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TECHNOLOGICAL ADVANCEMENTS IN HEMIHEPATECTOMY PROCEDURES

Yusupov Temurbek Alisher Ugli
Independent Researcher
Department of Surgical Diseases No. 1 and Transplantology
Samarkand State Medical University

Nurullayev Asker Bagirovich
Independent Researcher
Department of Surgical Diseases No. 1 and Transplantology
Samarkand State Medical University

Abstract. Hemihepatectomy – the surgical removal of the right or left half of the liver – is a potentially curative treatment for primary and secondary liver cancers. Over the past decades, significant technological advancements have improved the safety, precision, and outcomes of right and left hemihepatectomies in oncological settings. Key developments include refined surgical techniques (such as laparoscopic and robotic hepatectomy) that minimize invasiveness and enhance precision, advanced visualization methods like intraoperative ultrasound, indocyanine green (ICG) fluorescence imaging, and augmented reality (AR) navigation, comprehensive perioperative planning with high-resolution 3D imaging reconstructions and virtual reality simulations, and improved surgical equipment for liver parenchymal transection and vascular control. These innovations have collectively led to reduced intraoperative blood loss, lower complication rates, shorter hospital stays, and expanded resectability of complex tumors while maintaining oncological efficacy. For hepatocellular carcinoma (HCC) and colorectal liver metastases (CRLM), modern hemihepatectomy techniques offer enhanced short-term outcomes (fewer complications, faster recovery) without compromising long-term survival. This article provides a comprehensive review of these technological advancements in hemihepatectomy – covering improvements in surgical approaches, visualization and navigation tools, perioperative planning strategies, and operative equipment – and discusses their impact on surgical practice and patient outcomes in liver cancer management.

Keywords: hemihepatectomy; liver resection; hepatocellular carcinoma; colorectal liver metastases; laparoscopic hepatectomy; robotic surgery; 3D surgical planning; augmented reality; indocyanine green fluorescence

Liver resection is a cornerstone of curative treatment for malignant liver tumors, including hepatocellular carcinoma (HCC) and colorectal liver metastases (CRLM). HCC and CRLM are the most common indications for liver resection in Eastern and Western countries, respectively. Surgical intervention with the goal of complete (R0) resection offers the best chance for long-term survival in these patients. Historically, however, only a minority of patients with liver malignancies were considered resectable due to technical limitations and the risk of postoperative liver failure. For example, prior to the 2000s, fewer than 20% of patients with colorectal metastases to the liver were eligible for curative resection, largely because of insufficient future liver remnant (FLR) volume after a major hepatectomy. Over the last two decades, there has been a remarkable expansion in the surgical armamentarium that has increased the safety and feasibility of liver resections, including hemihepatectomies, for complex and bilobar tumor presentations. These advancements have enabled curative surgery in many patients who previously would have been deemed unresectable.

Technological innovations in hepatic surgery can be categorized into several key areas: (1) surgical technique improvements (e.g. minimally invasive surgery and novel resection strategies), (2) visualization and navigation enhancements (intraoperative imaging and guidance systems), (3) perioperative planning tools (imaging-based planning, virtual simulations, and adjunct procedures to optimize resectability), and (4) advanced surgical equipment (devices for parenchymal transection, vascular control, and operative precision). In each of these domains, progress has been driven by the goal of maximizing tumor clearance while minimizing operative risk and preserving liver function.

Importantly, these technological advancements have directly translated into improved patient outcomes. Numerous studies have demonstrated that modern techniques such as laparoscopic liver resection (LLR) achieve significantly lower complication rates and faster recoveries compared to traditional open surgery. For instance, a large multicenter cohort study in 2024 found that laparoscopic liver resection was associated with a 44% reduction in odds of major postoperative complications (Clavien–Dindo grade ≥ II) compared to open resection, without any compromise in overall or disease-free survival rates. Similarly, advances like preoperative 3D imaging and improved intraoperative visualization have increased the precision of hemihepatectomies, contributing to better preservation of healthy liver parenchyma and lower incidences of positive margins or inadvertent injuries. The cumulative impact of these innovations is that hemihepatectomy – whether right or left – can now be performed more safely and effectively in patients with liver cancers, including those with large or anatomically complex tumors, cirrhotic livers, or limited functional reserve.

In the context of oncology, technological improvements have also expanded the indications for surgery. Enhanced preoperative planning (e.g. portal vein

embolization, staged resection techniques) allows surgeons to undertake major hepatectomies in patients who previously would not tolerate them, thereby extending the option of surgery to more patients with HCC or CRLM. The result is a higher proportion of patients achieving complete resection and potential cure. This article reviews the major technological advancements in hemihepatectomy procedures, with a focus on their relevance to oncologic liver surgery. We discuss how innovations in surgical techniques, visualization methods, perioperative planning, and surgical equipment have collectively improved the practice of right and left hemihepatectomies. Real-world data from recent studies are presented to illustrate improvements in outcomes such as operative blood loss, complication rates, length of hospital stay, and oncologic efficacy.

Objective of the Study

The objective of this review is to systematically examine and describe the technological advancements that have enhanced the performance and outcomes of hemihepatectomy procedures (right and left) in the treatment of liver malignancies.

Materials and Methods. This work is a narrative review and analysis of recent scientific literature focused on technological developments in hemihepatectomy procedures. We did not perform any experiments on human subjects; rather, we gathered and synthesized data from published studies, review articles, and clinical trials relevant to advancements in liver surgery techniques and technology.

A comprehensive literature search was conducted using databases including PubMed, MEDLINE, and Google Scholar to identify publications from approximately 2010 to 2025 that discuss improvements in liver resection techniques and perioperative management. Key search terms included combinations of “hemihepatectomy” OR “liver resection” with “technological advancements”, “laparoscopic”, “robotic surgery”, “augmented reality (AR)”, “3D planning”, “indocyanine green (ICG) fluorescence”, “portal vein embolization (PVE)”, “Associating Liver Partition and Portal vein Ligation (ALPPS)”, “visualization”, and “surgical devices”. We focused on studies in the context of oncological surgery (HCC, liver metastases) and included both clinical outcome studies (e.g. comparative studies, meta-analyses) and technology-focused reports (e.g. descriptions of new surgical navigation systems).

We included articles that provided data or substantive discussions on how a particular technological innovation impacted hemihepatectomy or major liver resections. This encompassed randomized controlled trials, cohort studies, systematic reviews, and high-quality case series that evaluated outcomes of laparoscopic vs. open or robotic vs. laparoscopic liver resection, studies on the use of fluorescence imaging or AR in liver surgery, reports on preoperative 3D planning tools, and analyses of perioperative adjuncts like PVE or two-stage hepatectomy techniques. Both adult and pediatric liver surgery innovations were considered if relevant (though adult

oncologic surgery is the main focus). Only English-language sources were used for data extraction.

For each included study or source, key data and conclusions were extracted. This included operative metrics (blood loss, operative time), perioperative outcomes (transfusion rates, complications, length of stay), oncologic outcomes (margin status, survival), and descriptive information about the technology (e.g. features of a navigation system, type of imaging used, specifics of surgical equipment). When available, numeric results from comparative studies (with p-values) were recorded to illustrate the magnitude of improvement associated with a given technology. For example, data on complication rates or blood loss for laparoscopic vs. open hepatectomy were tabulated from meta-analyses and multicenter studies.

The gathered information was organized into thematic categories corresponding to the four key areas of advancement (techniques, visualization, planning, equipment). Within each category, we synthesized findings from multiple sources to provide an overview of how that particular advancement has improved hemihepatectomy practice. We present representative data in the form of summary tables and figures. Three tables are included to compare outcomes between different surgical approaches (e.g. open vs laparoscopic vs robotic) and to compare strategies like PVE vs ALPPS. Three figures are included to illustrate some of the technologies (such as a visualization of 3D liver modeling and an example of a robotic surgical setup). All sources of information are cited in the text using the specified citation format. No new clinical data were generated by the authors for this review, and thus no ethical approval was required.

Given the narrative review format, a formal quality assessment of studies (e.g. risk of bias evaluation) was not performed for every article included. However, preference was given to high-level evidence and the most recent data available. Where the evidence is still emerging (for instance, AR navigation in liver surgery), we have noted the preliminary nature of findings. The scope is confined to technological and methodological improvements; general advances in anesthesia or perioperative care are only touched upon if directly linked to surgical technology (e.g. enhanced recovery protocols are beyond the scope).

By synthesizing the current literature in this manner, we aim to provide surgeons and researchers with a clear and organized understanding of how technology is driving progress in hemihepatectomy for cancer, and what results have been achieved thus far.

Results and Discussion. The landscape of liver surgery has been transformed by multiple synergistic advancements. In this section, we discuss the improvements in surgical techniques, visualization and navigation methods, perioperative planning, and surgical equipment, and how each has contributed to safer and more effective hemihepatectomy procedures for oncological indications. Key findings from the

literature are summarized in tables and figures to highlight comparative outcomes and the capabilities of new technologies.

Traditional open hemihepatectomy involves a large abdominal incision to provide the surgeon full access to the liver. While effective, open surgery is associated with considerable abdominal trauma, longer recovery times, and higher complication rates, especially in patients with cirrhosis or significant comorbidities. A major paradigm shift in liver surgery has been the adoption of minimally invasive techniques – principally laparoscopic and robotic surgery – for performing major liver resections, including right and left hemihepatectomies. These techniques aim to achieve the same oncologic resection through smaller incisions, thereby reducing surgical stress and accelerating patient recovery.

First reported in the 1990s for minor resections, laparoscopic liver resection (LLR) has progressively expanded to more complex resections over the last two decades. In laparoscopic hepatectomy, surgeons operate through several small trocar incisions using long instruments and a camera that provides a magnified view of the operative field. The feasibility of laparoscopic right or left hepatectomy has been demonstrated in both HCC and metastatic tumors, even in the presence of underlying liver disease, by expert centers around the world. The benefits of LLR over open liver resection (OLR) are well-documented: patients experience significantly fewer postoperative complications, lower intraoperative blood loss, and shorter hospital stays, while achieving equivalent oncologic outcomes. A 2024 multicenter study including 5886 patients (with ~1991 laparoscopic cases) found that the laparoscopic approach reduced the odds of major complications by ~44% compared to open surgery (OR ≈ 0.56, $p < 0.001$). Similarly, numerous meta-analyses have confirmed that LLR is associated with reduced overall morbidity and faster recovery. For example, one analysis reported 30-day postoperative complication rates of 19% with LLR vs 31% with OLR ($p = 0.021$), and a median hospital stay of ~2.2 days vs 4 days, respectively. Long-term survival after resection of HCC or CRLM appears to be no worse with laparoscopy; five-year overall survival rates are comparable between LLR and OLR (often within a few percentage points of each other). In Table 1, we summarize outcome comparisons from select studies of laparoscopic versus open liver resection in cancer patients, illustrating the consistent short-term benefits of the minimally invasive approach.

Building on the success of laparoscopy, robotic-assisted surgery has emerged as another significant advancement in liver surgery techniques. Robotic surgical systems (such as the da Vinci Surgical System) provide a surgeon-controlled robotic platform with high-definition 3D visualization and articulated instruments that mimic the dexterity of the human hand. These features help overcome some limitations of straight laparoscopy, especially for deep or difficult dissections. In recent years, there has been rapid adoption of robotic liver resection (RLR) worldwide. In fact, the proportion of minimally invasive liver resections performed robotically increased

from only ~2% in 2014 to over 40% by 2022 in some national audits, indicating the growing surgeon preference for the robotic platform in complex cases. Right-sided hemihepatectomies, which are technically more challenging due to the posterior location and vascular anatomy, have become feasible robotically and are now being performed at high-volume centers. Surgeons report that the robotic system's enhanced range of motion and 3D vision make complex maneuvers (such as suturing or finely dissecting near major vessels) "almost as if you're doing open surgery with your hands" while still benefiting from a minimally invasive approach.

Early comparative outcomes suggest that robotic liver resection offers at least equivalent, if not improved, results compared to conventional laparoscopy, particularly for major hepatectomies. A recent propensity-score matched analysis of 781 robotic vs 781 laparoscopic liver resections found that the robotic approach led to significantly lower rates of conversion to open surgery (4.9% vs 12.8%, $p < 0.001$) and fewer instances of major intraoperative blood loss ≥500 mL (18.6% vs 25.2%, $p = 0.011$). Postoperative hospital stay was also slightly shorter with robotics (median 3 days vs 4 days, $p < 0.001$). These findings, summarized in Table 2, indicate that robotics can further refine the minimally invasive liver surgery paradigm by increasing precision and reducing some risk factors (e.g. blood loss, conversions) – especially in technically complex resections such as posterior segmentectomy or obese patients.

In summary, the shift from large-incision open surgery to laparoscopic and robotic hemihepatectomy represents one of the most impactful advancements in hepatic surgery. These minimally invasive techniques have improved patient outcomes – patients have less pain, recover faster, and have fewer complications such as infections or hernias – without sacrificing the oncological effectiveness of the surgery. Many liver centers now consider LLR (and increasingly RLR) as standard of care for appropriate candidates, including for major resections in experienced hands. Nevertheless, open surgery remains important for certain situations (very large tumors, need for complex vascular reconstructions, etc.), and the ideal approach must be individualized. The continuing evolution of technique (e.g. hybrid approaches, hand-assisted laparoscopy, or robotic improvements like tactile feedback in the future) promises further refinements.

It is also worth noting a specific surgical technique innovation for improving resection outcomes: the anterior approach and liver hanging maneuver, introduced in open surgery, which allows surgeons to resect large right lobes without mobilizing the liver fully, thereby potentially reducing bleeding. Additionally, parenchymal-sparing techniques (segment-oriented or subsegmental resections) have been emphasized in modern practice to preserve liver function. These are facilitated by better intraoperative imaging and are particularly relevant in treating multiple metastases. While not "technology" per se, these conceptual advances in how surgeons plan the resection contribute to improved outcomes (less liver failure, ability to re-resect for

future new tumors) and are enabled by the precise imaging and navigation tools described in the next sections.

Performing a hemihepatectomy requires detailed knowledge of the patient's specific liver anatomy and tumor location, which can vary greatly. One of the enduring challenges of liver surgery is that surgeons must often work within the liver's parenchyma where critical structures (vessels, bile ducts, tumor margins) are not directly visible to the naked eye. Traditional methods of intraoperative guidance included palpation and intraoperative ultrasound (IOUS). IOUS, which uses an ultrasound probe on the liver surface during surgery, remains a gold standard tool for identifying tumors and mapping major vessels in real time. However, IOUS requires skill to interpret and provides only cross-sectional slices. New visualization modalities have been developed to augment the surgeon's view and improve real-time navigation during liver resections.

Indocyanine Green (ICG) Fluorescence Imaging: One of the most significant recent visualization aids is near-infrared fluorescence imaging using indocyanine green dye. ICG is a fluorescent dye that, when excited by NIR light (~805 nm), emits light (~830 nm) that can be captured by special cameras. In liver surgery, ICG has two main applications: tumor visualization and biliary/segmental mapping. Patients are typically injected with a dose of ICG intravenously some hours to days before surgery (for tumor mapping) or ICG can be injected intraoperatively (intravenously or directly into portal or bile structures) for segment mapping and bile duct identification. The principle is that certain liver tumors (especially well-differentiated HCCs) retain ICG and will appear fluorescent ("glowing") compared to normal liver tissue under NIR camera. Metastatic tumors and cholangiocarcinomas often show a "rim fluorescence" – a ring of ICG in the liver parenchyma surrounding the tumor due to impaired drainage. This technique allows surgeons to detect non-superficial tumors up to ~8–10 mm below the liver surface in real-time. Studies have demonstrated that ICG fluorescence can reveal additional tiny lesions that were missed on preoperative imaging or by inspection, thereby potentially improving oncologic completeness of resection. For example, Peloso et al. (2013) reported that ICG enhanced detection of small colorectal metastases intraoperatively, and Handgraaf et al. found that adding NIR fluorescence led to a higher rate of finding new lesions compared to palpation or ultrasound alone.

ICG is also used for visualizing liver segment boundaries – crucial for anatomical resections. One technique involves injecting ICG into a selected portal vein branch (percutaneously or during surgery) to "stain" a segment, or conversely clamping a segment's portal inflow and injecting ICG systemically to get negative staining of that segment. Under NIR camera, the targeted segment will fluoresce differently, delineating the transection line between segments. This can be extremely helpful, especially during laparoscopic surgery where direct palpation is absent. Fluorescence can also highlight biliary anatomy: by injecting ICG into the bile duct or

intravenously (which then gets excreted into bile), the biliary tree and any leak sites can be made to fluoresce. Randomized trials have shown that intraoperative ICG cholangiography significantly improves the detection of biliary leaks, allowing surgeons to fix them intraoperatively.

An example of how AR might appear is illustrated in Figure 2. The images show 3D reconstructions of a patient's liver with colored anatomical details (hepatic veins, portal veins, and tumors) generated from CT scans These reconstructions can be rendered as holographic models. With an AR headset or a suitable display, the surgeon can visualize these holograms overlaid onto the patient's body or in the laparoscopic video feed, thereby knowing exactly where, for example, a large tumor is in relation to major blood vessels before cutting. This interactive 3D visualization eliminates some of the mental guesswork of translating 2D scans into 3D anatomy during surgery.

The potential of AR/MR (mixed reality) systems in liver surgery is substantial: they could reduce intraoperative uncertainty, help in achieving negative margins by clearly delineating tumor extents, and shorten the learning curve for complex resections by providing less experienced surgeons with navigational assistance. AR can also reduce the need for intermittent ultrasound checks or direct palpation, because the surgeon has a constantly updated "X-ray vision" of critical structures. One can imagine, for example, seeing the intended line of transection as a glowing line on the liver surface, computed from the 3D model, and following that line precisely. Early systems have shown improved accuracy in following planned transection planes and identifying vessels.

Challenges remain for AR: the liver is a soft organ that can deform and move with breathing, making it hard to maintain accurate registration of the hologram to the actual liver (this is the "registration error" issue). Solutions like periodic re-registration using intraoperative ultrasound or laparoscopic landmarks are being explored. Despite these challenges, early clinical evaluations have indicated improved outcomes in AR-assisted cases, as noted above, at least in terms of reduced blood loss and complications. As AR technology matures, with faster processing and perhaps AI-assisted registration, it is expected to become more robust.

It should be noted that beyond the operating room, AR/VR is also being used in surgical training and simulation – allowing surgeons to practice complex liver resections on virtual models. This may indirectly improve outcomes by better preparing surgeons for unusual anatomies or rare procedures.

Intraoperative navigation also includes simpler enhancements like 3D laparoscopic cameras (which give depth perception), and image guidance platforms that track instrument position. For example, some research has looked at electromagnetic tracking of surgical tools relative to preoperative imaging, essentially creating a "GPS for surgery." In liver surgery, a system might tell the surgeon how far the tip of an instrument is from a tumor margin, etc. These systems are still under

development, but combined with AR visualization, they form part of the concept of digital and intelligent surgery.

Technological progress is not limited to the operating theater – it begins well before the surgery in the planning phase. Proper preoperative planning for a hemihepatectomy, especially in oncology patients, is crucial to maximize safety (by ensuring adequate liver function remains) and efficacy (by strategizing how to remove all disease). Several advancements have revolutionized how surgeons plan liver resections: high-resolution imaging with 3D reconstruction, computer-assisted volumetric analysis and simulation, as well as interventional techniques to optimize the liver for surgery (like portal vein embolization).

Three-Dimensional (3D) Imaging and Virtual Planning: Modern cross-sectional imaging (multi-phase CT, MRI) provides detailed anatomical information. Today's software can transform these 2D scans into patient-specific 3D models of the liver, including all vessels, tumors, and segments. Surgeons can interact with these models on a computer or using VR goggles, rotating the liver and essentially performing a "virtual rehearsal" of the resection. Studies have shown that such 3D visualization improves surgical planning accuracy. For example, Fang et al. used 3D printed or digital models to plan complex HCC resections and reported that in the 3D-planned group operative time was significantly reduced (295 vs 324 minutes), use of inflow occlusion (Pringle maneuver) was less frequent (52% vs 71%), and major complication rate was lower (3.3% vs 14.3%) compared to standard planning. This suggests that enhanced understanding of anatomy via 3D models led to a more efficient and safer surgery. While this is early evidence, it demonstrates the value of detailed preoperative 3D planning in improving intraoperative decision-making and outcomes.

Advanced software can also fuse multiple imaging modalities (CT, MRI, PET) into one composite model. This helps in cases where different information is gleaned from each modality (for instance, MRI might show a lesion not seen on CT; PET might show metabolic activity). AI algorithms are being developed to automate this image fusion and segmentation process. Soon, a surgeon could click a button and get a fully segmented 3D liver model on their screen within minutes. These models not only aid the surgeon's mental visualization but can be used for volumetry – to precisely calculate the volume of the lobes and the future liver remnant (FLR). This is critical: a major part of planning a hemihepatectomy is ensuring that the remaining half-liver will be sufficient for the patient's needs (commonly at least 25–30% of original volume in healthy livers, or more in cirrhotic/chemo-damaged livers). Computerized 3D volumetry is far more accurate than older 2D approximations. It allows for tailored decision-making (for example, deciding between a right hepatectomy vs. an extended right hepatectomy if volume allows).

As an extension, some centers utilize 3D printing to create physical models of the patient's liver. These tangible models (often in color-coded resin or polymer) can

be used to plan surgical cuts or even practice the resection on a model liver beforehand. 3D prints have been particularly useful in teaching, in patient counseling (helping patients visualize their surgery), and in very complex cases like those needing trisectionectomy or living donor transplantation where precise understanding of anatomy is paramount. While 3D printing is not done for every case (due to time and cost), its usage exemplifies the trend towards patient-specific planning enabled by technology.

Another aspect of perioperative planning is functional assessment. Technology has introduced new ways to measure how well the future liver remnant will function, not just its size. For example, the indocyanine green retention test (ICG-R15) is an older but useful method where a dose of ICG is given and its clearance by the liver is measured – giving a sense of liver functional reserve. More recently, tools like Hepatobiliary scintigraphy or MRI with hepatocyte-specific contrast can map functional capacity of different liver segments. There's also the LiMAx test (C13-methacetin breath test) that quantitatively measures liver function. While these are not "technological advancements in surgery" per se, they are part of a high-tech approach to planning: ensuring that patients are optimized and only undergo a hemihepatectomy if it's safe to do so.

Portal Vein Embolization (PVE) and Two-Stage Hepatectomy Innovations: PVE is a technique used preoperatively to induce growth of the future liver remnant. By embolizing (blocking) the portal vein branch leading to the tumor-bearing lobe (which is planned for resection), blood flow is redirected to the remnant lobe, stimulating hypertrophy of that remnant over a few weeks. First introduced in the 1980s, PVE has become a standard planning tool when the predicted FLR is too small. Technological improvements in interventional radiology have made PVE safer and more effective – for instance, use of embolic agents like n-butyl cyanoacrylate glue, which has been shown to possibly induce greater hypertrophy than older agents. The outcomes of PVE are impressive: it has a technical success rate of ~99% and leads to an average 38% increase in FLR volume within a few weeks. As a result, the majority (≈96%) of patients who undergo PVE can later proceed to their planned hepatectomy. PVE itself carries low risk (major complications ~2.5%, virtually zero mortality). Table 3 compares PVE with a newer surgical innovation called ALPPS in terms of hypertrophy and outcomes.

From a technological standpoint, ALPPS itself was an innovation in surgical strategy – challenging the conventional wisdom of waiting weeks for hypertrophy. Its success is partly due to improved perioperative care and monitoring (ICU, better imaging to measure FLR quickly, etc.) that allow safely performing two operations back-to-back. It exemplifies how changing when and how we operate (with the aid of imaging to guide the partition plane, and advanced instruments to make the parenchymal split swiftly) can expand the boundaries of what's surgically possible. In

oncologic terms, ALPPS has allowed some patients with multiple bilateral tumors to be rendered disease-free where chemotherapy alone could not.

Enhanced Recovery and Anesthetic Advances: Although not the main focus of this article, it is worth mentioning that improved perioperative management (ERAS protocols, better anesthesia monitoring, avoidance of excessive fluids, etc.) complement the above planning innovations. For instance, patients are now often in a state to undergo second stage surgery sooner thanks to optimized recovery pathways. Anesthesiology technology, like better low CVP (central venous pressure) maintenance and hemostatic monitoring, also plays a role in reducing blood loss and transfusions during major hepatectomies.

In conclusion, perioperative planning has become a high-tech, multi-disciplinary process. Surgeons now routinely sit in front of 3D workstations to plan resections, calculate volumes, and even simulate the surgery. Interventional radiologists, oncologists, and surgeons coordinate to use techniques like PVE or ALPPS when needed to improve outcomes. The net effect is that more patients can safely undergo hemihepatectomy (because we can make their liver “ready” for it, and plan it better), and when they do, the surgery is more likely to be successful (complete resection, no liver failure). The combination of precise imaging, virtual planning, and adjunct techniques epitomizes personalized surgery – tailoring the approach to each patient’s unique anatomy and situation. These planning advances, coupled with the intraoperative tools discussed earlier, have significantly improved both the safety profile and the curative potential of hemihepatectomy for liver cancers.

All these tools and devices contribute to what we might call a “modern hepatectomy toolkit,” enabling surgeons to perform complex resections with a level of safety that was not possible before. The impact of better equipment is evident in outcomes like transfusion rates dropping and operation times shortening as techniques become more efficient. It is also evident in the broadening of indications: surgeons are more confident to attempt minimally invasive approaches or difficult resections knowing they have the instruments to handle challenges (e.g., a reliable stapler to divide a major hepatic vein safely if needed, rather than doing a risky hand-sewn stitch deep in the cavity). Table 2 and Table 1 data already encapsulate some of these improvements (less blood loss, etc.), which directly tie back to equipment efficacy as well as technique.

In summary, the technological advancements in surgical instruments and equipment for hemihepatectomy have largely aimed at improving precision and hemostasis. With ultrasonic dissectors, advanced energy devices, staplers, and robotic systems, surgeons can now divide the liver parenchyma and vasculature with minimal bleeding and greater control. These advancements, in concert with the better techniques and planning discussed earlier, have resulted in a marked decrease in perioperative risk. Modern series report low rates of severe hemorrhage or liver failure, reflecting both the preventative measures in planning (ensuring adequate

FLR) and the effectiveness of intraoperative tools to prevent major blood loss and handle it if it occurs.

Looking forward, we anticipate further equipment innovations: perhaps artificial intelligence-guided electrosurgical units that can detect a blood vessel ahead and alert the surgeon, or smart clips that measure bile leakage pressure, etc. Already, there is exploration into laparoscopic robots that could automate parts of resection. For instance, a concept of an autonomous cautery robot following a pre-planned path in the liver could one day assist surgeons. While such ideas are in their infancy, the trajectory of the field suggests that as computing and engineering merge more with surgery, equipment will continue to evolve rapidly.

Conclusions

Hemihepatectomy has been transformed from a high-risk operation performed only in select centers into a routinely feasible and safer procedure, thanks to the cumulative impact of technological advancements in surgical practice. In this comprehensive review, we have outlined how improvements in surgical techniques, visualization methods, perioperative planning, and operative equipment have each contributed to better outcomes for patients undergoing right or left hemihepatectomy, particularly for oncologic indications like HCC and metastatic colorectal cancer.

In the domain of surgical techniques, the shift to minimally invasive approaches – laparoscopic and robotic hepatectomy – stands out as a game changer. Robust evidence indicates that patients undergoing laparoscopic or robotic hemihepatectomy experience significantly reduced perioperative morbidity (lower complication rates, less pain, faster recovery) while achieving equivalent oncological results compared to open surgery. The adoption of these techniques, now bolstered by growing surgeon expertise and consensus guidelines, means that many liver resections can be done with smaller incisions and better patient satisfaction. Robotic surgery, in particular, has extended the frontiers of minimally invasive liver surgery by enabling complex maneuvers with precision; its rapid uptake worldwide underscores its perceived advantages in suitable cases. We conclude that minimally invasive hemihepatectomy, when performed by trained teams in appropriate patients, is the new standard that offers clear short-term benefits and does not compromise long-term survival.

Advances in visualization and navigation have provided surgeons with “augmented senses” during hepatectomy. The use of ICG fluorescence imaging for tumor identification and segment mapping is a practical innovation already widely in use; it improves the surgeon’s ability to achieve R0 resections and avoid biliary complications by highlighting structures that were previously invisible. Augmented reality and 3D navigation systems, though in earlier stages of adoption, have shown remarkable potential to reduce intraoperative blood loss and errors. As these digital technologies mature, we anticipate they will become integrated into routine practice, guiding surgeons much like GPS navigation guides drivers – offering real-time, patient-specific roadmaps of hepatic anatomy. The convergence of imaging, computer

science, and surgery in these AR/XR systems heralds a future of "intelligent surgery", wherein human skill is amplified by technology to achieve greater accuracy and safety than ever before.

In terms of perioperative planning, improvements such as high-fidelity 3D imaging, precise volumetric calculations, and innovative preparatory techniques like portal vein embolization have significantly enhanced surgical planning and patient selection. We found that careful preoperative optimization (for example, using PVE to induce hypertrophy) has extended curative surgery to patients who would otherwise be marginal or inoperable, thereby improving overall treatment outcomes in liver oncology. The ALPPS procedure, while more risky, exemplifies how bold new surgical strategies combined with improved perioperative care can further push the envelope of resectability for extensive disease. The key message is that thorough planning – utilizing the latest imaging and interventional tools – is absolutely vital for safe hemihepatectomy. Modern liver surgery is as much about preoperative work (imaging, simulations, portal interventions) as the operation itself. By leveraging these advances, surgeons can ensure adequate liver function post-resection and reduce the likelihood of postoperative liver failure, which has historically been the Achilles' heel of major hepatectomies.

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