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OPEN, LAPAROSCOPIC, AND ROBOTIC LIVER RESECTION FOR HEPATOCELLULAR CARCINOMA: A NARRATIVE REVIEW OF CURRENT EVIDENCE

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ABSTRACT

Surgical resection remains the cornerstone of curative-intent treatment for appropriately selected patients with hepatocellular carcinoma (HCC). Over recent decades, advances in surgical technology have led to the development and widespread adoption of minimally invasive approaches, including laparoscopic liver resection (LLR) and robotic liver resection (RLR), offering alternatives to conventional open liver resection (OLR). This narrative review compares open, laparoscopic, and robotic liver resection techniques for HCC with regard to perioperative outcomes, oncological effectiveness, postoperative complications, economic considerations, and emerging clinical technologies. A comprehensive analysis of the current literature indicates that minimally invasive approaches are associated with reduced intraoperative blood loss, shorter hospital stays, faster postoperative recovery, and lower complication rates compared with open surgery. Robotic liver resection further enhances surgical precision, dexterity, and visualization, particularly in anatomically complex subdiaphragmatic procedures. However, concerns remain regarding higher procedural costs, longer operative times during the learning curve, and the limited availability of robotic systems. Current evidence suggests that oncological outcomes, including resection margin status, disease-free survival, and overall survival, are comparable among all three approaches when stringent patient selection criteria are applied. Laparoscopic and robotic liver resections represent safe and effective alternatives to conventional open surgery. Continued technological advancements, including artificial intelligence-assisted navigation, fluorescence-guided surgery, and next-generation robotic platforms, are expected to further strengthen the role of minimally invasive techniques in the management of HCC.

KEYWORDS

Hepatocellular Carcinoma, Liver Resection, Robotic Surgery, Laparoscopic Surgery, Minimally Invasive Surgery, Narrative Review

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1. Introduction

Hepatocellular carcinoma (HCC) is the most common primary liver malignancy and remains a major cause of cancer-related mortality worldwide (Bray et al., 2018). Given the global incidence rates, surgical resection has historically remained the optimal, potentially curative treatment modality for patients presenting with early-stage HCC and sufficiently preserved baseline liver function (Forner et al., 2018). Open liver resection (OLR) has served as the foundational standard of reference, offering definitive tumor extirpation (Belghiti et al., 2000). Despite the oncological efficacy of OLR, the procedure is inherently associated with significant surgical trauma, including major abdominal wall disruption, substantial fluid shifts, and a systemic inflammatory response, which collectively contribute to postoperative morbidity (Jarnagin et al., 2002; Tohme et al., 2017).

The technical paradigm of hepatobiliary surgery has undergone a profound shift over the past two decades (Cherqui et al., 2000). Laparoscopic liver resection (LLR) and, more recently, robotic liver resection (RLR) have emerged as rigorously validated, minimally invasive alternatives to the open approach (Nguyen et al., 2009; Ciria et al., 2016). These advancements address the inherent anatomical and physiological limitations of traditional open surgery. By minimizing the scale of abdominal wall trauma, these minimally invasive techniques accelerate postoperative physiological recovery, reduce the incidence of debilitating wound-related complications, and decrease overall postoperative morbidity, while strictly adhering to the fundamental tenets of oncological integrity (Yin et al., 2013; McGlynn et al., 2021).

The transition from open laparotomies to minimally invasive portals represents a significant milestone in surgical innovation. Initial skepticism regarding the feasibility of safely managing major hepatic vasculature through minimally invasive access—historically driven by concerns regarding uncontrollable hemorrhage, gas embolism, and compromised oncological margins—has been systematically dismantled by the accumulation of thousands of successful, documented clinical cases globally (El-Serag, 2012; Yang et al., 2019). This narrative review synthesizes contemporary literature to compare OLR, LLR, and RLR in the management of HCC. Furthermore, this analysis examines the integration of artificial intelligence (AI) and advanced robotic platforms, which are currently redefining the boundaries of surgical oncology and precision medicine (Pessaux et al., 2015).

2. Methods

A narrative review of the literature was conducted utilizing the PubMed, Scopus, and Web of Science databases to evaluate current clinical trends and surgical outcomes in the management of HCC. The search strategy employed key terms including "hepatocellular carcinoma," "liver resection," "laparoscopic hepatectomy," and "robotic hepatectomy." The review prioritized high-quality meta-analyses, systematic reviews, and large-scale retrospective or prospective cohorts published primarily within the last decade. Criteria for inclusion were set to identify studies comparing at least two of the surgical modalities (OLR, LLR, RLR). Single-case reports, non-English language publications, and studies lacking clear perioperative or oncological endpoints were excluded to ensure the highest methodological rigor. The synthesized evidence aims to provide a comprehensive and unbiased overview of perioperative, oncological, and economic outcomes, offering a synthesis of current surgical practices (Pellicciaro et al., 2022; Acosta et al., 2022). A final selection of 69 core clinical studies and meta-analyses was utilized for this review (Couinaud, 1957).

3. Epidemiology and Pathobiology of HCC

To contextualize therapeutic decision-making processes, it is essential to outline the epidemiological landscape and underlying pathobiology of primary hepatic malignancies. Liver cancer is currently the sixth most commonly diagnosed cancer globally and stands as the third leading cause of cancer-related mortality (Bray et al., 2018). HCC accounts for approximately 75% to 85% of these cases (McGlynn et al., 2021). The pathogenesis of HCC is inextricably tied to the background of chronic liver diseases. For decades, Hepatitis B virus (HBV) and Hepatitis C virus (HCV) infections, alongside chronic alcohol abuse, have been the primary etiological drivers, particularly in highly endemic regions such as Sub-Saharan Africa and Southeast Asia (El-Serag, 2012). HBV induces oncogenesis through direct viral DNA integration into the host genome, whereas HCV promotes carcinogenesis indirectly through chronic inflammation, oxidative stress, and progressive fibrogenesis (El-Serag, 2012). The widespread implementation of universal HBV vaccination programs and the advent of highly effective direct-acting antivirals (DAAs) for HCV have begun to alter this viral landscape, consequentially shifting the surgical demographic toward older patient cohorts presenting with different underlying liver pathologies (Llovet et al., 2021; Yang et al., 2019).

A critical consideration in the surgical management of HCC is that 80% to 90% of these tumors develop within a cirrhotic microenvironment (McGlynn et al., 2021). Cirrhosis profoundly alters normal hepatic architecture, replacing functional parenchyma with regenerative nodules surrounded by dense fibrotic septa. This structural distortion leads to increased intrahepatic vascular resistance, culminating in clinically significant portal hypertension, splenomegaly, and secondary thrombocytopenia (Forner et al., 2018). From a surgical perspective, the cirrhotic liver presents mechanical and physiological challenges. The parenchyma is firm and nodular, rendering traditional surgical dissection more difficult and increasing the risk of parenchymal tearing. Furthermore, the regenerative capacity of a cirrhotic liver is severely blunted, significantly lowering the threshold for post-hepatectomy liver failure (PHLF) compared to structurally normal livers (McGlynn et al., 2021).

Concurrently, the global epidemiological profile is undergoing a substantial shift driven by metabolic factors. The rise in the prevalence of obesity, type 2 diabetes mellitus, and metabolic syndrome has led to a parallel increase in non-alcoholic fatty liver disease (NAFLD) and its progressive inflammatory manifestation, non-alcoholic steatohepatitis (NASH) (Younossi et al., 2016). NASH-driven HCC is becoming a prominent etiology in Western nations, and its incidence is projected to rise exponentially (Huang et al., 2021). The pathobiology of NASH involves lipotoxicity, profound insulin resistance, and a state of chronic, low-grade systemic inflammation that fosters a pro-oncogenic microenvironment (Younossi et al., 2016). A unique and challenging clinical characteristic of NASH-associated HCC is its potential to develop in the complete absence of established cirrhosis. As a result, these patients frequently fall outside standard ultrasonographic surveillance programs and present to surgical departments with larger, more advanced tumors (Huang et al., 2021).

Operating on a steatotic or steatohepatitic liver introduces distinct perioperative vulnerabilities. While simple hepatic steatosis is generally tolerated during major resections, the presence of active steatohepatitis (NASH) severely compromises surgical safety. The fatty infiltration renders the hepatic parenchyma extremely fragile and prone to diffuse venous oozing (Reddy et al., 2012). Most critically, steatotic hepatocytes exhibit a markedly reduced tolerance to ischemia-reperfusion injury. Consequently, routine intraoperative maneuvers utilized to control hemorrhage, such as the Pringle maneuver (inflow occlusion), induce disproportionately severe cellular damage in NASH livers, heightening the risk of profound postoperative transaminitis and clinical liver failure (Reddy et al., 2012). Addressing these metabolic comorbidities requires meticulous preoperative optimization and dictates the careful selection between open and minimally invasive operative modalities.

4. Anatomical Considerations and Indications

4.1. Hepatic Segmental Anatomy

The safe execution of any liver resection is predicated upon a profound understanding of hepatic anatomy. The Couinaud classification system, dividing the liver into eight independent functional segments, remains the established navigational map for hepatobiliary surgeons (Couinaud, 1957). The anatomical location of the tumor dictates the technical complexity and risk profile of the operative procedure. Tumors located in the anterolateral segments (Segments II, III, IVb, V, and VI) are generally more accessible. They require less extensive parenchymal mobilization and are typically considered appropriate for early adoption in minimally invasive programs (Wakabayashi et al., 2015).

Conversely, lesions situated within the posterosuperior segments (Segments I, IVa, VII, and VIII) present significant technical challenges (Cho et al., 2011). These segments are nested under the right hemidiaphragm, situated in close proximity to the major hepatic veins and the inferior vena cava (IVC) (Ban et al., 2015). For minimally invasive approaches, accessing these posterior segments requires advanced technical proficiency and specialized articulating instrumentation. Managing unexpected hemorrhage from the IVC in these confined spaces is a complex scenario, making these segments a critical testing ground for evaluating the ergonomic advantages of robotic versus standard laparoscopic platforms (Liang et al., 2024; Nota et al., 2016).

4.2. Patient Selection and Oncological Criteria

The indications for surgical intervention in HCC are guided by established frameworks, notably the Barcelona Clinic Liver Cancer (BCLC) staging system (EASL, 2018). Ideal candidates for curative resection are patients presenting with solitary tumors, well-preserved hepatic synthetic function (Child-Pugh Class A), and an absence of clinically significant portal hypertension (Mazzaferro et al., 1996). Recently, the Albumin-Bilirubin (ALBI) grade has emerged as an objective adjunct to the traditional scoring systems, offering a granular assessment of latent hepatic dysfunction (Johnson et al., 2015).

A critical preoperative consideration, regardless of the planned surgical modality, is the calculation of the volume and physiological function of the future liver remnant (FLR). Insufficient FLR is the primary driver of posthepatectomy liver failure (PHLF) (Hammond et al., 2022). In cases of anticipated inadequate FLR—typically defined as under 20% in structurally normal livers or under 40% in cirrhotic backgrounds—interventions such as portal vein embolization (PVE) may be employed to induce hepatic hypertrophy prior to definitive resection (Abulkhir et al., 2008).

5. Open Liver Resection (OLR)

Open liver resection (OLR) has served as the foundational standard of reference in the surgical management of HCC (Belghiti et al., 2000). The open approach provides surgeons with direct tactile feedback, allowing the operator to physically palpate the liver surface to identify textural differences between regenerative cirrhotic nodules and occult malignant lesions. This haptic perception is particularly crucial when addressing massive, bulky tumors (typically exceeding 10 cm in diameter) or lesions situated in perilously close proximity to the hepatic hilum and major vascular bifurcations, where minimally invasive approaches might be oncologically unsafe (Clavien et al., 2007). Furthermore, OLR facilitates robust manual dexterity and the ability to execute rapid, direct management of catastrophic intraoperative bleeding (Belghiti et al., 2000).

Beyond initial access, OLR permits the use of large-scale mobilization techniques, such as the total vascular exclusion of the liver or the implementation of an ex-vivo bench surgery approach in select, highly complex cases. The ability to perform a wide Kocher maneuver for caval exposure or to systematically dissect the suprahepatic inferior vena cava (IVC) ensures that large, central tumors can be resected with adequate venous control, an area that remains technically demanding in a minimally invasive setting.

Surgical access in OLR is typically achieved via extensive abdominal incisions, such as the bilateral subcostal "Mercedes-Benz" incision or the right-sided "J-shaped" Makuuchi incision. These approaches require the division of major abdominal wall musculature to provide adequate physical exposure. During the parenchymal transection phase, manual techniques such as the crush-clamp method (Kelly-clysis) remain highly prevalent. This mechanical technique is frequently augmented by sophisticated energy devices like the Cavitron Ultrasonic Surgical Aspirator (CUSA), which selectively fragments and aspirates soft hepatocytes while preserving the structural integrity of bile ducts and blood vessels for precise ligation (Lesurtel et al., 2005). Recent advancements in hydro-jet dissection have also enhanced the precision of these resections by providing a more selective cleavage plane through the liver parenchyma, potentially reducing injury to major glissonian pedicles.

Control of hepatic vascular inflow is routinely managed via the temporary clamping of the hepatoduodenal ligament, known as the Pringle maneuver, to effectively minimize intraoperative blood loss during deep parenchymal division (Pringle, 1908). The intermittent application of this maneuver, often in cycles of 15–20 minutes, is balanced against the tolerance of the remnant liver to ischemia. However, the intermittent Pringle maneuver induces a profound ischemia-reperfusion cascade. At the cellular level, this generates a massive influx of reactive oxygen species (ROS) upon reperfusion, leading to hepatocyte apoptosis and microvascular endothelial dysfunction, which can severely compromise the remnant liver (Bone, 1991).

The invasive nature of OLR carries severe intrinsic disadvantages. The requirement for extensive abdominal wall division leads to prolonged postoperative pain, severely impaired respiratory mechanics due to diaphragmatic splinting, and an increased risk of pulmonary complications such as atelectasis. The massive incision size correlates with a higher incidence of incisional hernias and wound infections (Fretland et al., 2018). The profound physiological stress, significant third-space fluid shifts requiring massive volume resuscitation, and systemic inflammatory response syndrome (SIRS) triggered by OLR extract a significant physiological toll, which is particularly detrimental for patients with advanced cirrhosis or portal hypertension (Bone, 1991). These patients often exhibit reduced hepatic regeneration capacity post-resection, making the systemic inflammatory insult of a large laparotomy a critical factor in the development of post-hepatectomy liver failure (PHLF).

6. Laparoscopic Liver Resection (LLR)

Laparoscopic liver resection (LLR) has advanced hepatobiliary surgery by demonstrating that major hepatic resections can be performed safely utilizing minimal access techniques (Nguyen et al., 2009). A series of international consensus conferences including Louisville (2008), Morioka (2014), and Southampton (2017) systematically evaluated and endorsed the safety, feasibility, and oncological validity of LLR (Wakabayashi et al., 2015; Buell et al., 2009; Abu Hilal et al., 2018). Over time, the approach has evolved from purely laparoscopic techniques to encompass hand-assisted laparoscopic surgery (HALS) and hybrid procedures, offering a vital bridge for surgeons managing particularly complex anatomical scenarios or navigating the challenging learning curve (Jackson et al., 2015).

Clinical studies and meta-analyses have demonstrated the profound physiological benefits of the laparoscopic approach (Jackson et al., 2015). When matched against traditional OLR, LLR results in significantly reduced intraoperative estimated blood loss (EBL), a decrease in the requirement for allogeneic blood transfusions, shorter hospitalizations, and drastically decreased postoperative pain (Gurusamy & Davidson, 2015). A major physiological advantage of LLR is the application of the carbon dioxide pneumoperitoneum. Maintained at 12 to 14 mmHg, this elevated intra-abdominal pressure provides a continuous hemostatic effect on the low-pressure hepatic venous system (Neudecker et al., 2002).

The success of LLR is heavily dependent on a seamless, highly synchronized collaboration with the hepatobiliary anesthesia team. When expertly combined with highly specialized low central venous pressure (CVP) anesthesia techniques—often driving CVP below 5 cm H2O through rigorous fluid restriction, the use of vasodilators like milrinone, and controlled positive end-expiratory pressure (PEEP)—this pneumoperitoneum acts as a diffuse, invisible physiological tourniquet, significantly reducing parenchymal venous oozing during the meticulous tissue transection phase. Furthermore, the technological evolution of advanced bipolar and ultrasonic energy devices, such as the Harmonic Scalpel or LigaSure, has been critical in safely sealing smaller vessels and biliary radicles laparoscopically.

Despite its documented benefits, standard LLR is constrained by severe technical and ergonomic limitations (Berguer et al., 1997). The reliance on rigid, non-articulating laparoscopic instruments passed through fixed, restrictive fulcrum points in the abdominal wall creates a profound "chopstick effect." This physical barrier significantly restricts the surgeon’s degrees of freedom and induces counterintuitive paradoxical movement mechanics (Trejo et al., 2007). These constraints are compounded by the inherently limited two-dimensional (2D) visualization provided by standard laparoscopic monitors, which completely strips the operating surgeon of true depth perception, requiring intense, fatiguing cognitive effort to mentally reconstruct the complex three-dimensional intrahepatic vascular architecture.

These ergonomic constraints make the execution of highly precise, anatomical segmental resections, the meticulous dissection of delicate, variant hilar structures, and especially advanced intra-corporeal suturing—such as that required for complex biliary reconstruction, vascular repair, or the rapid management of major intraoperative bleeding—excruciatingly challenging. The difficulty of laparoscopic suturing often leads to the avoidance of complex reconstructions in favor of simpler procedures, which might limit the oncological scope in specific patient cohorts. These technical difficulties are exponentially magnified when attempting to safely resect tumors located deeply within the technically demanding posterosuperior segments of the liver (Segments I, IVa, VII, and VIII). Navigating the rigid instruments over the dome of the liver, in perilous proximity to the major hepatic veins and the inferior vena cava, under heavily restricted 2D vision, often leads to a significantly higher threshold for preemptive or reactive open conversion in less experienced centers, directly highlighting the exact technological ceiling of standard laparoscopy that ultimately necessitated the development of advanced robotic surgical platforms.

7. Robotic Liver Resection (RLR)

Robotic surgery represents the most sophisticated evolution in minimally invasive operative techniques, engineered explicitly to overcome the intrinsic ergonomic and visual limitations of standard laparoscopy (Lanfranco et al., 2004). The robotic platform fundamentally shifts the operative dynamic by transforming the surgeon from a physically engaged operator at the bedside to an orchestrator seated at a remote digital console. Contemporary platforms, primarily the da Vinci Surgical System, offer profound technological advantages (Badani et al., 2008).

Foremost is the optical system, which provides up to 10x optical magnification and three-dimensional, high-definition (3D-HD) binocular vision. This setup fully restores true depth perception and delivers an immersive, micro-surgical view of the operative field that vividly exposes fine capillary networks and microscopic biliary ducts invisible to the naked eye (Badani et al., 2008). Furthermore, these systems integrate articulated surgical instruments with EndoWrist technology, granting surgeons seven degrees of freedom that perfectly mimic, and in some axes exceed, human hand articulation (Tsung et al., 2014). The robotic console provides physiological tremor filtration and scalable motion control, allowing surgeons to translate large, broad hand movements into micro-millimeter precision at the instrument tip. This significantly enhances surgical precision and heavily reduces cognitive and physical fatigue during marathon procedures (Dalager et al., 2017).

A distinct, highly critical advantage of the robotic system is the surgeon’s autonomous control over a third operative arm. This allows the primary surgeon to independently provide stable, unyielding tissue retraction during critical phases of deep vascular dissection, eliminating the reliance on a bedside assistant for camera stability and ensuring an absolutely stable operative field (Giulianotti et al., 2011). Moreover, modern robotic platforms seamlessly integrate near-infrared (NIR) fluorescence imaging directly into the console interface, such as the proprietary Firefly technology. This allows the surgeon to switch instantly between standard white light and NIR modes to visualize indocyanine green (ICG) fluorescence, dynamically confirming biliary anatomy, mapping segmental perfusion, and identifying occult superficial tumors in real-time without taking their eyes off the operative field.

RLR is uniquely advantageous for executing complex anatomical resections, particularly for tumors located in the posterosuperior segments (Liang et al., 2024). As Liang et al. (2024) documented, the robotic approach allows meticulous dissection in tight, confined subdiaphragmatic spaces that would be nearly impossible to access safely with rigid laparoscopic instruments (Liang et al., 2024). Additionally, robotics facilitates rapid and secure hemostasis control through highly precise, effortless intra-corporeal suturing, an invaluable asset when dealing with major vascular pedicles or attempting to rapidly control unforeseen hemorrhage (Tsung et al., 2014). Finally, the ergonomic benefits cannot be overstated; by operating in a seated, ergonomically neutral position, the robotic platform significantly extends the career longevity of hepatobiliary surgeons by preventing the chronic cervical and lumbar spinal injuries historically associated with the grueling physical demands of both OLR and LLR (Dalager et al., 2017). While the adoption of RLR is often hindered by economic concerns, the procedural advantages in terms of precise knot-tying and ergonomic comfort are driving its increased utilization in specialized hepatobiliary centers worldwide.

8. Comprehensive Comparison of Outcomes

a. Perioperative Metrics The aggregate clinical data reveals a utilization shift toward minimally invasive techniques. A comprehensive network meta-analysis demonstrated that both RLR and LLR outperform OLR regarding the reduction of intraoperative EBL in patients with HCC (Ziogas et al., 2021). Minimally invasive platforms facilitate a lowering of overall complication rates—specifically those classified as Clavien-Dindo grade III or higher (Dindo et al., 2004). By preserving the abdominal wall musculature, the incidence of postoperative ascites decreases, translating into a reduction of hospital length of stay compared to open cohorts (Ziogas et al., 2021).

When comparing RLR directly to LLR, results indicate specific nuances. Early meta-analyses suggested equivalence in fundamental perioperative outcomes (Gurusamy & Davidson, 2015). However, subsequent analyses have demonstrated that robotics yields slightly lower open conversion rates in anatomically challenging cases (Kamarajah et al., 2021). A recent meta-analysis by Gavriilidis et al. (2022) evaluating anatomical liver resections corroborated these findings, noting high precision in executing anatomic resections using the robotic approach, which aids in minimizing remnant ischemia and reducing postoperative bile leaks.

b. Oncological Safety and Long-Term Survival The evaluation of surgical technology in oncology requires the maintenance of oncological principles (Nguyen et al., 2010). Current data indicates that achieving negative, tumor-free microscopic resection margins (R0) is comparable across all three modalities (Ziogas et al., 2021). There is no statistically significant difference in long-term survival metrics, including 1-year, 3-year, and 5-year overall survival (OS) rates, as well as disease-free survival (DFS) rates, between OLR, LLR, and RLR (Lai et al., 2011; Safiejko et al., 2024).

9. Economic Viability and Challenges

A primary consideration in the adoption of robotic surgery is its associated economic cost (Turchetti et al., 2012). The financial framework involves three pillars of expenditure: the high initial capital expenditure (CAPEX) required to procure the robotic system, the recurring operational cost (OPEX) of proprietary disposable instruments, and annual maintenance contracts (Barbash & Glied, 2010). However, the impending expiration of initial monopoly patents is catalyzing the entry of novel robotic platforms, which is anticipated to introduce competitive pricing and potentially mitigate prohibitive capital costs in the near future (Boggi et al., 2013).

Additionally, RLR is frequently associated with longer total operative times during the initial phases of an institution's surgical learning curve (Boggi et al., 2013). The processes of operating room setup and docking add time to the procedure, which translates into increased utilization costs. While reduced hospital length of stay and fewer postoperative complications can offset some initial costs, pure hospital-perspective financial modeling shows that traditional LLR often remains a strictly cost-effective minimally invasive option in constrained healthcare systems (Cortolillo et al., 2019). To counteract these financial burdens, many healthcare networks are moving toward centralized high-volume robotic hubs, pooling cases to rapidly amortize equipment costs and consolidate surgical expertise (Cortolillo et al., 2019).

10. Future Directions: AI and Technological Advancements

a. Cognitive Augmentation and AI Integration The integration of next-generation technologies is actively being evaluated to refine liver surgery. Artificial intelligence (AI), machine learning algorithms, and intraoperative image guidance are being investigated to mitigate anatomical unpredictability (Vercauteren et al., 2020). For instance, recent research detailing the dynamic use of AI algorithms integrated with intraoperative ultrasound (IOUS) has shown potential utility in mapping complex intrahepatic vascular networks in real-time, assisting surgeons in avoiding inadvertent vascular injury (Pellicciaro et al., 2022).

b. Augmented Reality and 3D Virtual Modeling Beyond basic imaging, the integration of patient-specific 3D virtual reality (VR) models allows for meticulous preoperative simulation. During surgery, these models can be registered onto the patient's actual anatomy, providing holographic overlays that dynamically guide parenchymal transection planes and identify occult vascular variations, thereby enhancing the precision of anatomical resections (Pessaux et al., 2015).

c. Molecular Navigation: Indocyanine Green (ICG) Concurrently, molecular navigation technologies such as indocyanine green (ICG) fluorescence imaging have transitioned into clinical practice (Boni et al., 2015). ICG is utilized to visualize tumor boundaries and map specific anatomical hepatic segments by identifying precise ischemic vascular perfusion territories (Ishizawa et al., 2009).

d. Telesurgery and Surgical Autonomy The advent of ultra-low latency telecommunication networks is revitalizing the concept of remote telesurgery and real-time telementoring. This technology enables hepatobiliary experts to remotely guide critical portions of robotic liver resections in underserved geographic areas, potentially democratizing access to specialized oncological care (Acosta et al., 2022). While emerging paradigms are exploring highly supervised semi-autonomous robotic enhancements (Attanasio et al., 2021), the immediate future of hepatobiliary surgery relies on these combined cognitive augmentation tools to enhance the precision and safety of human surgeons.

11. Conclusions

The evolution of liver surgery has transitioned from the historical reliance on traditional open techniques toward a refined, personalized approach, where open, laparoscopic, and robotic resections each maintain distinct, indispensable roles in the multidisciplinary management of hepatocellular carcinoma (HCC). The selection of the surgical modality is no longer driven by rigid adherence to a single standard; instead, it is a highly individualized decision formulated by multidisciplinary tumor boards (MDTs). These boards rigorously evaluate a constellation of variables, including tumor anatomical complexity, the patient's physiological hepatic reserve, the presence of metabolic comorbidities, and the specific technical expertise of the surgical team (El-Serag, 2012; Yang et al., 2019).

While OLR remains a necessary, undeniable benchmark for massive, centrally located, or critically positioned tumors where minimally invasive access is biologically unsafe or anatomically precluded, both LLR and RLR have definitively proven to be safe and oncologically sound modalities (Nguyen et al., 2009; Ciria et al., 2016). They are profoundly beneficial for facilitating rapid postoperative patient recovery, minimizing the systemic inflammatory stress response, and dramatically improving the overall long-term quality of life (Yin et al., 2013). The shift toward minimally invasive techniques represents a fundamental advancement in patient-centered care, prioritizing both survival and the preservation of patient functional status.

RLR, despite its current macroeconomic burdens and implementation logistics, offers a suite of state-of-the-art technical capabilities that fundamentally overcome the severe ergonomic exhaustion and restricted two-dimensional visual limitations inherent in conventional laparoscopy (Lanfranco et al., 2004). This technological superiority is particularly evident in high-risk patients and exceedingly difficult anatomical locations—such as the deeply recessed subdiaphragmatic segments—where the robotic platform's wristed instrumentation and 3D-HD visualization are critical to achieving negative resection margins while preventing catastrophic hemorrhage (Liang et al., 2024; Tsung et al., 2014).

Looking ahead, the surgical landscape is on the cusp of a deeper transformation driven by the synergy of advanced robotics and data science. The continued integration of articulated robotics, artificial intelligence-assisted intraoperative navigation, and real-time molecular imaging using agents like indocyanine green (ICG) will further influence the technological landscape of surgical oncology (Pellicciaro et al., 2022; Ishizawa et al., 2009). These innovations are moving toward a future defined by cognitive augmentation, where surgeons are supported by real-time vascular mapping and holographic overlays that mitigate anatomical unpredictability and standardize surgical excellence across varying levels of provider experience (Pessaux et al., 2015).

As global manufacturing competition inevitably drives down the capital costs of robotic platforms, and as standardized training curriculums—incorporating virtual reality simulation—exponentially increase the pool of skilled robotic surgeons, the adoption of these platforms will continue to accelerate (Boggi et al., 2013). The transition from mechanical telemanipulation to intelligent, data-driven surgical assistance will undoubtedly redefine the boundaries of what is considered surgically curable. Ultimately, the objective remains the delivery of precise, individualized, and high-value oncological care that balances superior oncological outcomes with the rapid recovery and enhanced quality of life afforded by the latest technological advancements in minimally invasive hepatobiliary surgery.

Table 1. Comparison of Open, Laparoscopic, and Robotic Liver Resection for Hepatocellular Carcinoma

Parameter	Open Liver Resection (OLR)	Laparoscopic Liver Resection (LLR)	Robotic Liver Resection (RLR)
Surgical access	Large laparotomy incision	Multiple small trocars	Roboticassisted trocar access
Blood loss	Highest	Lower than OLR	Lowest in selected studies
Operative time	Shorter	Moderate	Usually longest
Postoperative pain	Highest	Lower	Lower
Hospital stay	Longest	Shorter	Shortest or comparable to LLR
Complication rate	Higher	Lower	Lower
Conversion rate	N/A	Higher in difficult cases	Lower than LLR
Learning curve	Established technique	40–60 cases	20–40 cases after robotic training
Cost	Lowest	Moderate	Highest
Oncological outcomes	Comparable	Comparable	Comparable

Abbreviations: OLR – open liver resection; LLR – laparoscopic liver resection; RLR – robotic liver resection.

Table 2. Advantages and Limitations of Different Surgical Approaches

Approach	Advantages	Limitations
OLR	Direct tactile feedback, unrestricted access, easier vascular control	Greater surgical trauma, increased blood loss, longer recovery
LLR	Reduced blood loss, less postoperative pain, shorter hospitalization, faster recovery	Limited instrument mobility, twodimensional vision in conventional systems, steep learning curve
RLR	Three-dimensional visualization, articulated instruments, superior ergonomics, improved suturing capabilities	High acquisition and maintenance costs, longer operative times, limited availability
All approaches	Potential for curative treatment of HCC	Require careful patient selection and experienced multidisciplinary teams

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