography. *Langenbeck's Archives of Surgery*, 407(8), 3553–3560. <https://doi.org/10.1007/s00423-022-02674-7>
- Bari, H., et al. (2021). Role of artificial intelligence in hepatobiliary and pancreatic surgery. *World Journal of Gastrointestinal Surgery*, 13(1), 7–18.
- Bektaş, M., Chia, C. M., Burchell, G. L., Daams, F., Bonjer, H. J., & van der Peet, D. L. (2024). Artificial intelligence-aided ultrasound imaging in hepatopancreatobiliary surgery: Where are we now? *Surgical Endoscopy*, 38, 4869–4879. <https://doi.org/10.1007/s00464-024-11130-0>
- Domínguez-Rosado, I., et al. (2020). Fellows' perspective of hepatopancreatobiliary training in Latin America. *HPB*, 22(2), 257–263.
- Efsthathiou, A., et al. (2025). Artificial intelligence and digital tools across the hepato-pancreato-biliary surgical pathway. *Journal of Clinical Medicine*.
- Gairola, S., et al. (2024). Artificial intelligence in perioperative planning and decision-making in hepatobiliary surgery. *Journal of Clinical Medicine*, 13.
- Husarova, T., et al. (2023). Intraoperative imaging in hepatopancreatobiliary surgery. *Cancers*, 15(14), 3748.
- Liu, R., et al. (2023). International experts consensus guidelines on robotic liver resection. *Hepatobiliary Surgery and Nutrition*, 12(6), 874–896.
- Ma, Y., et al. (2025). Intraoperative navigation system for liver resection based on edge-AI and multimodal AI. *Surgical Endoscopy*.
- Majlesara, A., Golriz, M., Hafezi, M., Saffari, A., Stenau, E., Maier-Hein, L., Müller-Stich, B. P., Mehrabi, A., & Ghamarnejad, O. (2017). Indocyanine green fluorescence imaging in hepatobiliary surgery. *Photodiagnosis and Photodynamic Therapy*, 17, 208–215.
- Martínez-Mier, G., et al. (2022). Hepato-pancreato-biliary surgery in Mexico and Latin America during the COVID-19 pandemic. *Cirugía y Cirujanos*, 90(5), 602–608.
- Potharazu, A. V., et al. (2023). Indocyanine green fluorescence in robotic hepatobiliary surgery: A systematic review. *International Journal of Medical Robotics and Computer Assisted Surgery*, 19(2), e2485. <https://doi.org/10.1002/rcs.2485>
- Ratti, F., Serenari, M., Corallino, D., & Aldrighetti, L. (2024). Augmented reality improving intraoperative navigation in minimally invasive liver surgery: An interplay between 3D reconstruction and indocyanine green. *Updates in Surgery*, 76(7), 2701–2708. <https://doi.org/10.1007/s13304-024-01857-9>
- Rompianesi, G., Pegoraro, F., Ramaci, L., Ceresa, C. D. L., Montalti, R., & Troisi, R. I. (2023). Preoperative planning and intraoperative real-time navigation with indocyanine green fluorescence in robotic liver surgery. *Langenbeck's Archives of Surgery*, 408, 292. <https://doi.org/10.1007/s00423-023-03024-x>
- Sutton, P. A., et al. (2023). Fluorescence-guided surgery: Comprehensive review. *BJS Open*, 7(3), zrad049.
- Tang, R., Ma, L. F., Rong, Z. X., Li, M. D., Zeng, J. P., Wang, X. D., & Liao, H. E. (2018). Augmented reality technology for preoperative planning and intraoperative navigation during hepatobiliary surgery: A review of current methods. *Hepatobiliary & Pancreatic Diseases International*, 17(2), 101–112.
- Verbeek, F. P. R., van der Vorst, J. R., Schaafsma, B. E., Swijnenburg, R. J., Gaarenstroom, K. N., Elzevier, H. W., van de Velde, C. J. H., Frangioni, J. V., Vahrmeijer, A. L., & Hutteman, M. (2012). Image-guided hepatopancreatobiliary surgery using near-infrared fluorescent light. *Journal of Hepato-Biliary-Pancreatic Sciences*, 19(6), 626–637. <https://doi.org/10.1007/s00534-012-0534-6>
- Wang, X., Teh, C. S. C., Ishizawa, T., Aoki, T., Cavallucci, D., Lee, S. Y., Panganiban, K. M., Perini, M. V., Shah, S. R., Wang, H., Xu, Y., Suh, K. S., & Kokudo, N. (2021). Consensus guidelines for the use of fluorescence imaging in hepatobiliary surgery. *Annals of Surgery*, 274(1), 97–106. <https://doi.org/10.1097/SLA.0000000000004718>
- Zhang, W., et al. (2021). Augmented reality navigation for stereoscopic laparoscopic anatomical hepatectomy of primary liver cancer. *Surgical Endoscopy*.

- Zhang, W., et al. (2021). A narrative review of near-infrared fluorescence imaging in hepatectomy for hepatocellular carcinoma. *Translational Cancer Research*, 10(2), 1061–1073.