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Hybrid operating room applications for precision hepatobiliary surgery: A narrative review

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Abstract

This review summarizes the key applications of a hybrid operating room (HOR) in hepatobiliary surgery and explores the advantages, limitations, and future directions of its utilization. A comprehensive literature search was conducted in PubMed to identify articles reporting on the utilization of HORs in liver surgery. So far, the HOR has been limitedly applied in hepatobiliary surgery. It can offer an optimal environment for combining radiological and surgical interventions and for performing image-guided surgical navigation.

KEYWORDS

interventional radiology, liver, minimally invasive surgical procedures, multimodal imaging, operating rooms

1 | INTRODUCTION

Hybrid operating rooms (HORs) enable the integration of (interventional) radiological and surgical procedures in a single multifunctional setting (Figure 1). A HOR is, in essence, a surgical theater equipped with radiological imaging systems such as computed tomography (CT), fluoroscopy, and digital subtraction angiography or magnetic resonance imaging (MRI) devices.¹ The emergence of HORs transformed the landscape of surgical practice by enabling the

development of novel treatment modalities and improving the efficacy and safety of existing treatments. Over time the HOR has become indispensable in providing high-quality patient care in various surgical disciplines.²

The first reported clinical use of a HOR was in a cardiothoracic procedure.³ Gradually, it has been implemented in other surgical specializations such as vascular, neuro-, orthopedic, and trauma surgery.^{2,4} Presently, many centers are equipped with these state-of-the-art facilities.⁵ The availability of on-site imaging in the surgical

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environment eliminates the need for patient transfers and facilitates immediate assessment of operative results. Therefore, merging surgical and radiological environments may significantly reduce anesthesia and total procedure time.^{6–8} Imaging technologies are especially valuable in minimally invasive procedures whereby access, haptic feedback, and visualization are often limited. In conventional operating rooms, surgeons largely rely on preoperative imaging to identify the relevant pathology and anatomical structures. Real-time imaging provides an immediate depiction of reality, helping to enhance surgical precision and therefore increase the chance of operative success.^{6,9} Various studies have demonstrated that HOR utilization leads to increased safety and efficiency.^{10,11}

The development of new technology and treatments has more recently led surgeons and interventional radiologists to explore the applicability of the HOR for facilitating liver interventions. Patients presenting with tumors in the liver must often undergo multiple

treatments dependent on the number, size, and location of the lesions.^{12,13} The HOR provides the unique possibility of combining the surgical resection with other minimally invasive radiological procedures, such as percutaneous tumor ablation with CT or portal vein embolization (PVE) within the same environment. This allows reduction of the number of steps in long multistage treatment strategies. Another key application of HOR in liver surgery is image-guided surgical navigation. It is thought that the addition of advanced imaging technologies to operating suites increases efficiency and enhances surgical precision, ultimately improving patient outcomes following liver surgery.¹⁰

This review aims to explore the applications of a HOR, specifically in the treatment of liver tumors. Hereby providing insights into the potential benefits, limitations, and future directions of HORs within the field of hepatobiliary surgery.

2 | METHODS

A comprehensive literature search on the use of HORs in liver surgery was conducted using the PubMed electronic database from inception until July 27, 2023. The following keywords were included: “hybrid operating room,” “liver,” and “hepatectomy.” A summary of the search strategy is given in Table 1. Only articles published in the English language were considered. No restrictions were set with regard to article type or design. Reference lists of relevant articles were manually screened for additional studies. The retrieved publications were screened on the basis of title, abstract, and full-text by two authors (G. P. C. and R. J. S.) independently.

2.1 | Fast-track two-stage hepatectomy (TSH)

To achieve curative treatment of hepatic malignancies, tumors must be cleared completely with resection margins free of disease while



FIGURE 1 Hybrid operating room equipped with cone beam computer tomography and Da Vinci operating robot.

Items	Specification
Date of search	July 27, 2023
Databases and other sources searched	PubMed and manual search of reference lists
Search terms used	(“Surgery, Computer-Assisted”[Mesh] OR “Hybrid operat*”[tiab] OR “hybrid surg*” OR “Computer-Assisted surger*”[tiab]) AND (“Hepatectomy”[Mesh] OR (“liver neoplasms”[Mesh]) OR “liver surg*”[tiab] OR “Liver”[tiab] OR “hepatic surger*”[tiab])
Timeframe	No specified start date until July 27, 2023
Inclusion and exclusion criteria	Inclusion criteria: Studies in the English language reporting on the use of hybrid operating room for liver procedures.
Selection process	Independent selection of articles by G. P. C. and R. J. S. Consensus achieved through discussion.

TABLE 1 The search strategy summary.

sparing a sufficient future liver remnant.¹⁴ In the case of colorectal liver metastases, for example, patient survival outcomes are dependent on their resectability.^{15,16} Tumors can be deemed unresectable owing to the involvement of anatomy or high-risk for post hepatectomy liver failure due to a low predicted functional liver remnant (FLR).¹⁷ TSH is a treatment strategy developed to address the issue of low predicted FLR in patients with technically resectable tumors. TSH involves clearing the FLR of disease in a first-stage resection, then performing a contralateral PVE, and eventually completely clearing the liver of disease in a second-stage hepatectomy.¹⁸ PVE induces hypertrophy of the contralateral hemiliver, often accompanied by an increase in liver function.¹⁹ This allows the FLR to compensate for the loss of liver capacity succeeding the second resection. The implementation of TSH has made previously unresectable patients resectable, giving them a chance at curative treatment.^{20,21} However, 30%–38% of patients starting a TSH trajectory fail to complete it either due to inadequate liver growth, complications of the first intervention, or, more commonly, disease progression (either lesion growth or appearance of new lesions rendering the disease unresectable).^{22,23} Recovery time and the time necessary for liver tissue regeneration between interventions are inhibitory factors for quick progression to the secondary, curative-intent resection. Furthermore, patients often do not receive chemotherapy in the interval between the first and second stages, forming an additional risk for the progression of the disease.²⁴

In an attempt to shorten the interval between resections, a fast-track TSH approach was proposed by Odisio et al. in which PVE is performed as an adjunct to the first resection in a HOR.²⁵ They demonstrate the feasibility and safety of this strategy in a case series.²⁶ The cohort ($n = 19$) had a 59% completion rate of second stage hepatectomy following a first successful combined PVE and resection procedure. Although failure to complete the treatment was quite high in this cohort, it could be largely attributed to the presence of extensive disease in this small sample. There were no complications which could be seen as a direct result of combining the surgical resection and radiological PVE procedure, and all patients who underwent the procedure showed sufficient liver hypertrophy. The median interval between resections (5.6 weeks) and median interval to adjuvant chemotherapy (8.1 weeks) were shorter than the intervals reported in the literature so far.^{18,27}

Fast-track TSH is a promising treatment strategy which appears to be a safe and feasible. Intraoperative combination of first stage (minimally-invasive) hepatectomy with PVE in a HOR results in shorter intervals between therapies, possibly limiting the chances of disease progression and reducing the drop-out rate in TSH. Moreover, shorter chemotherapy-free intervals have been found to be related with better oncologic outcomes.^{24,28,29}

2.2 | Endovascular imaging and interventions

The availability of the appropriate devices and equipment in a HOR allows techniques commonly applied in interventional radiology, such

as angiography, to be used in combination with hepatobiliary surgical interventions.

The feasibility of same-procedure operation and embolization in the HOR is demonstrated by Hagiwara et al. in the case of a hemorrhagic traumatic liver laceration.³⁰ The HOR allowed surgical action, such as perihepatic packing and application of the Pringle maneuver to take place together with the transarterial embolization performed by the interventional radiologist in the same session. This case illustrates how collaboration within the HOR can spare important minutes in the treatment of patients in critical condition. The use of a hybrid operation room for addressing traumatic hemorrhage has shown to be associated with faster hemorrhagic control.³¹ Endovascular procedures can aid in both identifying and treating the bleeding vessel hereby complementing surgery for traumatic liver injury.³²

Additionally, the HOR has proven effective in addressing portal vein complications following liver transplantation.³³ Portal vein stenosis or occlusion is a rare but a severe complication of liver transplantation requiring immediate attention. Hakoda et al. found the HOR helpful for its flexibility to convert to a surgically assisted approach immediately after diagnosis without needing to displace the patient.

In addition to standard indications, the HOR can be also prove useful in specific cases of hepatic lesions with vascular involvement. Ishikawa et al. reported on the use of angiography during the surgical resection of multiple giant liver cysts exerting pressure on the inferior vena cava and portal vein.³⁴ CT-angiography was used to intraoperatively monitor the effect of cyst fenestration on the degree of vascular decompression (Figure 2). If cyst fenestration appeared to be insufficient in decompressing the vessels, the surgeons would need to resort to alternative strategies, such as resection of the caudate lobe and stenting of the vessels. The real-time feedback was helpful for confirmation of operative success. Similarly, Maker et al. outline in a case report how they used angiography in the HOR to perform hepatic haemangioma inflow embolization followed by resection within the same setting without moving the patient.³⁵ Intraoperative surgical ligation was not a good option in this case due to the inaccessibility of the vessels caused by obstruction by the lesion. Control of arterial inflow through embolization before resection facilitated the surgical removal of the giant haemangioma. This allowed for a safer and technically less complex operation. In addition, on-table embolization potentially avoids postembolization pain sometimes experienced by patients undergoing preoperative embolization in separate sessions.³⁶

The above cases are illustrative of how the HOR can be effective in the management of patients requiring a combination of surgical and radiological interventions. Although some of the cases described may be uncommon, and the evidence is largely anecdotal, it is nevertheless important to be aware of the possibilities the HOR can offer when formulating a treatment plan. Utilization of vascular imaging techniques and interventions in liver surgery may be essential for minimizing risks and for operating safely in select cases.

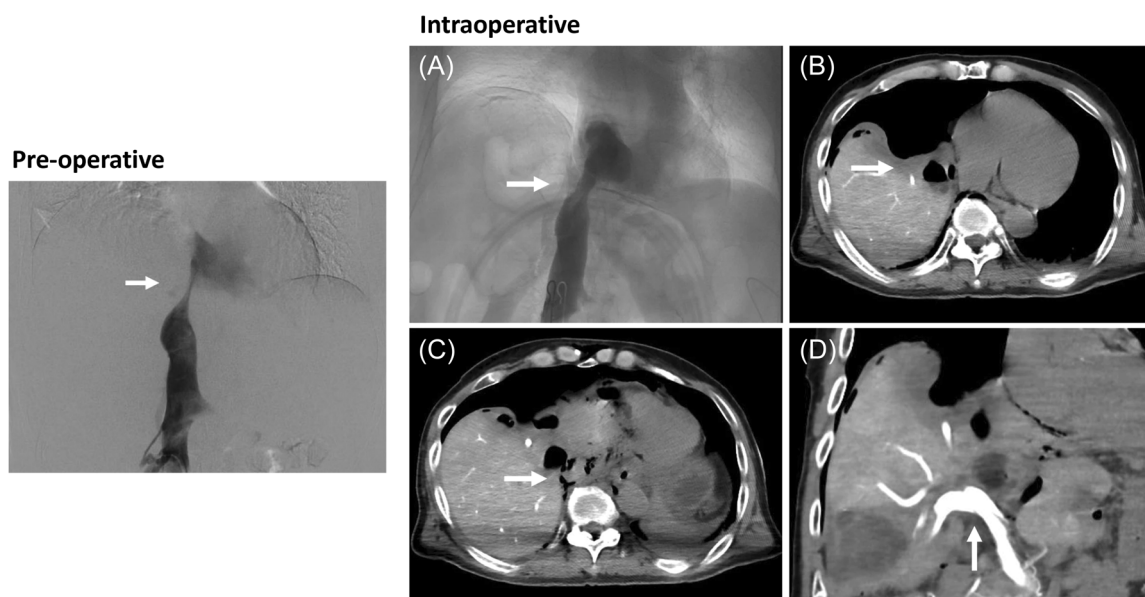


FIGURE 2 Images performed pre- and intraoperatively confirmed that cyst fenestration resolved the stenosis of the inferior vena cava (A, B, C) and portal vein (D). Image source.³⁴

2.2.1 | Image guided surgical navigation and augmented reality (AR)

Minimally invasive liver surgery offers improved patient outcomes yet presents a greater technical challenge compared with open liver surgery.³⁷ This is partly owing to a lack of haptic feedback, making the identification of lesions and surrounding anatomy more difficult. Preoperative imaging is essential for identifying the relevant anatomy and devising a surgical plan.³⁸ However, intraoperatively surgeons primarily need to rely on their judgment of the preoperative scans and spatial cognition. Intraoperative ultrasound has been employed as a tool to help surgeons orientate themselves.³⁹ It allows them to intermittently identify anatomical structures and resection margins. However, ultrasound is limited by its two-dimensionality and reduced image quality in the presence of air at the resection plane.³⁹ The use of indocyanine green (ICG) fluorescence imaging has also gained popularity in liver surgery as a navigation tool for identifying tumors, biliary structures, and segmental boundaries.⁴⁰ The availability of additional imaging modalities in the HOR could further facilitate intraoperative orientation during hepatic resection. Below we discuss some examples of HOR applications for surgical navigation. Image-guided techniques performed outside of a HOR are not within the scope of this paper.

The use of ICG to facilitate the identification of segments for anatomical resections requires dye to be injected into the pedicle of the respective segment. This is a technically demanding task, especially when performed minimally invasively and for segments with intraparenchymally located pedicles.^{41,42} Ueno et al. made use of the imaging facilities in the HOR to radiologically guide the injections before proceeding with resection.⁴¹ They tested the feasibility of this method in 10 patients and found that it allowed

the precise resection of anatomical segments. The planned resection volume corresponded with the actually resected specimen to a high degree.

Various teams have been searching for the optimal way to fuse three-dimensional models constructed from preoperative scans with intraoperative images.⁴³ This would enable more accurate localization of tumors and critical structures, possibly improving procedure safety as well as oncological outcomes.⁴⁴ AR refers to the integration of visual elements with real-time images of the surgical field.^{43,44} AR therefore allows surgeons to look beyond the surface of the liver. This type of surgical navigation technology is already routinely used in surgery involving rigid structures, such as orthopedic surgery and neurosurgery.^{45,46}

Kenngott et al. published the first clinical report on the use of intraoperative cone beam CT imaging in a HOR as a tool for surgical navigation in liver surgery.⁴⁷ They superimposed three-dimensional models onto intraoperative fluoroscopic images allowing surgeons to visualize the tumor in relation to the laparoscopic instruments. Their method had an acceptable degree of accuracy (maximum error of 2.5 mm) in experiments using a phantom liver and was subsequently successfully applied in a laparoscopic resection of a hepatocellular carcinoma in a 50-year-old patient. Falkenberg et al. also utilized intraoperative fluoroscopy for guidance during resection.⁴⁸ They placed radiopaque fiducials (coils and gold rods) near the tumor to help guide surgeons during resection. Perioperative cone beam CT images were then laid over the fluoroscopic images and displayed next to the laparoscopic images (Figure 3). Surgeons found fluoroscopy to be a valuable addition alongside intraoperative ultrasound for locating lesions. The primary limitation of the aforementioned technologies was that the images were not updated throughout the procedure leading to misalignment of the models with

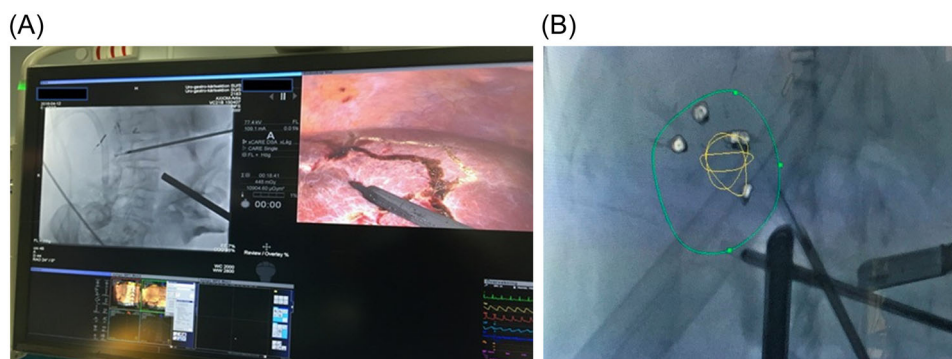


FIGURE 3 (A) Screen in a hybrid operating room projecting fluoroscopic and laparoscopic images side by side. (B) Dynamic overlay of the tumor (yellow) and planned resection margin (green) from three-dimensional perioperative cone beam computed tomography on the intraoperative fluoroscopic images. Fiducials (white patches on the image) are used to accurately overlay the images. Image source.⁴⁸

the surgical reality. This meant that the navigation was mainly valuable during the early phase of the resection before major tissue deformations occurred. More recently, Ivaschenko et al. developed a navigation system capable of correcting for tissue deformation using electromagnetic tracking by assuming the liver segments acted like a locally rigid body.⁴⁹ Electromagnetic sensors were placed intraoperatively to track organ and patient motion, and intraoperative cone-beam CT registration was used to calibrate the system. The instrumentation was then projected onto a dynamic three-dimensional patient model constructed from a preoperative MRI scan. This enabled surgeons to map their location in relation to the tumor and other anatomical structures with an average accuracy of 4.0 mm. Disadvantages, including longer procedure duration, disruption of workflow by the C-arm, and exposure to radiation, were recognized by all three groups. Moreover, the navigation systems were not integrated with the visual laparoscopic images meaning users had to interpret the images separately.

So far, 3D liver models have mainly been utilized adjacent to the operation images, without image overlay.^{43,44,50} Real-time integration of liver models with optical surgical field images has proven difficult. The challenge lies in the constant deformation of tissue due to factors such as movement, pneumoperitoneum, and tissue manipulation, making the preoperative scans less applicable as the operation progresses.^{43,51} Soler et al. and Peterhans et al. suggested methods relying on user manipulation and landmark registration to realign the optical view with the liver models.^{52,53} However, this approach is limited by its necessity of additional handling by surgeons and sensitivity to human errors making it imprecise. Shekar et al. demonstrated the concept of live AR in porcine models, whereby continuous CT-imaging was laid over laparoscopic images to generate visuals of the surgical field with underlying vasculature.⁵⁴ A Norwegian group attempted to ensure the continuous realignment of digital models with laparoscopic images using intraoperative CT imaging with multiple registrations (Figure 4).^{55,56} They found that intraoperative imaging was able to improve the accuracy of AR images in a porcine model. Interestingly, computer-based algorithms were able to more

accurately overlay images compared to models based on intraoperative clinician annotations.⁵⁶

With the integration of imaging within the operative environment, new therapeutic and diagnostic possibilities arise. The enhanced surgical precision offered by image-guided procedures could help push the boundaries of surgery for tumors formerly thought to be unresectable. So far, the HOR has mainly been used in experimental settings for image-guided surgery. Currently, the literature mainly consists of proof-of-concept and feasibility studies. Future research should continue to develop surgical navigation systems as well as focus on determining its clinical benefits. Concerns regarding the lack of precision, added procedure time, workflow disruption, and costs need to be addressed before widespread clinical implementation of these technologies can take place.

2.2.2 | Future applications: Combined resection and ablation

Total hepatic clearance of disease by either resection or ablation is the only curative option for patients with liver cancer.⁵⁷ Preference for resection or ablation is dependent on the size, number, and location of lesions as well as the presence of underlying liver disease.^{58,59} In many patients, a multimodal approach is required whereby both resection and ablation are employed to address all tumors. Combined resection and ablation strategies have shown to be safe, effective, and have good oncologic outcomes.^{13,60,61} Access to the lesions can be achieved through open, laparoscopic, or percutaneous approaches.^{62–64} Ultrasound, CT, MRI, or stereotactic guidance can be used to locate lesions and guide needle placement during ablation.^{65,66} Computer-assisted stereotactic guidance for lesion targeting has been found to improve ablation accuracy.^{67,68}

Ultrasound guided ablations can be performed concurrently with resection. Okuno et al. reported on a new strategy in which resection and CT-guided ablation scheduled in two sequential sessions.⁶⁹ Theoretically, a hybrid OR could allow CT-guided ablations to be combined with resection under the same anesthesia. The feasibility

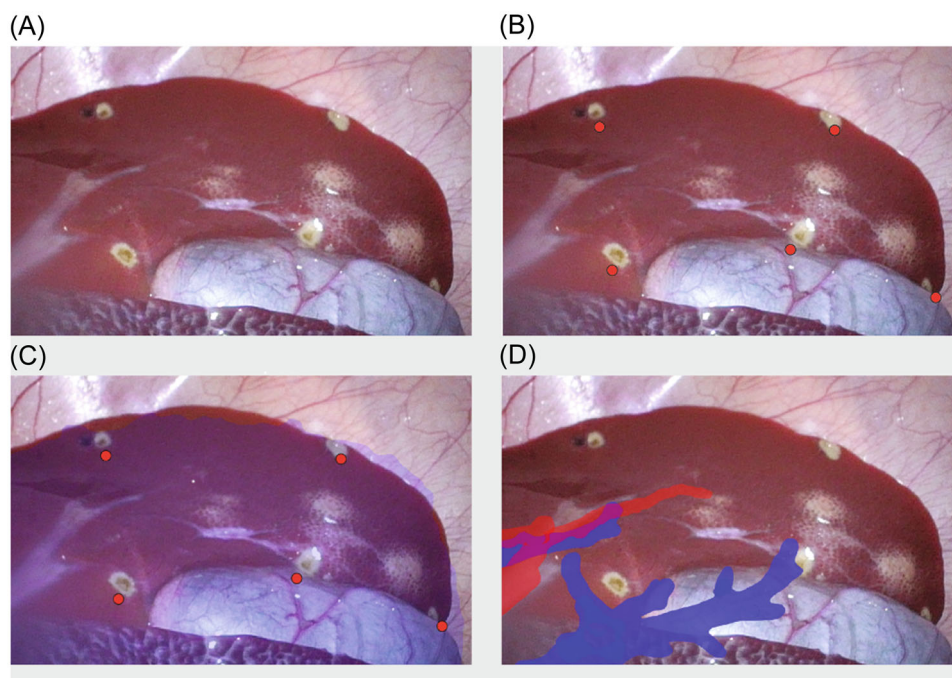


FIGURE 4 Intraoperative image (A) with overlay of cauterization points for target registration error measurement (B) and augmented reality overlay of liver parenchyma (C) and vasculature (D). Image source.⁵⁵

of this has been demonstrated in thoracic surgery for the resection and ablation of pulmonary metastases.⁷⁰ Moreover, Banz et al. demonstrated how preoperative CT-scans can be integrated with intraoperative instrumentation and ultrasound to successfully ablate and resect bilobar colorectal liver metastases.⁷¹ Potentially, the use of intraoperative CT-scans could further enhance the accuracy of this technique by helping to compensate for intraoperative tissue deformations. CT-hepatic arteriography (CTHA) is innovatively being applied to assist in liver ablation procedures.⁷² CTHA involves the injection of small doses of contrast directly in the proper hepatic artery via an intra-arterial catheter to aid visualization of the hepatic vasculature.⁷³ CTHA facilitates vascular visualization and verification of ablative success, making it a promising tool for ablation-guidance.^{74,75} So far, no studies have been published reporting on same-procedure resection and ablation for liver lesions using CT or MRI. It can be hypothesized that a fast-track approach to combined resection and CT-guided ablation could economize on anesthesia time and total hospital stay as opposed to separate procedures.

2.3 | Limitations of the HOR in liver surgery

It is important to recognize the limitations of the HOR. Its application in hepatobiliary surgery faces economic, safety, and logistical concerns. These challenges must be adequately addressed when considering the use of HOR in clinical practice.

First and foremost, the use of a HOR is considerably more costly than a conventional operating theater. Patel et al. found that the costs per minute for the HOR and conventional operating room are

€19.88 and €9.45, respectively.⁷⁶ This sizeable cost difference cannot be overlooked in the present context of scarce healthcare resources. To accept these high operating costs, a clear advantage must be proven in the use of the HOR. However, it is important to consider that patients undergoing a combined procedure, such as in the case of fast-track TSH and combined ablation, total time in the HOR will perhaps require less total room time than two separate procedures. Combining interventions can save on time for patient preparation, positioning, as well as anesthesia induction and recovery as this merely needs to occur once in a HOR. Therefore, despite the high procedural and overhead costs of a HOR total cost-expenditure per patient might be lower. Cost-effectiveness analyses should be conducted to verify these ideas. Given the versatility of a HOR and its relevance across a range of surgical specialties, it is improbable that the investment would be underutilized. However, practitioners should continue to look critically at the indications for HOR use. Liao et al. found that a large proportion of neurosurgical procedures conducted in a HOR could have also been performed in a conventional operation room without compromise.⁷⁷

Second, the use of intraoperative imaging raises health and safety concerns about the increased exposure to radiation for both the patient and operating room personnel. Cumulative exposure to ionizing radiation from imaging devices in the HOR may increase the risks for developing certain cancers.^{78,79} It is therefore necessary that measures are put in place to limit radiation exposure as much as possible. Precautions include the use of protective clothing, radiation protection shields, and taking distance from the radiation source.^{80,81} Some of these recommendations may, however, prove difficult and inconvenient in the context of an operation. Yet, it should be noted

that for some of the utilizations outlined in this review, such as in combined procedures (fast-track TSH and combined ablation), the exposure to radiation will not increase in comparison with conventional procedures. Since merely the location and timing of the procedure is adapted and not the nature of the procedure itself.

Third, the integration of imaging modalities into the operating room is accompanied by additional logistical challenges regarding the availability of facilities, scheduling, patient positioning, and intraoperative workflow disruptions.⁸² The multidisciplinary nature of the HOR requires the surgery, anesthesiology, and radiology staff to work closely together. The development of novel techniques demands adaptations to current practices meaning this level of collaboration necessitates flexibility from all parties involved. Ideally, teams should be specifically trained for the unique working conditions in the HOR.^{82,83} The downside being the additional use of resources and time needed for training a specialized staff. Moreover, the scarcity of HORs also calls its widespread applicability into question.

Fourth, there is still a large knowledge gap with regard to the effectiveness of the HOR in liver surgery. According to the IDEAL framework, the development of new surgical innovations should follow a stepwise pathway: Idea, Development, Exploration, Assessment, and Long-term follow-up.⁸⁴ The application of the HOR in liver surgery is still in the early stages, considering the available evidence is largely anecdotal consisting of small cohorts, experimental studies, and case reports. Larger comparative studies are needed to assess the true value of the HOR.

3 | CONCLUSIONS

The HOR is a one-stop shop for surgical and radiological interventions used in a variety of surgical disciplines. Its application to hepatobiliary surgery has so far been limitedly studied. Although results seem promising, the use and effectiveness of the HOR in liver surgery needs to be explored further.

CONFLICT OF INTEREST STATEMENT

R. J. S. is a proctor for Intuitive Surgical (Intuitive Surgical Inc., Sunnyvale, CA, USA). The remaining authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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