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Review

# Use of Three-Dimensional-Printed Liver Models for Clinical Education and Surgical Planning: A Systematic Review

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## Abstract

Hepatobiliary surgery is a technically complex subspecialty within general surgery, which requires a comprehensive understanding of complex liver and liver tumour anatomy. The current body of literature highlights the use of three-dimensional-printed liver models (3DPLMs) reconstructed from medical imaging datasets may improve clinician comprehension of patient-specific liver anatomy thus creating a useful tool for hepatobiliary surgical planning and clinician training. The purpose of this systematic review was to examine the clinical utility and feasibility of 3DPLMs in hepatobiliary surgical planning and clinical education and investigate whether these applications influence patient outcomes. Studies were retrieved from three electronic databases (ProQuest, PubMed and Scopus) according to predetermined eligibility criteria. In total, 25 eligible articles were identified, including 18 original research articles and seven case reports. An inductive content analysis approach suitable for heterogeneous bodies of literature was used to synthesise key concepts in this review. There are significant case report and descriptive evidence to support the use of 3DPLMs in clinical education, preoperative planning and intraoperative guidance of patient liver and tumour anatomy to improve hepatobiliary surgical decision making. The studies presented display a large variance in cost and times necessary for the production of 3DPLMs, as studies did not include the software, equipment and full expense of materials used. Additionally, studies concentrated on different aspects of the 3DPLMs production process making them not comparable. This review demonstrates the potential value of 3DPLMs in clinical education, preoperative planning and intraoperative guidance in hepatobiliary anatomy and surgery. Future studies, in particular, randomised controlled trials and experimental research are required to investigate the relationship between 3DPLMs and clinical education and surgical planning outcomes.

**Keywords:** three-dimensional printing; liver; education; surgical planning; model; intraoperative guidance

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## 1. Introduction

A technically complex subspecialty within general surgery is the performance of operations or interventional procedures involving the hepatobiliary system [1]. There is considerable anatomical variability within the liver lobes, portal vein, hepatic artery, hepatic veins, and biliary tract, all of which can potentially complicate surgical approaches and learning [2–4]. This variability in liver morphology, combined with technical difficulties, prolonged training requirements, high surgical risks and frequent postoperative complications, makes education and surgery on the hepatobiliary system challenging [2]. Traditionally, tools used for teaching include videos, atlases and computed tomography (CT) imaging which are still widely used in medicine [5]. While these methods are essential, they require the surgeon to conceptually reconstruct spatial and depth location information

from two-dimensional (2D) images [6,7]. Due to the liver's complex anatomy and marked variations between patients, conventional teaching methods regularly fail to provide learners with a sufficient understanding of the hepatobiliary system [8]. As a result, educational outcomes are inadequate and surgical skill acquisition remains a challenge [8]. Furthermore, due to the complexity and variability of the spatial relationships between intrahepatic structures, a comprehensive pre- and intra-operative understanding of hepatic anatomy and pathology is crucial for enhancing patient outcomes [9].

Three-dimensional printing (3DP) (a type of additive manufacturing) enables the rapid fabrication of accurate and precise anatomical models using specialised printers [10]. With the continual advancements in 3D printer software, hardware and material diversity, 3DP has garnered an extensive applicability across the medical field [11]. More specifically, the segmentation of a patients' liver pathology and anatomy from their medical imaging data, such as CT images, can be reconstructed in a 3D file format that is suitable for 3DP which can then be used to print a liver model [12,13]. In the past, clinicians and students comprehension of medical images has been restricted to 2D representations on computer screens or in textbooks [14]. Conversely, 3DP directly converts medical imaging data (e.g., CT scans or magnetic resonance imaging) into high-fidelity 3D structures [15]. This ability makes 3DP a robust alternative to traditional methods of teaching in the medical field. Improvements in processing speed, material costs and resolution have significantly increased its accessibility [16]. Therefore, current 3D-printed models can achieve anatomical precision and a higher fidelity as well as simulate human tissues realistically, thus showing a strong promise for surgical simulation and technical training [17].

The current literature shows that 3D-printed models can facilitate skill acquisition and advanced procedural training across multiple surgical disciplines [18–21]. Regarding hepatobiliary surgery, 3D-printed models have been used in endoscopy, laparoscopy, tumour localisation, preoperative planning and anatomical teaching [22–25]. Therefore, reproducible, high-quality simulations are crucial for improving technical proficiency and decision-making capabilities [22–25]. However, traditional training methods for clinicians face increasing constraints including heavy workloads and a lack of operative exposure. Incorporation of 3D-printed models into hepatobiliary preoperative planning and training may help address these challenges by providing additional opportunities for hands-on, safe, ethical practice [22–25]. By integrating detailed 3D visualisation of hepatobiliary anatomy, 3DP may provide a transformative instrument in surgical preoperative planning and education [26–28]. While surgical training has traditionally relied on traineeship models with direct supervision within an operating theatre, current studies have highlighted the value of simulation as a way to provide effective, transferable and safe procedural training [29,30]. However, limitations are still prevalent as high-fidelity models can be expensive, and there are concerns of a lack of standardisation in manufacturing protocols and accuracy [30].

Previous systematic reviews demonstrate that 3D-printed liver models (3DPLMs) enhance preoperative planning, clinician education and anatomical visualisation [26,27,31,32]. This review aims to build on the previous 3DPLM body of literature by providing an updated critical review of the utilisation of 3DPLMs for surgical skill acquisition and preoperative planning, exploring whether these applications enhance clinician training and patient outcomes. Due to the increasing incidence of primary liver cancer and the rapidly evolving nature of 3DP technology [11], an updated review is justified to contribute to the current body of literature to improve clinicians' education and preoperative comprehension of hepatobiliary anatomy. The existing reviews are either over five years old [31,32] or focus on isolated applications such as surgical education and tumour-specific surgical planning which limits their applicability to current, integrated practice. Furthermore, rapid advancements in 3DP technology and its expanding clinical use have not been comprehensively synthesised across surgical and educational domains. Therefore, this critical review will address the following research question: Do 3DPLMs enhance clinician training and preoperative surgical planning of the hepatobiliary system?

## 2. Materials and Methods

### 2.1. Search Strategy

A comprehensive literature search was conducted through searching three main databases comprising ProQuest, PubMed and Scopus. The search strategy used the keywords “3D printing”, “model/phantom”, “liver/hepatic”, “teaching/surgery”. The complete search strategy is provided in Table 1. The search strategy was restricted to either title, title/abstract or anywhere except full text to improve relevance depending on the search matrix of the database source. To further expand the search results, truncation and the search engine wildcard asterisk (\*) were used. For this review, the final search was performed in March 2026.

Table 1. Search strategy.

Concept 1 3D printing	Concept 2 Model	Concept 3 Liver	Concept 4 Teaching/Surgery
“3D print*” OR “3D-print*” OR “three-dimensional” OR “three dimensional” OR “additive manufactur*” OR “three-dimensional print*” OR “3-dimensional print*”	model* OR phantom	liver OR hepat*	teach* OR train* OR instruct* OR simulat* OR educat* OR surg* OR oper* OR “intervention*”

### 2.2. Inclusion and Exclusion Criteria

A journal article was included if it was performed on humans, full-text, peer-reviewed and published in English within the last five years and researched the use of 3DPLMs use in clinician training and/or surgical planning. Due to the rapid advances in 3DP technology in recent years, a five-year publication date was chosen to ensure currency [11]. Articles were only included if they were original research and excluded if they were review articles, letters, guidelines, or editorials. Results investigating the production of 3DP material or methods were included, as these aspects may directly influence 3DPLM’s clinical feasibility and validity [33]. Due to the limited number of original research articles currently within the literature case reports were included which is common practice in past 3DPLM reviews [27,31,32]. To ensure the focus of the review remained appropriate, articles were excluded if they exclusively focused on bioprinting or virtual 3D models.

### 2.3. Article Identification, Screening and Quality Appraisal

Once all searches were performed, duplicate articles were removed. Subsequently, the titles and abstracts of the remaining articles were then screened to exclude irrelevant results. After screening the full text of the remaining articles, 17 eligible articles were identified [34–50]. Subsequently, the resultant articles’ reference lists were examined to identify six secondary articles [6,51–55]. Two additional articles were identified during a manual search serendipitously [56,57]. Therefore, for this review a total of 25 articles were identified for inclusion (Figure 1). Data extraction and analysis was performed by one assessor (B.R) with another assessor (Z.S) checking the details for moderation.

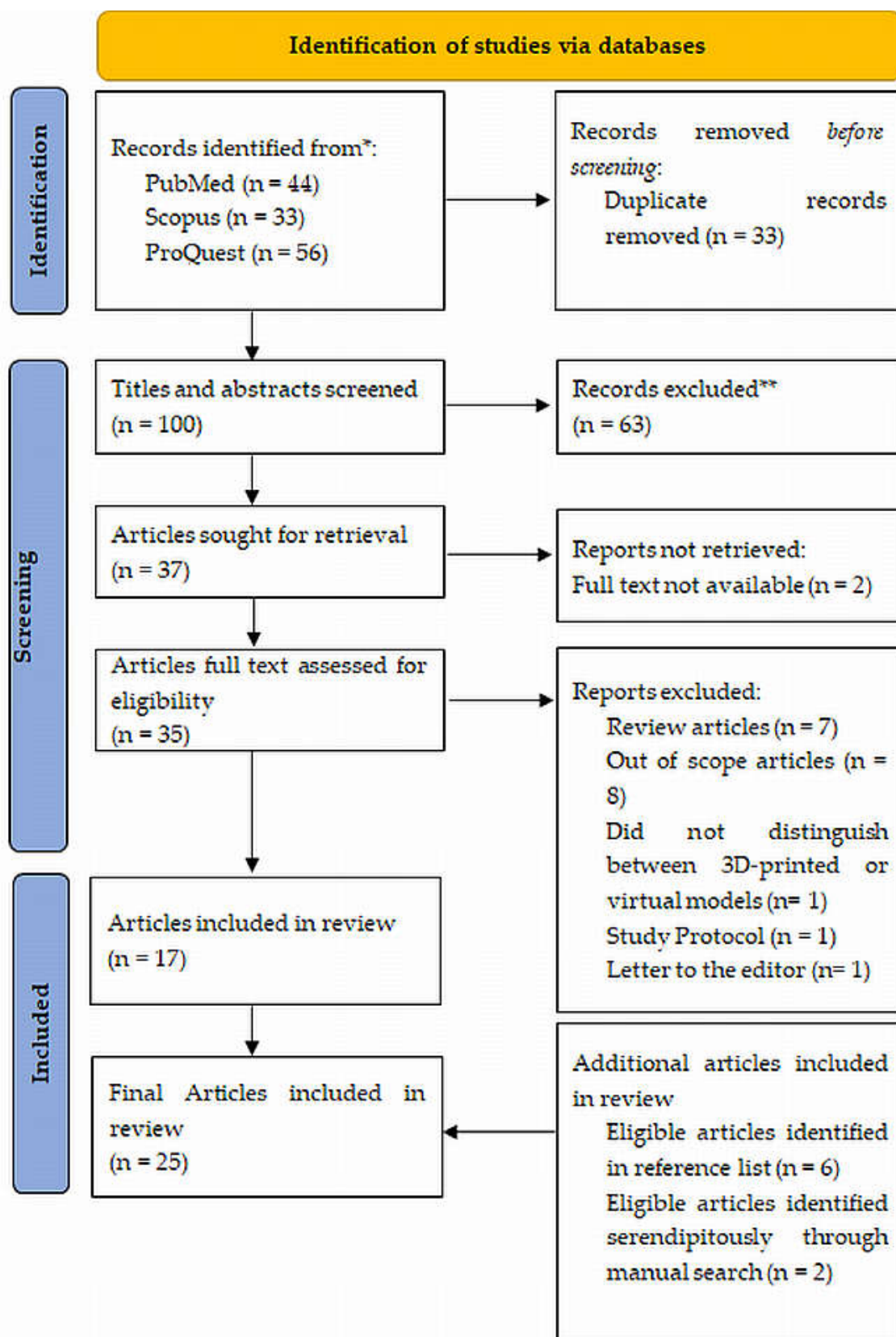


Figure 1. PRISMA flow diagram of literature search [58].

In this review, quality appraisal of the included articles was completed using the Mixed Methods Appraisal Tool (MMAT) developed by Hong et al. [59] as it allows for the methodological quality appraisal of qualitative, quantitative and mixed-methods studies [59]. This tool utilises two screening questions to determine whether a study is empirical and suitable for appraisal [59]. Once a study is

deemed eligible, it is assigned to the appropriate category (qualitative, quantitative randomised controlled, quantitative non-randomised, quantitative descriptive or mixed methods) and the corresponding five criteria are applied to appraise the quality of the included articles [59]. The MMAT was selected as it is an established tool devised to overcome the challenges of critically appraising mixed studies reviews in healthcare, making it applicable for the studies included within this review [59].

#### 2.4. Data Extraction and Synthesis

Given the heterogeneity of the included articles, an inductive content analysis approach was used to extract and synthesise data [60]. This method appropriately defines the key concepts of the body of literature through extraction and synthesis [60].

### 3. Results

The studies identified and included in this review are highly heterogeneous, comprising seven case reports and 18 original research studies. Of the 18 original research articles, of which two use true experimental research methodologies, four are quasi-experimental studies, three descriptive surveys, one ethnographical study and eight observational studies. Table 2 shows additional summaries of the key characteristics of each article.

**Table 2.** Eligible articles characteristics and key findings.

Articles	Purpose	Country of Origin	Study Design	Sample	Imaging modality/3D model software/3D printing method	3D printing materials	Production cost and time	Key Findings
Cheng et al. (2022) [6]	Method to reduce cost and improve efficiency of 3DPLM creation. Investigate the effects and value of 3DPLM in complex laparoscopic hepatectomy procedures	China	Prospective comparative	Patients with complex hepatobiliary lesions n = 54	CT E3D, Cura SLA	Photosensitive resin	\$104.40 USD 56.8h	The 3DP liver model assisted in preop planning and intraoperative navigation, however, there was no significant improvement of intra- or postoperative outcomes
Aranovich et al. (2025) [34]	Develop a specialised educational program using a 3DPLM for managing high grade liver injuries	Israel	Single-group cross-sectional	General surgery and trauma residents n = 8	CT N/S N/S	TPU-95	N/S N/S	3DPLM improved participant proficiency indicating potential for improved patient outcomes
Bao et al. (2023) [35]	Evaluating the value of 3DPLMs in trainees' understanding of liver tumour location and surgical procedures	China	Quasi-experimental	Medical trainees n = 30	CT Mimics, Magics Material jetting	Photosensitive resin	\$260 USD 14h	Use of 3DPLM significantly improved the trainees' surgical procedure understanding, surgical planning, and tumour location
Cao et al. (2024) [36]	Develop a reusable 3DPLM to	China	Single-group cross-sectional	Patients with complex liver cancer	MRI E3D, Cura FFF, SLA	Silicone, hydrogel,	N/S N/S	3DPLM potentially replicates minimally invasive resection of

	simulate surgical resection of complex liver cancer		n = 2			photosensitive resin		complex liver cancer, demonstrating value in simulated surgery
Cheng et al. (2023) [37]	Comparing the educational value of 2D imaging, 3DVR and 3DPLM for hepatic tumour location and surgical planning	China	Randomised controlled	HPB surgical interns n = 62	CT E3D SLA	Photosensitive resin	N/S N/S	Using 3DPLM significantly enhanced the interns' ability to indicate correct tumour location and design appropriate surgical plans
Chua et al. (2022) [38]	Investigate the use of low-cost FFF and SLA 3DP to create a realistic 3DPLM for medical education	Singapore	Descriptive experimental	3DPLM n = 4	N/S Blender FFF, SLA	PLA, PETG, silicone	N/S N/S	Developed a workflow to create four different 3DPLM for use in liver anatomy education
Elisei et al. (2024) [39]	Develop a 3DPLM that can be used for the training of surgeons in image-guided interventional procedures	Romania	Single-group cross-sectional	Residents and specialist surgeons n = 33	CT InVesalius, Autodesk Fusion 360 with Netfabb FFF	Mold: ABS Phantom: gelatine, silicone	Mold: €1000 Gelatin phantom: €8-15 Silicone phantom: €85 42h	The multi-modal 3DPLM provided an realistic model for simulation of image-guided interventional procedures of the liver for surgical training
Fukumitsu et al. (2023) [40]	Evaluate the use of a patient-specific 3DPLM as an intraoperative navigation tool for surgical safety	Japan	Quasi-experimental	Patients requiring advanced HPB surgery n = 15	CT SYNAPSE HPB VINCENT SLA, DLP	Acrylic resin	\$700-2500 USD N/S	Accurate patient-specific 3DPLM was an effective intraoperative navigation tool to improve safety and psychological stress, but did not reduce blood loss or operative time
Igami et al. (2024) [41]	Investigate the value of 3DPLM on patients undergoing $\geq 3$ repeated hepatectomy for intraoperative navigation for trainee surgeons	Japan	Ethnographical	Patients undergoing $\geq 3$ repeated hepatectomy n = 17	CT $\geq 3$ PLUTO Material jetting	Acrylic and polyurethane resin	50,000¥ 18h	Use of 3DPLM improves surgical trainees anatomical understanding and preoperative planning in complex surgical cases
Labakoum et al. (2025) [42]	Develop an accurate patient-specific 3DPLM for education, preoperative planning and surgical rehearsal	Morocco	Descriptive survey	Medical trainees (2 surgical residents, 3 senior medical students) n = 5	CT 3D Slicer, Meshmixer, Cura FFF, LCD	Mold and intrahepatic structures: PLA Model: gelatine	Model: \$50 USD 128h	3DPLM developed was low-cost and anatomically accurate showing potential for surgical training simulations and preoperative planning
Lopez-Lopez et al. (2021) [43]	Verify the accuracy of 3DPLM and investigate its utility regarding liver surgical planning, teaching and provision of	Spain	Multicentre study: Case report, descriptive survey, randomised control	Patients with complex hepatic tumours n = 35 HPB surgeons n = 23 Medical students n = 75	CT and MRI 3D-MSP N/S	TPUR, ABS	€950 22h	3DPLM showed good correlation with CT/MRI, and the models supported surgical education and planning and enhanced patient understanding of

	patient information							their surgery and pathology but did not affect the surgical outcome.
Lu et al. (2023) [44]	Develop a soft self-healing 3DPLM for preoperative planning and surgical training	China	Single-group cross-sectional	Patients presenting for liver surgery n = 5	CT N/S SLA	Elastomeric copolymer	N/S N/S	Produced a high-fidelity self-healing 3DPLM for use in preoperative planning and surgical training which may enhance patient safety
Maehigashi et al. (2024) [45]	Explore the effects of using 3D computer and 3DPLM on the spatial reasoning of liver anatomy of experts and novices	Japan	Quasi-experimental	University students n = 48 Digestive surgeons n = 22	CT PLUTO SLA	Acrylic resin	N/S N/S	Use of 3DPLM improved spatial reasoning for novices and increased the expert's confidence in their spatial reasoning
Sanchez-Garcia et al. (2024) [46]	Demonstrate the feasibility and accuracy of using 3DPLM in paediatric liver transplant decision-making and living donor selection	United States of America	Prospective multi-centre cohort	Paediatric liver transplant candidates n = 28 Living liver donors n = 41	CT and MRI IQQA-Liver, Mimics FFF	Photopolymer resin	N/S N/S	3DPLM is a highly accurate way to estimate recipient liver volume and reduce costs in a living donor program, while potentially improving surgical decision-making and improving organ allocation efficiency
Smilie et al. (2021) [47]	Develop a method for producing 3DPLM for use in anatomical and surgical teaching	United Kingdom	Case report	3DPLM n = 1	CT Simpleware ScanIP, GrabCAD, Meshmixer Material Jetting	Photopolymer	£1,343 58h	3DPLM provide a suitable alternative to cadaveric teaching, but further development is required to ensure human liver tissue characteristics are simulated for more realistic surgical training
Tooulias et al. (2021) [48]	Create a patient-specific, accurate 3DPLM with a tumour for surgical resection	Greece	Case report	Patient with liver tumour for surgical resection n = 1	CT N/S N/S	N/S	N/S N/S	3DPLM may promote a more targeted tumour resection where a larger volume of healthy liver tissue is preserved
Valls-Esteve et al. (2023) [49]	Produce a low-cost method for producing patient-specific 3DPLMs for training and simulation	Spain	Case report	Paediatric patients with complex hepatic tumours n = 3	CT IntelliSpace Portal FFF and SLS	PA12, PLA, silicone	$\mu = \text{€}549$ 8-24h	3DP mould used to cast soft, transparent silicone liver model allowing for surgical rehearsals and improve pre-operative planning
Yao et al. (2024) [50]	Evaluate the value of 3DPLM in surgical planning of laparoscopic liver resection in complex HPB disease	China	Retrospective cohort	Patients with complex liver disease n = 62	CT E3D, Cura SLA	Photosensitive resin	N/S N/S	Use of 3DPLM for preoperative planning can aid in reducing postoperative complications

Arm et al. (2022) [51]	Develop and characterise a 3DPLM to aid in surgical planning, teaching and rehearse liver tumour resection	United Kingdom	Case report	Patient with liver tumour n = 1	CT Mimics FFF	Thermoplastic aliphatic polyester, PLA and PVA	N/S N/S	3DPLM closely mimicked the mechanical properties of real liver tissue for surgical simulation and preoperative planning
Aseni et al. (2021) [52]	Develop a transparent 3DPLM to investigate surgeon understanding of anatomical spatial changes during surgery to optimise preoperative planning	Italy	Descriptive survey	6 HPB surgeons and 6 radiologists n = 12	CT and MRI 3D Slicer FFF	ABS	N/S N/S	Transparent 3DPLM improved surgeons' understanding of positional changes of intrahepatic structures during surgery
Huettl et al. (2021) [53]	Comparing the clinical value of 2D imaging, 3DVR and 3DPLM regarding preop planning for liver surgery	Germany	Quasi-experimental	Medical students and HPB doctors n = 30	CT Synapse 3D N/S	TPUR, ABS	N/S N/S	Use of 3DPLM enables partially faster and more accurate identification of liver tumour location
Raichurkar et al. (2021) [54]	Investigate the feasibility and clinical utility of a patient-specific 3DPLM for preoperative planning in living donor liver transplants	India	Case report	Paediatric patient with end stage liver failure n = 1	CT Osirix Material jetting	Silicone	25,000 Rupees ~One week	3DPLM improved visualisation of hepatic structures and facilitated surgical planning through preoperative simulation
Tan et al. (2021) [55]	Develop a high-fidelity, durable and soft 3DPLM with a hollow biliary system for surgical planning and simulation	Germany	Case report	3DPLM n = 1	N/S SolidWorks, Meshmixer FFF	Silicone rubber, rubber-like photopolymer TangoBlack+, ABS	N/S N/S	3DPLM accurately mimicked human liver tissue and successfully simulated surgical procedures
Al-Thani et al. (2024) [56]	Develop a realistic 3DPLM for HCC preoperative planning	Qatar	Descriptive survey	HPB surgeons n = 3	CT SolidWorks, Blender FFF	Mold: ABS Phantom: silicone, gelatine	N/S N/S	A flexible 3DPLM made from 10% gelatine to water mixture showed decent fidelity to real liver tissue which may hold value in improving medical training and preoperative planning
Giehl-Brown et al. (2023) [57]	Investigate the influence of 3DPLM on preoperative decision making and patient satisfaction	Germany	Randomised controlled	Patients presenting for liver surgery n = 40	CT Meshmixer and segmentation by MeVis FFF	PLA	N/S N/S	3DP group had improved understanding of their liver disease and surgery; no significant difference between non-3DP and 3DP group

Abbreviations—2D: 2-dimensional, 3D: 3-dimensional, 3DPLM: 3D-printed liver model, 3DP: 3D printer, 3DVR: 3D volume rendering, HCC: hepatocellular carcinoma, HPB: hepatopancreatobiliary, CT: computed Tomography, MRI: magnetic resonance imaging, FFF: fused filament fabrication, SLA: stereolithography, ABS: acrylonitrile butadiene styrene, TPU: thermoplastic polyurethane, TPUR: transparent polyurethane rubber, PVA: polyvinyl acetate, PLA: polylactic acid, PETG: polyethylene terephthalate glycol, DLP: digital light processing, LCD: liquid crystal display, PA12: polyamide 12, N/S: not specified.

Due to the heterogeneous nature of the included literature the MMAT from Hong et al. [59] was used for quality assessment, with the results shown in Appendix A Table 1A-5A. All studies included were eligible for appraisal using the MMAT as they met the screening criteria. Therefore, 11 articles met 75-100% of the MMAT criteria, indicating high-quality. There were 13 articles that met 50-75% of the MMAT criteria, representing moderate quality, and one article [35] met less than 50% of the evaluation criteria indicating low quality. A principal limitation of the included studies and by extension this review, is the small proportion of methodologically rigorous study designs for the application of 3DPLMs in clinical education and surgical planning. Most of the reported evidence is descriptive, qualitative, or case reports, and lack methodological rigour or statistical significance, therefore, generalisations cannot be made regarding the use of 3DPLMs in hepatobiliary education and surgical planning. However, in this review, distinct themes appear that may provide explanatory power for 3DPLM's clinical utility in hepatobiliary surgery and education potentially encouraging future research to rigorously investigate the influence of 3DPLMs on clinician education and patient surgical outcomes.

### 3.1. Surgical Planning and Intraoperative Guidance

Fourteen studies (56%) described the use of 3DPLMs improving surgical planning for hepatobiliary surgeries [6,36,37,40,43,44,46,48,50–54,56]. With ten of these studies being original research articles [6,36,37,40,43,44,46,50,53,56]. The remaining three investigated how patient-specific 3DPLMs enhanced trainee surgeons' anatomical understanding and surgical planning [37,43,53], however, their observations were less applicable to the preoperative decision-making of experienced surgeons.

Four articles (16%) reported the clinical utility of 3DPLMs for intraoperative navigation and guidance during hepatobiliary surgery [6,40,41,49]. Two of them were original research studies that supported these findings [6,40]. The remaining two studies were qualitative [41] and case report [49] evidence, thus restricting their generalisability.

### 3.2. 3DPLMs Can Improve Patient Outcomes

One study by Yao et al. [50] demonstrated that the use of 3DPLMs could significantly reduce intraoperative and postoperative surgical complications, thus improving patient outcomes. The majority of the remaining articles did not demonstrate statistically significant enhancements in surgical outcomes for patients [6,34,36,37,39,40,43,44,47–49,55,57]. However, there was still considerable evidence (mostly qualitative, descriptive or case report evidence) to suggest the use of 3DPLMs can improve hepatobiliary surgical planning, performance and safety thereby improving patients' clinical outcomes.

Four articles (16%) reported how the use of 3DPLMs can improve patients' comprehension of their hepatobiliary anatomy, pathology and planned surgical intervention, improving their capacity to give informed consent [43,48,49,57]. Of these articles, two are original research studies [43,57].

### 3.3. Clinical Education and Surgical Simulation

Eight articles (32%) described how 3DPLMs can improve anatomical/surgical teaching of the hepatobiliary system and related surgical procedures [35,37,38,43,45,47,55,56]. Only two of these were original research articles that demonstrated the use of 3DPLMs in clinical teaching can significantly improve surgical trainees' understanding of hepatobiliary anatomy and pathology and

surgical procedures [35,37]. The remaining six articles are primarily case reports, descriptive or qualitative evidence [38,43,45,47,55,56]. However, their findings further suggested the use of 3DPLMs may provide a suitable alternative to traditional clinical education methods, such as cadaveric material, 3D volume renders (3DVR) or atlases. Compared with conventional methods, 3DPLMs may improve surgical trainees' spatial understanding of liver anatomy and pathology as well as their comprehension of surgical procedures.

Seven articles (28%) demonstrated the use of 3DPLMs for surgical simulation for hepatobiliary surgery [34,36,39,42,44,49,51]. Only three of these are original research articles [34,36,39]. The remaining four provided case report or descriptive evidence [42,44,49,51]. Despite most evidence comprising qualitative, descriptive or case report evidence, this evidence suggests that the use of 3DPLMs may improve the preparedness of trainee surgeons and by extension their surgical performance.

#### 3.4. Diversity of 3DPLM Development and Technical Innovation

The diverse 3DP materials, technologies, costs and times in 3DPLM production are demonstrated in Table 2. In this review, fused filament fabrication was the most common 3DP technology reported (44%), followed by stereolithography (28%) and material jetting (16%). This is consistent with the commonly utilised 3DP materials which include silicone (28%), acrylonitrile butadiene styrene (24%), and polylactic acid (20%). To represent liver parenchyma, transparent materials (silicone or silicone-like material) were used in nine articles (36%).

Across the included articles, the utilised imaging protocols, segmentation and processing methods were varied. However, the 3DPLMs accuracy was generally satisfactory for clinical use with studies describing CT-validated spatial errors of less than five millimetres [40,43,48,49] or <0.6%-2% [43,46,55]. Most of the articles developed 3DPLMs based on CT datasets (76%), three articles used a combination of MRI and CT imaging data, two studies used anatomical atlases, and one study exclusively used MRI imaging data, to segment their 3DPLMs.

#### 3.5. Need for Experimental Studies

A majority of the articles described the necessity for more methodologically rigorous, true-experimental research to demonstrate the feasibility and clinical utility of 3DPLMs in preoperative and intraoperative hepatobiliary surgical outcomes and in surgeon education [6,34–37,40–43,46,50,53,54,57]. Further research is also required to determine a standardised, best-practice approach to the production of 3DPLMs regarding monetary and time considerations [34,36,41,42,46,47].

## 4. Discussion

Several key findings have been identified from the analysis of the 25 articles included in this review. First, the use of 3DPLMs can improve intraoperative guidance and surgical planning in hepatobiliary surgery by providing a tangible representation of a patient's liver pathology and anatomy. 3DPLMs provided a tool that improved a patient's comprehension of liver anatomy facilitating more accurate and targeted surgical plans and enhancing surgical decision-making. Therefore, 3DPLMs may improve overall surgical outcomes for patients undergoing hepatobiliary surgery. Second, this review highlights their use of 3DPLMs to improve spatial reasoning, tumour localisation, surgical confidence and procedural understanding amongst experts and trainees regarding their pedagogical value.

Historically, CT and/or magnetic resonance imaging (MRI) images of patients have been used for hepatobiliary surgical planning. The clinician then uses the 2D axial and multiplanar images or 3DVRs to establish appropriate biliary/vascular reconstruction approaches and planes of dissection/resection. This requires the surgeon to view these images on a 2D screen and to conceptualise a 3D visualisation mentally of a patient's complex liver pathology and anatomy.

3DPLMs can assist this by providing a tactile [34,40,44,51–54,56], cognisable [6,35,37,39,40,42,44,49–51,53–55,57], colour coded [6,35,40–44,47–49,52,53,57], transparent [35,39–41,43,45,52–54], self-healing [44], and manipulable [34,36,37,41,43,51] representation of patient-specific liver anatomy. This improves liver tumour localisation [35,37,43,53] and enhances the comprehension of the highly varying and intricate and spatial relationships between hepatic internal structures [38,41,42,45,47,52]. This improved understanding of anatomy supports clinicians in choosing the most appropriate surgical techniques [6,34,36,37,49,50,52] and resection planes [40,42–44,54].

The previously described depiction of 3DPLM's value in preoperative planning and intraoperative guidance is predominantly based on case reports or qualitative evidence which limits its external validity. Lopez-Lopez et al. [43] surveyed hepatobiliary surgeons, who indicated that using a 3DPLM could improve preoperative planning and intraoperative guidance by providing improved 3D visualisation of margins and planes of resection and enhanced perception of spatial relationships. Fukumitsu et al. [40] report the potential value of 3DPLMs in complex hepatobiliary cases where surgical approaches must be modified and their usefulness as an intraoperative navigation system to minimise accidental bleeding and secure planned hepatectomy resection lines. These studies suggest 3DPLM's clinical utility for preoperative planning and intraoperative guidance; however, they are limited by small sample sizes and a lack of methodological rigour. Further studies warrant the use of 3DPLMs in surgical planning for the medical intern population. A randomised controlled trial showed statistically significant improvements in interns' ability to appropriately design surgical plans compared to using 3DVR or CT [37]. Furthermore, Igami et al. [41] performed an ethnographical study that suggested the clinical value of 3DPLMs for intraoperative guidance in non-expert surgeons. While these studies were conducted with greater methodological rigour, they demonstrate 3DPLMs only among hepatobiliary surgical interns. However, Heuttl et al. [53] conducted a quasi-experimental study that indicated there was no statistically significant difference in the surgical planning ability of experienced hepatobiliary surgeons' when using 3DPLMs or 3DVR. While this study lacked adequate controls (e.g., 2D axial imaging) or sample size, it may suggest that the clinical utility of 3DPLMs for experienced hepatobiliary surgeons is redundant [6]. Therefore, the clinical merit of 3DPLMs may be constrained to complicated surgical hepatobiliary cases, where there are complex liver-tumour relationships or the lesion location is deep to intrahepatic structures [6,36,41,43,46,48].

Hepatobiliary surgeons must be skilled in relating 2D reconstruction of a patient's liver anatomy with the surgical field [6]. Multiple studies, therefore, suggest the value of 3DPLMs for intraoperative navigation in hepatobiliary surgery [6,40,41,49,50]. Surgeons can position and contrast the 3DPLM directly in the operating field thus enhancing their understanding and navigation of liver anatomy. Therefore, 3DPLMs can be used to confirm the localisation of intrahepatic vasculature to modify surgical approaches, improve localisation and identification of lesions and may reduce the risk of intraoperative complications. However, these findings are again drawn from case report or qualitative evidence, lack methodological rigour and cannot be generalised. There was only one article by Cheng et al. [6] that stated that the use of 3DPLMs in preoperative planning and real-time intraoperative guidance led to modifications in surgical strategies for four patients (16.7% of cases) due to the model providing enhanced localisation of intrahepatic structures. However, this study was limited by the heterogeneity of included cases and small sample size.

While 3DPLMs have demonstrated preoperative and intraoperative benefits in hepatobiliary surgery, this review identified limited significant evidence suggesting their value in improving patient surgical outcomes. Only six of the identified studies included in this review reported patient intraoperative or postoperative outcomes [6,40,43,46,50,57]. There was a limited statistically significant positive correlation between the application of 3DPLMs and surgical operating time, blood loss, pathological outcomes, intraoperative outcomes, postoperative complications, recovery conditions, deviation of surgical concept and duration of hospital stays. However, Yao et al. [50] demonstrated significant improvements in intraoperative blood loss, postoperative complications and major complications in patients who received the 3DPLM compared with a control group,

however, this finding is not supported by the broader literature. Though there is limited significant evidence regarding patient outcomes, this does not negate the possible value of 3DPLMs in influencing those outcomes. The lack of significance in these studies may be attributed to small sample sizes that does not overcome the heterogeneity the included cases, single-centre designs, subjective measures and differences in surgeon experience [6,40,43,57]. Overall, there is a large amount of qualitative evidence supporting the use of 3DPLMs to improve hepatobiliary surgical approaches thus minimising potential complications. Which in turn may increase the chance of postoperative success and decrease the likelihood of future complications, suggesting that 3DPLMs may directly enhance clinical outcomes. From the literature, what is clear is that there is a need for multi-centred, methodologically rigorous clinical trials to verify the clinical use of 3DPLMs in preoperative planning and intraoperative guidance in hepatobiliary surgery [6,40,43,50,57]. A study developed by Huber et al. [61] aims to address these limitations by including sufficient patients and appropriate control groups and was scheduled for completion in 2024. Studies of this calibre are paramount to advancing the clinical utility of 3DPLMs.

3DPLMs could potentially improve patients' comprehension of their pathology, surgical procedure and post-operative complications [43,48,49,57]. Giehl-Brown et al. [57] performed a randomised controlled trial demonstrating statistically significant improvements in patients' understanding of their surgical procedure when 3DPLMs were used compared with patients who received standard education sheets. Lopez-Lopez et al. [43] also reported improved patient understanding and communication following the use of 3D-printed liver models is indicated by questionnaire responses; however, they did not state whether this was statistically significant. This finding is consistent with the current literature regarding the educational value of 3D-printed models in patient education [62–64]. By using 3DPLMs to enhance patients' knowledge about their hepatobiliary surgery it can enhance their ability to give informed consent and participation in preoperative decision-making [57]. Greater understanding of healthcare following 3DPLM-based surgical education may also increase a patient's postoperative compliance, positively correlating with a decreased postoperative complication and length of hospital stays [57].

The current evidence highlights the extensive role of 3DPLMs in hepatobiliary anatomical education and surgical training with broad consensus among experts and trainees regarding their pedagogical value. For anatomical teaching, 3DPLMs may exceed conventional methods such as atlas-based learning, by improving anatomical understanding [37,42,45,53], spatial visualisation [37,42,45,53], procedural comprehension [34,35], surgical planning [37,42,43] and tumour localisation [37,45,53]. Furthermore, it is reported that the trainees exhibit higher levels of confidence and satisfaction regarding hepatobiliary education and surgical procedures [34,35,37,42]. 3DPLMs provide greater retention of spatial knowledge through visual-haptic multisensory integration, allowing trainees to comprehend and observe hepatobiliary anatomy from multiple perspectives thus developing their understanding of intrahepatic structures. Furthermore, 3DPLMs enable trainees to practise surgical procedures in a simulated environment becoming familiar with surgical techniques demonstrating increased proficiency in real surgeries. These 3DPLMs provide a low-risk scenario for recognising and rectifying technical errors, potentially mitigating the risk of intraoperative mishaps and complications. The included studies conduct isolated training sessions that provide proof of concept, but do not indicate long-term retention of knowledge or skill. Despite promising results, these studies are limited by short training exposures, minimal longitudinal data and small sample sizes.

This review extends previous systematic reviews by providing a comprehensive and critical synthesis of the use of 3DPLMs across both clinical education and surgical planning [26,27,31,32]. Prior reviews have typically focused on either educational applications or surgical planning in isolation, this review integrates both domains to evaluate 3DPLMs clinical utility. By incorporating current literature and offering an analysis of educational, technological and clinical utility this review provides a more comprehensive and critical perspective to guide future research and clinical implementation.

## 5. Conclusions

This review provides further evidence suggesting the use of 3DPLM as a critical tool in hepatobiliary clinical education and surgical planning by improving anatomical understanding, skill acquisition and preoperative and intraoperative guidance. These models offer a reproducible, safe platform for complex surgical rehearsal which could optimise clinical decision-making and improve procedural performance in hepatobiliary surgery. Future studies should prioritise longitudinal, randomised controlled, multi-centre trials with large sample sizes to determine the feasibility and clinical value of 3DPLMs in hepatobiliary surgery. This future research should focus on investigating perioperative and postoperative patient surgical outcomes. Additionally, such studies should assess the long-term impact of 3DPLM use in clinician education, including anatomical and surgical understanding to better establish its benefits.

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