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Review

Surgical Anatomy for Liver Cancer: Revisiting Segmental Liver Anatomy Beyond Couinaud in the Era of 3D Simulation and Minimally Invasive Liver Resection

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Abstract

Couinaud's eight-segment model remains the universal language of liver surgery; however, contemporary multidetector computed tomography (CT), three-dimensional (3D) reconstruction, and minimally invasive surgery have exposed substantial variability in third-order or more peripheral portal branching. This variability becomes clinically important when hepatocellular carcinoma and other liver malignancies are treated with small, parenchymal-sparing anatomical resections, where third-order or more peripheral portal territories define the oncologic unit at risk. This review examines the current evidence of surgical anatomy relevant to liver surgery, focusing on third-order portal branches and comparing classical Couinaud segmentation with CT/3D reconstruction-based portal territories. Clinically relevant variations in the right anterior (S5/S8) and right posterior (S6/S7) sections are described, while the more limited and heterogeneous evidence for the left hemiliver is explicitly acknowledged. In the right anterior section, craniocaudal, ventrodorsal, trifurcation, and other branching patterns may alter the practical interpretation of S5/S8 anatomy. In the right posterior section, bifurcation and loop-type portal configurations have distinct implications for S6/S7-oriented resection and individual anatomy-based resection. Comparable variability in the left hemiliver, particularly around the umbilical portion and segment 4 branches, further supports individualized preoperative territory mapping. A two-level anatomical planning framework is proposed as a conceptual strategy: Couinaud-based anatomy for first- and second-order resection and individualized CT-based anatomy for third-order or more peripheral resection. This framework is supported by anatomical observations and technical feasibility, but it has not been shown to improve perioperative or oncological outcomes. Evidence supporting anatomical liver resection in general should not be regarded as direct validation of cone-unit (small portal territory) resection, which requires prospective and independent clinical evaluation. The current status of preoperative simulation and intraoperative implementation using ultrasound, indocyanine green fluorescence, and navigation/fusion technologies is discussed. Finally, emerging directions, including automated vessel segmentation and AI-assisted territory analysis, are considered.

Keywords: Couinaud's segmentation; portal vein; third-order branches; cone unit; 3D CT reconstruction; anatomical liver resection; hepatocellular carcinoma; indocyanine green; navigation

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1. Introduction

Couinaud's description of functionally independent liver segments provided the conceptual foundation for anatomical liver resection and remains a standard framework in hepatobiliary surgery [1]. The Brisbane 2000 terminology harmonized international nomenclature and reinforced the hierarchical view of liver division (first-order hemiliver, second-order section, third-order segment) [2,3]. However, Brisbane 2000 did not define how to identify segmental borders in vivo or how to describe anatomical units smaller than one segment. The Tokyo 2020 update, developed by the Precision Anatomy for Minimally Invasive HBP Surgery (PAM-HBP) consensus, explicitly addressed the anatomical resection of a segment or smaller units and introduced standardized terminology for peripheral portal territories, including the 'cone unit' [4]. A cone unit is a three-dimensional (cone-shaped) liver parenchymal territory supplied by a selected third-order or more peripheral Glissonean pedicle. Unlike a Couinaud segment, which is a conventional named unit intended for the universal language of liver anatomy, a cone unit is patient-specific, may be smaller than a segment or a subsegment, and is defined by the actual branching and perfusion territory of the selected peripheral portal pedicle.

With current multidetector computed tomography (CT) and routine three-dimensional (3D) reconstruction, surgeons can interrogate portal branching beyond the third-order, and studies have shown that portal territories distal to the second-order branches frequently diverge from classical Couinaud borders. Intersegmental hepatic veins do not always coincide with true portal 'watersheds', especially at third-order or more peripheral levels [5–8]. This discordance is most consequential in liver cancer management. Hepatocellular carcinoma (HCC) can spread within portal territories via microscopic portal invasion and dissemination, providing the biologic rationale for anatomical resection of the tumor-bearing portal territory [9–11]. Since many patients have chronic liver disease, parenchymal-sparing anatomical resection at the subsegmental level is increasingly pursued to balance oncologic clearance with functional preservation [9–12]. In addition, the recent widespread adoption of minimally invasive liver resection has increased the importance of small anatomical resection. Disorientation may occur during complex parenchymal-sparing laparoscopic resection of small deep tumors because of reduced tactile feedback and the trade-off between a magnified local view and an overview of the entire operative field. In this setting, resection of the small anatomical territory containing the tumor has been increasingly adopted [4,5]. Resection of the accurately mapped tumor-bearing territory can facilitate removal of the lesion even when continuous direct localization of the tumor is difficult during surgery.

In this narrative review, we examined the current evidence of surgical anatomy relevant to liver surgery, comparing conventional Couinaud segmentation with CT/3D reconstruction-based portal territories at third-order portal branches. Clinically relevant variability in the right anterior (S5/S8) and right posterior (S6/S7) sections are described, while the more limited and heterogeneous evidence for the left hemiliver is explicitly acknowledged. A viewpoint of two-level anatomical planning for liver resection is proposed: planning with Couinaud-based anatomy for first- and second-order resection and that with individualized CT-based anatomy for third-order or more peripheral resection. The latter is presented as an anatomically and technically supported concept that may assist description and operative planning in selected cases; it is not a clinically validated standard. Its clinical utility, perioperative and oncological effects, and generalizability across the liver require prospective, independent validation. The current status of preoperative simulation and intraoperative implementation using ultrasound, indocyanine green fluorescence, and navigation/fusion technologies is discussed. Finally, we also discuss emerging directions, including automated vessel segmentation and AI-assisted territory analysis.

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This article was prepared as a narrative review. PubMed/MEDLINE, Embase, and the Cochrane Library were provisionally searched from database inception to 31 August 2026 using combinations of the terms 'liver anatomy', 'Couinaud', 'portal vein', 'third-order portal branch', 'peripheral portal territory', 'cone unit', 'anatomical liver resection', 'parenchymal-sparing hepatectomy', 'three-dimensional simulation', 'navigation', 'hepatic vein', 'hepatocellular carcinoma', 'intrahepatic cholangiocarcinoma', and 'colorectal liver metastases'. Reference lists of relevant reviews, consensus statements, and key original studies were also screened. English-language anatomical studies, clinical series, consensus documents, systematic reviews, and methodologically relevant technical reports were selected when they directly addressed peripheral portal or venous anatomy, individualized territory mapping, or clinical implementation of limited anatomical resection. This was a narrative review and the approach was not equivalent to a systematic review: study selection was purposive rather than protocol driven, screening and extraction were not performed through a formal systematic-review workflow, and no formal risk-of-bias or certainty-of-evidence assessment was undertaken. The cited literature was used to construct and critically discuss an anatomical and technical hypothesis, not to establish comparative clinical effectiveness. Accordingly, further universal prospective examinations are needed for establishing comparative effectiveness or supporting a clinical recommendation in liver resection.

2. Couinaud's Segmentation and CT/3D Territory-Based Segmentation

Couinaud's segmentation is robust for planning major hepatectomy and sectionectomy because it aligns closely with first- and second-order portal division in most patients [1,2]. In this context, portal inflow territories and major hepatic veins provide reproducible reference planes. However, Couinaud's model implicitly assumes that each third-order portal branch supplies a consistent segmental territory with almost equal volume and one main trunk of portal vein, except segment 1. Contemporary imaging demonstrates that a Couinaud segment may contain multiple third-order branches of variable size and orientation, and their perfusion territories can cross classical borders [6,13]. This becomes clinically relevant when the operative goal is to remove the tumor-bearing portal territory at the segmental or subsegmental level.

Three-dimensional reconstruction using preoperative contrast-enhanced CT depicts the liver parenchyma, portal and hepatic venous trees, tumors, and the spatial relationship between planned resection territories and preserved vessels. Its established value is primarily anatomical visualization, volumetry, and recognition of vascular variants [13–15]. Virtual hepatectomy can support the estimation of resection volume and surgical margins; however, these capabilities should not be equated with proven improvement in long-term oncological outcomes. Comparative evidence for reductions in blood loss or complications is encouraging in selected settings but remains heterogeneous, and robust outcome data specifically validating cone-unit resection are not yet available.

For portal anatomy, CT-based series revealed frequent variants of portal branching. CT arterial portography and multidetector CT studies have reported portal vein variants in approximately 20–35% of patients, emphasizing the need to recognize variants before complex resection, portal vein embolization, or transplantation [16–19]. Even when first- and second-order anatomy is conventional, variability increases distally, and third-order or more peripheral territories cannot be assumed from a schematic standard atlas of Couinaud's segmentation.

3. Third-Order or More Peripheral Portal Anatomy in the Liver

3.1. Right Anterior Section

Significant variability exists in the branching and territorial configuration of the right anterior section at the level of the third-order branches and beyond. Although the classical Couinaud framework divides this region into a cranial segment 8 and a caudal segment 5, the actual territory supplied by individual third-order portal pedicles in the anterior section does not always follow a simple cranio-caudal arrangement. This uncertainty is clinically important because the border between S5 and S8 lacks a consistently visible anatomical landmark, and limited anatomical resections in this region often require the surgeon to choose between a Couinaud-based craniocaudal concept and a patient-specific portal territory [1,6,20–25].

The ventro-dorsal concept was strongly promoted by Cho, Ryu, and colleagues. In their 3D CT/CTAP-based re-evaluation of right-liver portal ramification, all branches arising from the right anterior trunk were divided into right ventral portal branches and right dorsal portal branches, with the anterior fissure vein crossing between these two territories. Therefore, they proposed that the anterior section could be divided into ventral and dorsal components rather than into S5 and S8 (caudal and cranial ones) and described the anterior fissure as a surgically exploitable plane—the so-called "third door" of the liver [21,22]. In this concept, the right anterior section is divided into the antero-ventral segment and antero-dorsal segment, demarcated by the anterior fissure vein; however, subsequent MDCT evaluation showed that, although the anterior fissure vein could frequently be identified, its use as a reliable boundary was sometimes difficult, particularly when it drained proximally into the middle hepatic vein or when the venous course did not clearly form a parenchymal plane [23].

Later comparative 3D analyses refined this debate rather than replacing one model with the other. Kobayashi et al. reported that the right anterior portal vein showed a craniocaudal pattern in 53% of patients, a ventro-dorsal pattern in 23%, a trifurcation pattern in 13%, and miscellaneous patterns in 11%; V8 was identified in 91% of evaluable patients but served as a useful ventro-dorsal landmark in only 63%. These findings support the view that ventro-dorsal segmentation is anatomically meaningful in selected patients, but that ventro-dorsal segmentation to every right anterior section cannot be applied universally [24]. Similarly, Ishii et al. classified right anterior tertiary portal ramification into craniocaudal, ventrodorsal, trifurcation, and quadfurcation types, and further highlighted the PV8c branch, identified in 53.6% of patients, as a small but characteristic medial horizontal branch that may complicate strict assignment of peripheral territories to standard S5/S8 or ventral/dorsal labels [25].

From a surgical standpoint, the right anterior section should therefore be treated as a high-variability area in which the operative unit is determined by the individual portal territory rather than by a fixed schematic border. In patients with a clear craniocaudal pattern, S5- or S8-oriented anatomical resection remains reasonable; in patients with a clear ventro-dorsal pattern, ventral or dorsal anatomical resection of the anterior section may better match the true portal drainage territory. Hepatic vein-guided approaches leveraging the anterior fissure vein, middle hepatic vein, right hepatic vein, and V8 can be useful to standardize parenchymal-sparing anatomical resection, but these landmarks should be interpreted in the context of preoperative 3D simulation rather than used as independent substitutes for portal-territory mapping (Figure 1C,D) [21–26].

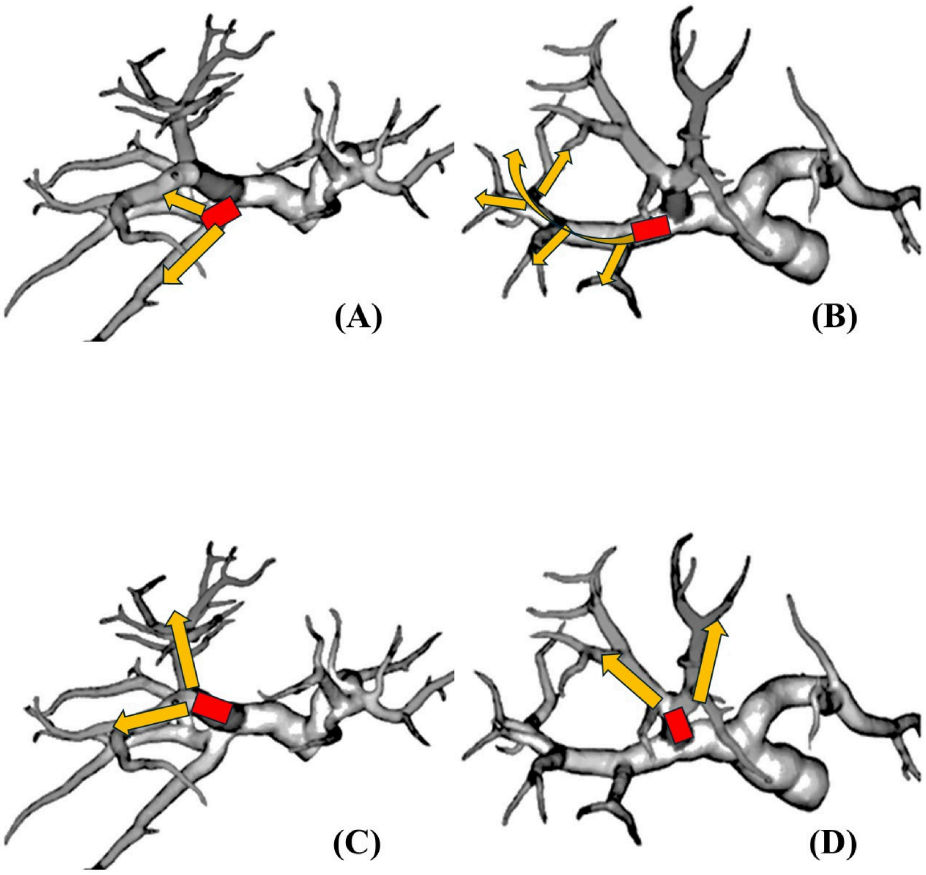


Figure 1. Variability of third-order portal branching patterns in the right posterior (S6/S7) and right anterior (S5/S8) sections. ((**A**) Front view) Couinaud-type P6/P7 bifurcation of the right posterior portal branch. ((**B**) Caudal view) Loop/arch-type posterior branching with a single trunk issuing sequential branches. ((**C**) Front view) Couinaud-type craniocaudal branching concept in the right anterior section. ((**D**) Caudal view) Ventral/dorsal branching concept in the right anterior section.

3.2. Right Posterior Section

Third-order anatomy of the right posterior section has been extensively studied. S7 anatomical resection and posterior sectionectomy are technically demanding, especially in minimally invasive procedures [7], and right posterior section grafts for living donor transplantation have also been reported recently [27]. These procedures depend heavily on peripheral portal and venous landmarks during surgery. A CT during arterial portography study demonstrated that a Couinaud-type bifurcation into P6 and P7 occurred in only 41% of cases; 50% of cases showed a loop-like single trunk issuing sequential branches, and 9% showed trifurcation with an intermediate branch occupying the putative S6/S7 border (Figure 1A,B) [28]. Furthermore, a subsequent 3D CT study proposed intersegmental veins as landmarks between S6 and S7 and reported high identification rates in the initial laparoscopic application [29].

In our previously published study, we retrospectively analyzed CT-based 3D reconstruction images of the portal and hepatic veins [30] (Table 1). Among the 100 cases, the posterior portal vein was divided into two major branches supplying segments 6 and 7, with subsequent peripheral arborization, in 45 (bifurcation type). In 53 cases, the posterior portal vein formed a loop-type trunk that issued sequential small branches (loop type). The remaining two cases (2%) were categorized as other patterns: one showed simultaneous multiple branching after the common stem, and one had a P6 branch arising from the right anterior portal system. In the bifurcation type, the 3D length of the common stem

before the bifurcation measured 8.89 ± 7.87 mm, and the volume of Segment 6 (the area supplied by the first branch toward the right caudal direction = Segment 6) corresponds to 43.8% ± 12.6% of the whole right posterior section. In the loop type, the 3D distance from the origin of the right posterior portal vein to the first branch measured 17.3 ± 8.36 mm, which is approximately twice that in the bifurcation type ($p < 0.001$), and the volume of the first-branch portal territory corresponds to 14.9% ± 8.64%, which is approximately one-third of that in the bifurcation type ($p < 0.001$). Our data show that when the first branch from the posterior trunk is divided earlier, the branching type tends to be bifurcation type, and the volume of the area supplied by the first branch from the posterior trunk is much larger in the bifurcation type than in the loop type. Hepatic vein anatomy in the posterior section was also categorized in our study as HV type 1 (presence of portal fissure-plane forming intersegmental vein), HV type 2 (presence of landmark vein without plane formation), or HV type 3 (neither). The distributions of these hepatic venous patterns were compared between portal branching types to assess their surgical implications. The HV-type 1/2/3 distributions according to portal branching pattern were 29:16:0 (64.4%:35.6%:0%) in the bifurcation type and 25:14:14 (47.2%:26.4%:26.4%) in the loop type ($p < 0.001$). In the bifurcation type, the IRHV or the distal part of the RHV always lies between segments 6 and 7 as landmarks for segmentectomies, and their tributaries frequently (in almost two-thirds of cases) delineate the intersegmental fissure plane between the caudal and cranial parts (S6 and 7). In the loop type, one-fourth of patients had neither a venous landmark nor a fissure-plane-forming vein. Wang et al. identified an intersegmental fissure vein (ISV) between S6 and S7 in 82% of patients (derived from the RHV in 92% and IRHV in 8%) and successfully implemented ISV-guided laparoscopic segmentectomies with favorable perioperative outcomes, including R0 rates [29]. In contrast to their findings, a fissure-plane-forming ISV was not identified in 35.6% and 52.8% of cases in Bifurcation and loop types of portal vein branching pattern, respectively, in our study. Furthermore, 26.4% of loop-type cases lacked even a non-plane-forming landmark vein. These findings identify anatomical discordance that may be relevant when planning segmentectomy or smaller anatomical resections in the posterior section. Although Couinaud's classification of segments 6 and 7 is applicable to patients with bifurcation-type anatomy, approximately half of patients have loop-type branching, sometimes without venous landmarks, and do not fit this model. The strategy based on Couinaud's classification (segments 6 and 7) using a Glissonean and/or hepatic vein-guided approach remains valuable for approximately half of patients. However, the remaining patients may not fit this strategy. In patients with loop-type portal branching without an intersegmental venous landmark, individualized peripheral portal mapping may provide an anatomical description for preoperative planning. Since these observations derive predominantly from our single-center retrospective mapping study without real surgical data using it, it should be prospectively examined whether surgical planning based on portal mapping can improve technical, perioperative, or oncological outcomes of performed surgery [4,31–36].

The oncological rationale for portal-territory resection is strongest for HCC, in which microscopic portal venous invasion and intrahepatic dissemination along portal branches are well recognized [9–12,37]. This rationale may also be relevant to intrahepatic cholangiocarcinoma, for which retrospective comparative evidence suggests a possible survival advantage of anatomical over non-anatomical resection, although tumor biology, lymphatic spread, and margin status remain major determinants [38]. In bifurcation-type posterior anatomy, a major cranial or caudal branch defines a plausible shared portal territory at risk. In contrast, in loop-type anatomy, adjacent cone units drain separately into the posterior trunk. Theoretically, dissemination from one cone unit to an adjacent unit may be less direct, and the conventional division of the posterior section into cranial and caudal parts

may be less relevant, as shown in Figure 2. The evidence of anatomical resections is mostly derived from first- or second-order portal territories, not presented for the level of cone units (third or more peripheral orders). This proposed theoretical hypothesis requires rigorous clinicopathological validation. Figure 2 is therefore only an illustration of a branching-based hypothesis and should not be interpreted as proven evidence of tumor behavior, a rationale for limiting resection or cone-unit resection directly without validation. However, even taking these undefined factors into account, accompanied by the absence of supporting evidence for anatomical resection in metastatic cancers, the importance of cone unit resection is increasing under the recent widespread adoption of minimally invasive liver resection. Decreased tactile feedback and overview of the operative field in the procedure can easily lead to disorientation. In this situation, resection of the accurately mapped tumor-bearing territory can facilitate the removal of the lesion, even when continuous direct localization of the tumor is difficult during surgery [4,5]. This proposed relationship between loop-type portal anatomy and tumor spread remains theoretical and has not been demonstrated by pathological mapping, recurrence-pattern analysis, or comparative clinical outcome data.

Table 1. Summary comparison of bifurcation- and loop-type right posterior portal anatomy and the proposed surgical planning implications from our previously published 100-case CT-based 3D mapping study [30].

Feature	Bifurcation Type	Loop Type
Portal configuration	Two major P6/P7 branches after a relatively short common stem	Sequential small cone-unit branches from a longer arch-like trunk
Prevalence (2% were other patterns)	45%	53%
Applicability of conventional S6/S7 concept	Applicable	Frequently incomplete or potentially misleading
Venous landmarks	RHV/IRHV landmark present in all cases; fissure-plane-forming vein in 64.4%	No venous landmark in 26.4%; fissure-plane-forming vein in 47.2%
Surgical planning implication	Couinaud-oriented segmentectomy with Glissonean and/or vein-guided approaches can be applied	Individualized cone-unit planning, integrating simulation and navigation, may be considered

Translating preoperative territory maps into intraoperative planes during surgery planned according to a cone-unit strategy requires complementary modalities. Reviews have summarized how indocyanine green (ICG) fluorescence can demarcate hepatic segments either by portal injection (positive staining) or intravenous injection after inflow control (negative staining) [32,33] (Figure 3). Prospective evidence suggests that ICG-guided recognition of boundaries is feasible and may reduce major liver-related complications in selected cohorts undergoing anatomical resection [35]. Real-time virtual sonography and fusion navigation systems can co-register intraoperative ultrasound with preoperative CT/3D simulation to navigate the planned planes in real time [36]. ICG guidance nevertheless has practical limitations, including variable staining quality, dependence on dose and timing, limited penetration of near-infrared fluorescence into deep parenchyma, and failure of a demarcation line to define the entire deep transection plane. Currently, ICG, intraoperative ultrasonography, and anatomical identification of portal and hepatic venous structures are used complementarily as components of multimodal navigation [32–35,39].

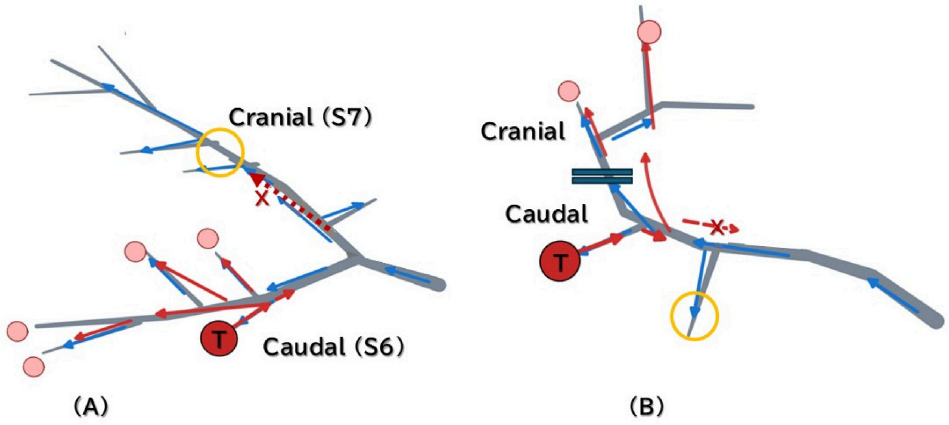


Figure 2. Hypothetical schema of possible tumor spread patterns in bifurcation- and loop-type posterior portal anatomy. (Adapted from Imanaka et al. [30] under the Creative Commons Attribution License.) (**A**) Bifurcation type; (**B**) loop type. The diagram illustrates an anatomical hypothesis based on portal branching and potential drainage pathways. Red circle with "T", tumor; pink circles, possible dissemination; blue arrows, physiological portal flow; red arrows, hypothetical drainage from the tumor-bearing area; interrupted red arrow with "X", a pathway hypothesized to be less direct; yellow circle, an adjacent territory potentially spared. This theoretical hypothesis requires rigorous clinicopathological validation. This figure is only an illustration of a branching-based hypothesis and should not be interpreted as proven evidence of tumor behavior, a rationale for limiting resection or cone-unit resection.

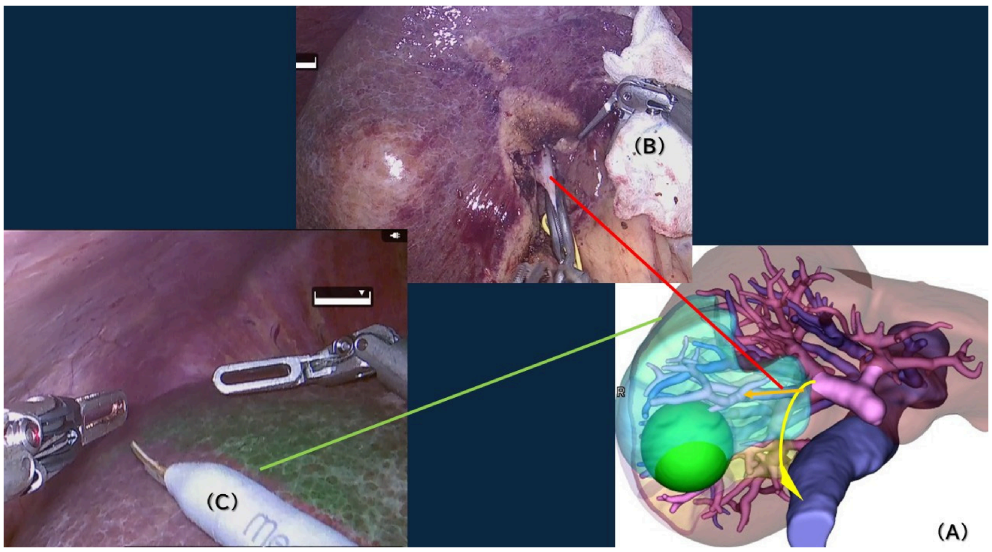


Figure 3. Simulation and navigation for liver resection. (Reproduced/adapted from Imanaka et al. [30] under the Creative Commons Attribution License.) (**A**) Preoperative CT simulation image. Purple, hepatic veins and vena cava; pink, portal vein; green, hepatocellular carcinoma; curved yellow arrow, looped posterior portal vein; ocher arrow, first third-order branch of the posterior portal vein. The tumor was mainly located inside the first third-order branch territory and robotic resection of an extended territory was planned. (**B**) Intraoperative findings. The first branch from posterior portal vein was dissected and clamped (red line). (**C**) ICG injection after clamping the branch showed a clear demarcation line indicating the tumor-bearing area.

3.3. Left Hemiliver

Comparable discordance exists in the left hemiliver. Portal and hepatic venous anatomy show fine-caliber variations around the umbilical portion, P2/P3 branching, segment 4 inflow, and tributaries of the left and middle hepatic veins, while comprehensive studies integrating these structures at cone-unit resolution are scarce [6,20,40–43]. The umbilical

portion is an intuitive landmark, but small branches may cross conventional S2/S3/S4 boundaries. Accordingly, neither portal inflow nor a single hepatic vein should be assumed to define a fixed deep plane. Patient-specific 3D mapping should identify the tumor-bearing portal pedicle and assess venous drainage in both the target and remnant territories. The greater detail devoted to the right posterior section in this review reflects the availability of recent quantitative data, including our own study, and a specific bifurcation-versus-loop framework, not anatomical uniformity of the left hemiliver. The fact that discordance existed in the left hemiliver has yet to be well documented, also limits generalization of the proposed anatomical hypothesis to the entire liver.

The left lateral section is generally more regular than the right anterior or posterior sections; nevertheless, the relationships among P2, P3, the left hepatic vein, and the umbilical portion do not always conform to a simple two-segment map. P2 is often represented by a single large branch, whereas P3 commonly arises from the left horn of the umbilical portion. Segment 4 is more variable, typically receiving multiple branches from the right horn and adjacent junctional areas [38]. Cranio-lateral branches arising from the cranial side of the umbilical portion have also been reported and may be relevant to right trisectionectomy, extended left-sided resection, and parenchymal-sparing procedures near the left portal trunk [39]. CT-based analysis has further shown that segment 4 may receive 2–8 portal branches, usually 3–6, with occasional branches from the transverse left portal vein or, rarely, the right portal vein [37]. These findings do not support rigid subdivision of segment 4 into S4a and S4b solely on the basis of portal inflow.

Therefore, for left-sided segmentectomy or smaller anatomical resections, planning should include the following: (i) identification of the origin and number of segment 4 branches; (ii) separation of the tumor-bearing territory from adjacent P2, P3, and P4 territories; (iii) assessment of the left and middle hepatic veins as potential, but not absolute, boundary landmarks; and (iv) intraoperative confirmation of the planned transection plane by ultrasonography, ICG fluorescence, or fusion navigation when available. This individualized approach is particularly important around the umbilical portion, where injury to an unrecognized segment 4 or cranio-lateral branch may cause unnecessary ischemia or congestion, whereas incomplete territory mapping may compromise anatomical clearance [6,32–39]. Further systematic studies integrating portal and hepatic venous variations at cone-unit resolution are needed.

4. Surgical Translation and Future Perspectives

A tiered view of anatomical concordance is clinically useful. At the first- and second-order levels, Couinaud's segmentation generally coincides with CT territory maps, enabling major hepatectomy and sectionectomy to remain Couinaud-based with minimal compromise [2–4]. Discordance increases at the third-order level, where segmental borders may not correspond to Couinaud's portal segmentations, and hepatic veins may not reliably delineate functional boundaries [5–8]. The PAM-HBP consensus emphasized that accurate border recognition requires integrating portal branching patterns, hepatic veins, and intraoperative modalities (ultrasound, fluorescence, and 3D simulation) rather than assuming fixed planes [6].

For tumors requiring major hepatectomy or sectionectomy, Couinaud/Brisbane-based planning remains appropriate because the resection unit corresponds to stable first- and second-order portal division and established venous planes [2–4]. In these cases, the main value of 3D simulation is risk assessment (future liver remnant, venous drainage, variant recognition) rather than redefining the unit of resection [14–16].

For parenchymal-sparing segmental or subsegmental anatomical resections, patient-specific mapping of a third-order or more peripheral portal territory may be considered as an anatomical planning aid for surgery in selected cases (Figure 4). The Tokyo 2020 terminology defines a 'cone unit' as a peripheral portal territory representing the smallest functional unit relevant to anatomical resection [4]. This concept is rooted in Glissonean pedicle-based anatomy [31] and has been popularized in minimally invasive limited liver resection. Although precise identification of the tumor-bearing territory is needed for safe limited resection, the specific conditions in minimally invasive liver resection, such as reduced tactile feedback and loss of an overview of the entire surgical field, easily lead to disorientation of tumors and other important structures. When third-order anatomy deviates from Couinaud borders, "cone-unit" planning, which involves resection of the small portal territory containing the tumor, may also reduce unnecessary loss of noncancerous parenchyma in cirrhotic patients. When cone-unit-based resection is performed, minimally invasive anatomical liver resection increasingly leverages standardized extrahepatic Glissonean pedicle isolation and hepatic vein-guided transection. Laennec's capsule-based approaches propose that dissection planes between the capsule and surrounding structures can standardize isolation of Glissonean pedicles and hepatic veins, potentially improving safety and reproducibility in this setting [44]. 'Inter-Laennec' approaches for tumors near major hepatic veins have also been described to preserve veins and avoid congestion while maintaining surgical margins [45]. Although existing reports of Glissonean, hepatic vein-guided, and Laennec's capsule-based approaches with navigation techniques demonstrate the feasibility of identifying or approaching small anatomical territories [31–36,44,45], they do not establish superiority of cone-unit resection [4] over conventional segmentectomy or non-anatomical resection oncologically. Selection of a resection must continue to incorporate tumor biology, required margin, liver function, venous drainage, technical feasibility, and alternatives including non-anatomical parenchymal-sparing resection.

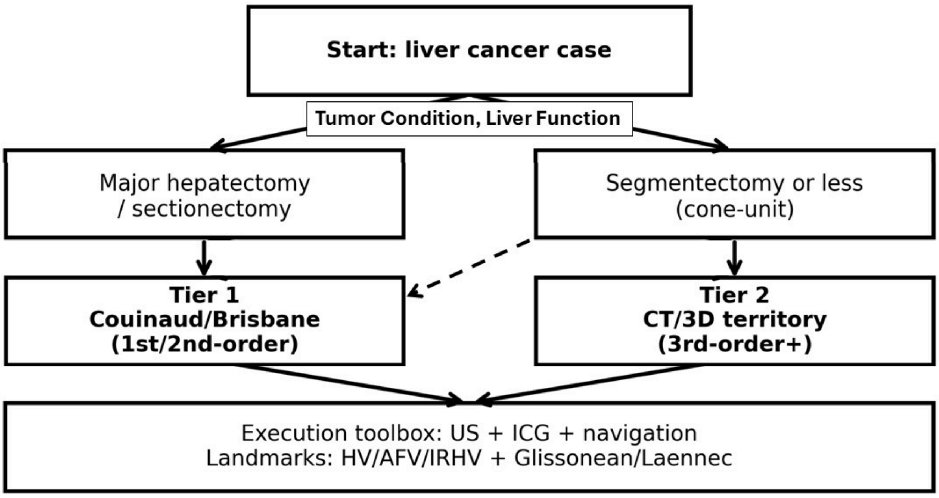


Figure 4. Two-level anatomical planning hypothesis based on anatomical hierarchy.

The schema distinguishes conventional Couinaud-based planning for liver resections at first- and second-order levels from optional patient-specific planning at third-order or more peripheral levels. Since supporting evidence is predominantly anatomical and technical and uneven across liver regions, independent replication of studies and comparative clinical validation are required to clarify whether this approach has perioperative or oncological benefits.

Translating preoperative CT-based territory maps into intraoperative planes during cone-unit-based surgery requires complementary modalities. Reviews have summarized how indocyanine green (ICG) fluorescence can demarcate hepatic segments either by portal injection (positive staining) or by intravenous injection after inflow control (negative staining) [32–34]. Prospective evidence suggests that ICG-guided recognition of boundaries is feasible and may reduce major liver-related complications in selected cohorts undergoing anatomical resection [35]. Real-time virtual sonography and fusion navigation systems can co-register intraoperative ultrasound with preoperative CT-based 3D simulation to navigate planned planes in real time [36].

The biological justification for removing the complete tumor-bearing portal territory is most direct in HCC and may also be relevant in intrahepatic cholangiocarcinoma because portal and intrahepatic microscopic extension can contribute to recurrence; nevertheless, current outcome evidence of anatomical resection does not validate resection of a specific cone unit level small resection [37,38]. For colorectal liver metastases and other secondary tumors, cone-unit planning is not primarily intended to prevent portal dissemination. Its value is to define a reproducible, patient-specific small resection volume that contains a deep lesion and an intended margin while preserving uninvolved parenchyma and minimizing residual ischemic or congested territories. This may be increasingly important in laparoscopic and robotic surgery, where palpation is limited and deep small tumors can be difficult to localize continuously during transection. Parenchymal-sparing strategies for colorectal liver metastases can preserve future treatment options and are compatible with acceptable oncological outcomes in selected patients, but the added clinical benefit of a cone-unit-based rather than non-anatomical parenchymal-sparing approach remains to be tested [46]. Thus, portal-territory mapping should be integrated with hepatic venous drainage, the required surgical margin, tumor biology, and the likelihood of repeat treatment rather than applied as a universal oncological rule.

Automated vessel segmentation and territory computation, currently used in preoperative simulation, are advancing rapidly and represent the technical bridge between descriptive liver anatomy and reproducible precision surgery. Current 3D simulation systems can automatically extract portal and hepatic venous trees, identify branch hierarchy, calculate peripheral perfusion territories, and estimate functional remnant volume. A two-step AI algorithm has already been reported to automate anatomical virtual liver resection with high accuracy for major divisions, potentially reducing the manual workload required for 3D planning and making territory-based planning more accessible outside highly specialized centers [47]. When the system exports these data into intraoperative navigation platforms, AI could be the next logical layer in the evolution, enabling dynamic interpretation and overlay of these data onto real-time images integrated with information from relevant anatomical landmarks, ICG fluorescence, and intraoperative ultrasonography. Future AI-assisted systems should be evaluated using clinically meaningful endpoints, such as accuracy of portal-territory resection, preservation of venous drainage, surgical margin status, concordance of resection planes with ICG-demarcated boundaries, intraoperative variables (operative time, blood loss, conversion), postoperative morbidity (bile leakage, postoperative liver function, reoperation), length of stay, readmission, and long-term oncological outcomes [7,13–15,32–36].

This review and the proposed two-level anatomical planning hypothesis have important limitations. The review methodology is not equivalent to that of a systematic review: study selection was purposive, no prespecified systematic-review protocol was applied, and no formal risk-of-bias or certainty-of-evidence assessment was performed. The evidence base is uneven across anatomical regions of the liver and is concentrated predominantly in right-sided anatomy; consequently, liver-wide generalization is not justified. In particular,

the detailed bifurcation-versus-loop classification of the right posterior section is supported to a considerable extent by our own single-center retrospective 100-case study [30], with limited independent validation using the same definitions. The proposed oncological rationale, including the hypothesis concerning tumor spread in loop-type anatomy, remains theoretical and has not been demonstrated by pathological mapping or clinical outcome data. Evidence supporting anatomical liver resection in general must be distinguished from evidence specifically supporting cone-unit resection and cannot be used as direct validation of the latter. Comparative evidence demonstrating improved perioperative or oncological outcomes specifically attributable to cone-unit resection is currently lacking. Territory maps also depend on CT acquisition quality, contrast phase, reconstruction algorithms, and manual correction, and automated vessel extraction may omit or misclassify small branches. The liver deforms after mobilization, pneumoperitoneum, traction, and parenchymal transection, reducing direct correspondence between preoperative models and intraoperative anatomy. Navigation and fluorescence platforms are not universally available, and ICG has limited depth penetration and variable staining. A portal-territory-only strategy may create or leave venous congestion if hepatic venous drainage is not assessed simultaneously. Future studies should independently validate regional portal and venous classifications and prospectively compare cone-unit planning with alternative approaches, assessing pathological correspondence, technical feasibility, margin status, congested or ischemic remnant volume, complications, recurrence patterns, and long-term outcomes.

5. Conclusions

Couinaud's segmentation remains indispensable as the universal language of liver surgery but does not fully describe third-order or more peripheral portal territories considered during parenchymal-sparing liver cancer surgery. CT-based 3D reconstruction can depict patient-specific portal anatomy and may support individualized planning, particularly in the right posterior and anterior sections. We therefore present a two-level concept for organizing anatomical assessment: Couinaud-based planning for first- and second-order anatomical resections and CT-guided cone-unit planning as a potential framework for third-order or more peripheral resections (Figures 2 and 4). This proposal is an anatomical and technical concept rather than a clinically validated standard. Evidence supporting anatomical liver resection in general does not directly validate cone-unit resection, and current comparative evidence does not demonstrate superior perioperative or oncological outcomes attributable to the cone-unit approach. Independent anatomical and pathological validation, together with prospective multicenter comparative studies, is required before clinical benefit, superiority over alternative strategies, or liver-wide applicability can be claimed.

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