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Three-dimensional visualisation combined with intraoperative ultrasound in laparoscopic hepatectomy for complex hepatolithiasis: a propensity score-matched retrospective cohort study

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Short Report

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Abstract

Objective

Complex hepatolithiasis remains challenging for laparoscopic hepatectomy. Three-dimensional visualisation technology (3DVT) alone is limited by its static, preoperative nature, whereas intraoperative ultrasound (IOUS) lacks a global anatomical overview, and quantitative evidence for their synergistic benefit remains insufficient. This propensity score-matched (PSM) retrospective cohort study evaluated whether combined 3DVT and IOUS navigation improves perioperative safety and long-term outcomes compared with conventional two-dimensional imaging in patients with complex hepatolithiasis.

Results

Among 180 patients who underwent laparoscopic hepatectomy between January 2020 and December 2025, 66 matched pairs were analysed. The combined-navigation group had significantly shorter operative time, less intraoperative blood loss and lower conversion and transfusion rates than the control group (all $P < 0.05$). The one-stage stone clearance rate was 100.0% versus 90.9% ($P = 0.028$), and the overall postoperative complication rate was 3.0% versus 18.2% ($P = 0.009$). Over a mean follow-up of approximately 37 months, the stone recurrence rate was 1.5% versus 10.6% ($P = 0.039$), with significantly better recurrence-free survival (log-rank $P = 0.039$). Combined navigation was an independent protective factor for postoperative complications (OR = 0.313, 95% CI 0.107–0.915; $P = 0.034$).

1. Introduction

Hepatolithiasis has a prevalence of less than 1.3% in Western populations but reaches 2%–25% in East and Southeast Asia, and is particularly common in the Yangtze River basin and South China [1][2][3]. In China, complex phenotypes characterised by multi-segmental intrahepatic biliary strictures, hepatic atrophy–hypertrophy complex and vascular anatomical variations are especially common and remain difficult to manage [4][5][6]. Because of the repeated cycle of inflammation and bile stasis, these patients have a 2.4- to 10-fold increased risk of cholangiocarcinoma compared with the general population, representing a major challenge for regional hepatobiliary surgery [7][8][9].

Anatomical hepatectomy is the curative treatment for complex hepatolithiasis [10]. Laparoscopic liver resection has been increasingly used in hepatobiliary surgery. However, three major difficulties remain in complex cases. First, two-dimensional cross-sectional imaging (CT/MRCP) relies on the surgeon's subjective spatial reconstruction and cannot accurately quantify the individual affected biliary territory, which may lead to an inappropriate resection plane [11][12]. Second, the static model constructed from preoperative 3DVT cannot correct for intraoperative liver deformation and positional changes. The reported incidence of transection plane deviation can reach 12.7%, directly affecting the completeness

of stone clearance [13][14]. Third, although IOUS provides real-time imaging, it lacks a global view of the biliary tree and cannot independently achieve precise navigation in complex cases [15][16]. Most previous studies have evaluated 3DVT or IOUS alone in surgery for hepatolithiasis and have shown improved surgical precision to some extent [17][18]. However, studies on their combined application remain scarce, and most have focused only on short-term perioperative outcomes without long-term recurrence data beyond three years, thus failing to explore the effect on long-term prognosis. Furthermore, Western studies have mainly included localised, simple cases, which differ substantially from complex phenotypes in Asian populations in terms of surgical difficulty and recurrence patterns. Their conclusions therefore cannot be directly applied to complex cases in Asia [19][20]. Studies on 3DVT combined with indocyanine green (ICG) fluorescence have only validated short-term efficacy and have not provided long-term prognostic evidence [21]. Accordingly, this study used PSM to adjust for baseline confounding and systematically evaluated the effect of preoperative 3DVT combined with IOUS on perioperative safety, short-term efficacy and long-term stone recurrence in patients with complex hepatolithiasis undergoing laparoscopic hepatectomy, aiming to provide high-quality evidence for precise laparoscopic liver resection.

2. Materials and methods

2.1 Study design and ethics approval

This was a single-centre retrospective cohort study conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of our hospital (No. HEYLL2026140). Written informed consent was waived because of the retrospective design. The study design and reporting followed the STROBE statement [22].

2.2 Inclusion and exclusion criteria

Patients diagnosed with complex hepatolithiasis who underwent laparoscopic hepatectomy in our hospital between January 2020 and December 2025 were included.

Inclusion criteria: (1) Preoperative enhanced CT/MRCP confirmed hepatolithiasis meeting any complex classification criterion (Dong's classification, Nakayama classification) [23][24][25]: (i) stones involving bilateral hepatic lobes or ≥ 2 independent hepatic segments; (ii) concomitant localised intrahepatic biliary stricture or dilatation; (iii) a history of ≥ 1 previous open or laparoscopic biliary operation; (iv) concomitant common bile duct obstruction, biliary cirrhosis or portal hypertension. (2) Underwent laparoscopic hepatectomy. (3) Complete clinical and follow-up data.

Exclusion criteria: (1) Concomitant intrahepatic cholangiocarcinoma or other systemic malignancy. (2) American Society of Anesthesiologists (ASA) grade ≥ IV or severe cardiac, pulmonary or renal insufficiency precluding surgery. (3) Missing clinical, imaging or follow-up data.

2.3 Definitions

One-stage stone clearance rate

absence of residual intrahepatic stones on enhanced abdominal CT at 4 weeks after surgery [10][26].

Stone recurrence

new intrahepatic stones detected by imaging (ultrasound/CT/MRCP) more than 6 months after surgery [4][10].

Postoperative complication grading

complications were graded according to the Clavien–Dindo classification, and grade III or higher was defined as a severe complication [27][28].

2.4 Three-dimensional model construction and preoperative planning

Imaging acquisition: preoperative enhanced CT was performed using a SOMATOM Definition Flash 256-slice spiral CT scanner (Siemens Healthineers, Forchheim, Germany) with a slice thickness of 0.8 mm, and Digital Imaging and Communications in Medicine (DICOM) data were exported. 3DVT software: IQQA-3D liver imaging interpretation and analysis system (EDDA Technology, USA). 3DVT: the DICOM data were imported into IQQA-3D. Hepatobiliary surgeons and radiologists (both with associate senior titles or above) jointly performed automatic segmentation and manual correction of the liver, bile ducts, stones and vessels (portal vein, hepatic artery and hepatic vein). Preoperative planning: the software calculated the total liver volume, planned resection volume and future liver remnant volume. Based on portal territory analysis, multiple resection plans were simulated to determine the optimal transection plane [11][13] (Additional files : Figures S1 and S2).

2.5 Surgical procedures

All operations were performed by teams led by senior associate chief surgeons or above. In the study group, the resection extent and key vascular landmarks were determined preoperatively based on the 3DVT model. Intraoperatively, a laparoscopic ultrasound probe (Esaote MyLab Twice) was used for ultrasound calibration and image acquisition. The criteria were as follows [11][15]: (1) spatial registration and confirmation of key vascular landmarks planned preoperatively; (2) dynamic monitoring and guidance of the liver transection plane to ensure negative margins and avoid injury to major ducts; (3) postoperative confirmation of no residual stones (Additional files : Figure S3). In the control group, surgical planning was based on conventional preoperative two-dimensional CT/MRCP images, and IOUS navigation was not used. The remaining surgical steps were identical in both groups.

2.6 Postoperative management and follow-up

Both groups received the same perioperative management. Follow-up was performed at 1 month after surgery, every 3 months within the first 12 months, and every 6 months thereafter. Follow-up included assessment of clinical symptoms, liver function tests and abdominal ultrasound. Enhanced CT/MRCP was performed when recurrence was suspected.

2.7 Outcome measures

Primary endpoints: one-stage stone clearance rate, overall postoperative complication rate and long-term stone recurrence rate.

Secondary endpoints: operative time (min), intraoperative blood loss (mL), intraoperative transfusion rate, conversion rate, ALT/AST/TBIL on postoperative days 1 and 3, postoperative hospital stay (days) and duration of abdominal drainage tube placement (days).

2.8 Statistical analysis

SPSS version 27.0 was used for data analysis. Variables including sex, age, BMI, previous abdominal surgery, comorbidities (hypertension, diabetes mellitus), ASA grade, Child–Pugh class, preoperative albumin, total bilirubin, transaminases, coagulation function, blood cell counts and CRP were included in a logistic regression model to calculate propensity scores. A 1:1 nearest-neighbour matching algorithm with a caliper of 0.1 was used for PSM [29][30]. Normally distributed continuous variables were presented as mean ± SD and compared using the independent samples t-test; non-normally distributed variables were presented as median (IQR) and compared using the Mann–Whitney U test. Categorical variables were presented as counts (%) and compared using the chi-square test or Fisher's exact test. Stone recurrence-free survival was estimated using the Kaplan–Meier method and compared between groups with the log-rank test. Variables with $P < 0.1$ in univariate analysis were entered into a multivariable logistic regression model to identify independent risk factors for postoperative complications. $P < 0.05$ was considered statistically significant.

3. Results

3.1 Baseline characteristics before and after PSM

Before PSM, the study group (n = 84) and control group (n = 96) differed significantly in ALT ($P = 0.035$) and AST ($P = 0.044$) (Table 1). After PSM, 66 pairs were successfully matched. All included covariates had standardised differences < 0.10 and P values > 0.05, indicating well-balanced baseline characteristics (Table 1 and Additional files : Table S1).

Table 1
Comparison of baseline clinical characteristics before and after PSM

Variable	Before PSM				After PSM			
	Study group (n = 84)	Control group (n = 96)	SMD	P value	Study group (n = 66)	Control group (n = 66)	SMD	P value
Sex (male/female)	32/52	33/63	0.077	0.734	22/44	21/45	0.032	0.854
Age (years)	58.46 ± 12.61	60.60 ± 11.27	0.179	0.229	59.85 ± 10.93	60.60 ± 10.90	0.069	0.911
Previous abdominal surgery (yes/no)	59/25	56/40	0.251	0.097	44/22	45/21	0.032	0.850
Hypertension (yes/no)	27/57	30/66	0.019	0.758	16/50	17/49	0.035	0.841
Diabetes mellitus (yes/no)	20/64	16/80	0.178	0.356	13/53	13/53	0.000	1.000
Coronary heart disease (yes/no)	8/76	5/91	0.166	0.378	1/65	1/65	0.000	1.000
Child–Pugh class (A/B)	55/29	65/31	0.047	0.721	47/19	45/21	0.066	0.700
ASA grade (1/2/3)	12/63/9	21/66/9	0.198	0.568	12/52/2	12/51/3	0.034	0.900
Preoperative neutrophils ($\times 10^9$/L)	6.68 ± 5.28	5.34 ± 3.79	0.292	0.129	5.39 ± 3.89	5.34 ± 3.87	0.013	0.863
Preoperative lymphocytes ($\times 10^9$/L)	1.68 ± 0.90	1.44 ± 0.71	0.296	0.063	1.51 ± 0.78	1.51 ± 0.78	0.000	0.985
Preoperative CRP (mg/L)	27.52 ± 32.45	25.38 ± 33.22	0.065	0.164	27.77 ± 35.81	27.92 ± 36.15	0.004	0.937
Preoperative total albumin (g/L)	43.46 ± 5.45	43.67 ± 6.40	0.035	0.729	44.04 ± 5.70	44.31 ± 5.23	0.049	0.527
Preoperative total bilirubin (μmol/L)	35.35 ± 52.56	34.13 ± 52.20	0.023	0.3	36.06 ± 57.32	36.20 ± 57.95	0.002	0.975

Note: SMD, standardised mean difference.

Variable	Before PSM				After PSM			
	Study group (n = 84)	Control group (n = 96)	SMD	P value	Study group (n = 66)	Control group (n = 66)	SMD	P value
Preoperative ALT (U/L)	119.20 ± 174.28	74.36 ± 79.87	0.331	0.035	71.19 ± 69.23	68.32 ± 68.02	0.042	0.857
Preoperative AST (U/L)	125.73 ± 199.57	73.81 ± 90.85	0.335	0.044	77.26 ± 99.87	76.48 ± 98.05	0.008	0.922
BMI (kg/m²)	24.17 ± 2.66	24.30 ± 2.92	0.047	0.866	24.19 ± 2.60	24.24 ± 2.57	0.019	0.969

Note: SMD, standardised mean difference.

3.2 Intraoperative safety indicators

After PSM, the study group had significantly shorter operative time (P = 0.012), significantly less intraoperative blood loss (P = 0.015) and significantly lower conversion and transfusion rates than the control group (all P < 0.05) (Additional files : Table S2).

3.3 Postoperative short-term liver function, stone clearance and complications

On postoperative day 1, ALT, AST and TBIL levels were significantly lower in the study group than in the control group (all P < 0.05). On postoperative day 3, no significant differences in liver function were observed between the two groups, suggesting that combined navigation reduced transient intraoperative liver injury (Additional files : Table S3).

The one-stage stone clearance rate in the study group was 100.0%, significantly higher than the 90.9% in the control group (P = 0.028). The overall complication rate in the study group (3.0%) was significantly lower than that in the control group (18.2%, P = 0.009). All complications improved after conservative treatment, and no Clavien–Dindo grade III or higher complications occurred in either group. Postoperative hospital stay and duration of abdominal drainage tube placement were significantly shorter in the study group (Table 2).

Table 2
Comparison of stone clearance, hospital stay and complications after PSM

Variable	Study group	Control group	Statistical value	P value
One-stage stone clearance rate	100.0%	90.9%	2.510	0.028
Stone recurrence (n/%)	1	7	4.239	0.039
Postoperative hospital stay (days)	7.27 ± 2.17	9.45 ± 2.86	4.746	< 0.001
Postoperative drainage tube duration (days)	7.29 ± 2.56	9.86 ± 4.33	3.972	< 0.001
Postoperative complications (total)	2	12	6.775	0.009
Bile leakage	1	7	3.327	0.068
Intra-abdominal infection/collection	1	5	1.517	0.211

3.4 Long-term stone recurrence-free survival

The follow-up duration was 36.74 ± 15.90 months in the study group and 37.55 ± 18.76 months in the control group (P = 0.792). Only one patient (1.5%) in the study group developed stone recurrence, compared with seven patients (10.6%) in the control group. Kaplan–Meier analysis showed that recurrence-free survival was significantly better in the study group than in the control group (log-rank χ^2 = 4.239, P = 0.039) (Fig. 1).

3.5 Multivariable logistic regression analysis of postoperative complications

Variables with P < 0.1 in univariate analysis were entered into the multivariable logistic regression model. The results showed that 3DVT combined with IOUS navigation was an independent protective factor for postoperative complications (OR = 0.313, 95% CI: 0.107–0.915, P = 0.034), whereas previous abdominal surgery was an independent risk factor for postoperative complications (OR = 6.361, 95% CI: 1.200–33.700, P = 0.028) (Additional files : Table S4).

4. Discussion

Complex hepatolithiasis is a refractory biliary disease with a high prevalence in East Asia. Laparoscopic surgery for this condition has long faced three technical difficulties: difficult spatial reconstruction from two-dimensional imaging, intraoperative mismatch of static three-dimensional models, and the limited field of view of single-modality real-time navigation. After adjusting for baseline confounding with PSM, this study confirmed that a whole-process navigation strategy combining 3DVT and IOUS improved perioperative safety, increased the one-stage stone clearance rate and significantly reduced long-term stone recurrence, providing evidence for precise laparoscopic treatment of this disease.

The navigation group showed significant advantages in operative time, blood loss, conversion rate and postoperative transient liver injury. The core mechanism is the complementary static planning and dynamic calibration effect, which represents an integrated global–local information loop rather than a simple additive effect. Preoperative 3DVT quantifies the individual diseased biliary tree through portal territory analysis and predefines the transection plane and key vascular landmarks [17][18][19]. In addition, this study found that adding IOUS real-time navigation to 3DVT achieved a one-stage stone clearance rate of 100.0% and shortened operative time by approximately 30 min, suggesting that IOUS effectively compensates for the inherent limitations of the static three-dimensional model. Previous studies have shown that deviation between preoperative static models and actual intraoperative anatomy can reach 12.7%. IOUS allows spatial registration of key vascular landmarks and dynamic correction of the transection plane. The improved ALT, AST and bilirubin levels on postoperative day 1 are attributable to reduced mechanical injury to the liver parenchyma and bile ducts, as well as shorter operative time and consequently less hepatic ischaemia–reperfusion injury [11][18][31]. These findings are consistent with the core principle of precision liver surgery: minimal trauma and maximal functional preservation.

Over a mean follow-up of approximately 37 months, the recurrence rate was 1.5% in the study group, significantly lower than the 10.6% in the control group. This is the key novel finding and provides the first evidence that combined navigation improves long-term outcomes. Previous studies have mostly focused on short-term perioperative efficacy. For example, Huang et al. [21] reported that 3DVT combined with ICG fluorescence reduced intraoperative bleeding and immediate residual stones but did not assess recurrence. The pathological basis of hepatolithiasis recurrence is the residual diseased biliary tree: residual strictures and bile stasis reinitiate the cycle of chronic inflammation, cholestasis and stone formation. The 3DVT + IOUS navigation strategy ensures complete resection of the diseased biliary territory by preoperative territory analysis and offsets resection deviation caused by intraoperative liver deformation, thereby eliminating the anatomical basis for recurrence. In addition, Western studies have mainly included localised, simple cases [1][20]. For example, the conclusions of van der Heijde et al. [19] cannot be directly extrapolated to the complex hepatolithiasis population in China and East Asia. This study focused on complex hepatolithiasis and is therefore more relevant to clinical practice in Asia.

Multivariable analysis showed that 3DVT + IOUS was an independent protective factor for postoperative complications, whereas previous abdominal surgery was an independent risk factor, consistent with previous studies [14][19]. For high-risk patients with multiple previous biliary operations and anticipated severe abdominal adhesions, 3DVT + IOUS navigation should be prioritised.

Limitations

Limitations

Single-centre, retrospective design and residual confounding. Despite PSM adjustment, unmeasured confounders cannot be fully excluded, and causal inference remains limited.

Reduced sample size after matching. Matching without replacement yielded 66 pairs, which may limit statistical power for rare secondary outcomes; non-significant differences should be interpreted with caution.

Pre-matching imbalance. Baseline ALT and AST differed between groups before matching; although covariates were well balanced after PSM, this reflects the inherent selection bias of a retrospective cohort.

Moderate follow-up duration. With a mean follow-up of approximately 37 months, late stone recurrence beyond this window may be underestimated; longer follow-up is warranted.

Operator dependence and generalisability. 3DVT segmentation and IOUS interpretation are operator-dependent, and all procedures were performed in a single high-volume centre by experienced surgeons, which may limit generalisability to lower-volume settings.

Conclusions

The whole-process navigation strategy combining preoperative 3DVT and IOUS can significantly improve the precision and safety of laparoscopic hepatectomy for complex hepatolithiasis and reduce short-term complications and long-term recurrence, supporting a shift from experience-based to navigation-guided surgery in high-risk complex cases. Multicentre, large-sample prospective randomised controlled trials are needed to further validate these findings. Future research should also explore augmented reality real-time fusion projection, multimodal ICG fluorescence navigation and a unified three-dimensional imaging-based surgical difficulty scoring system to standardise precise diagnosis and treatment of complex hepatolithiasis.

Abbreviations

Alanine aminotransferase (ALT)

American Society of Anesthesiologists (ASA)

Aspartate aminotransferase (AST)

Body mass index (BMI)

Common bile duct (CBD)

Computed tomography (CT)

Confidence interval (CI)

C-reactive protein (CRP)

Digital Imaging and Communications in Medicine (DICOM)

Indocyanine green (ICG)

Intraoperative ultrasound (IOUS)

Interquartile range (IQR)

Left hepatic duct (LHD)

Magnetic resonance cholangiopancreatography (MRCP)

Odds ratio (OR)

Propensity score matching (PSM)

Standard deviation (SD)

Strengthening the Reporting of Observational Studies in Epidemiology (STROBE)

Three-dimensional visualisation technology (3DVT)

Total bilirubin (TBIL)

Declarations

Ethics approval and consent to participate: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Huai'an Second People's Hospital (approval No. HEYLL2026140). Written informed consent was waived because of the retrospective design.

Consent for publication: This study did not include any images or case details that could identify individual patients; therefore, consent for publication was not required.

Availability of data and materials: Because the data involve patient privacy and are subject to ethical approval conditions and institutional data management regulations, the raw data supporting the findings of this study cannot be made publicly available. De-identified data in compliance with applicable regulations may be made available upon reasonable request and with approval from the relevant institutions.

Competing interests: The authors declare that there are no conflicts of interest that could affect the results or interpretation of this study.

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Authors' contributions:M.J.L., H.B.L., and X.F. contributed equally to this work and share first authorship. M.J.L., H.B.L., and X.F. conceived and designed the study, collected and analyzed the data, and drafted the manuscript. H.R.L., C.W., and C.Y.L. participated in clinical data collection, follow-up, and data curation. X.Y.C. performed radiological image acquisition and interpretation. C.C. conceived and supervised the study, acquired funding, and critically revised the manuscript. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

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Figures

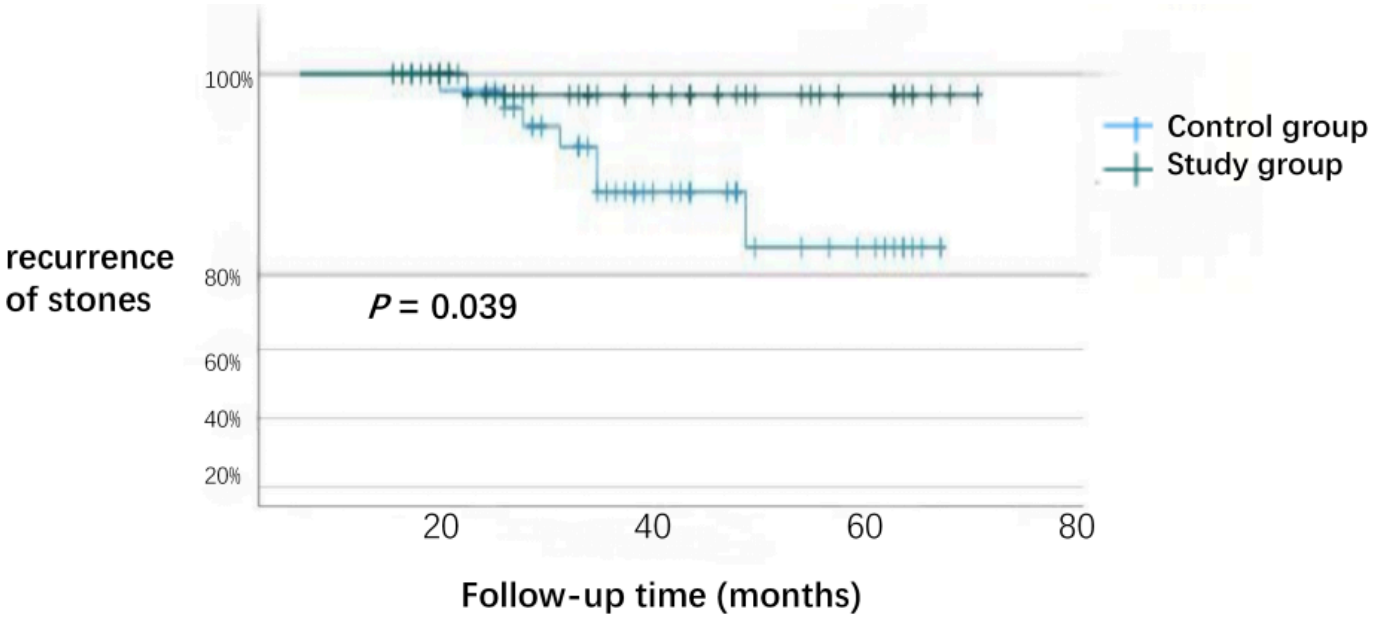


Figure 1

Stone recurrence-free survival curves for the two groups (log-rank P=0.039).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Additionalfiles.docx