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· 临床研究 ·

三维可视化技术在肝脏主要脉管空间构型与肝叶体积分布评估中的临床应用

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摘要

背景与目的: 肝脏脉管系统解剖变异复杂, 且不同脉管之间存在高度个体化的空间关系, 传统二维影像在整体构型识别和空间定量分析方面存在局限。本研究基于三维可视化技术, 系统评估肝门区及肝内主要脉管的空间构型特征及其与肝叶体积分布的关系, 探讨其在精准肝脏外科手术前评估中的应用价值。

方法: 回顾性纳入上海交通大学医学院附属仁济医院 610 例活体肝移植供体及 158 例胆管扩张患者, 基于增强 CT 数据构建肝动脉、门静脉、肝静脉及胆管的三维可视化模型。对门静脉分型、肝静脉解剖特征、胆管走行方式以及肝内外脉管的空间位置关系进行系统分析, 并进一步比较不同构型下肝叶及区域体积分布的差异。

结果: 三维可视化技术能够清晰呈现肝门区及肝内脉管的立体走行及相互关系。门静脉不同拓扑分型患者的肝段及区域体积分布存在显著差异, 其中右前支起源于左支的门静脉构型患者右后区体积占比明显增加。存在肝右后下静脉且直径 ≥ 5 mm 者, 其右后区体积占比亦显著高于其他患者。肝外空间关系分析显示, 肝右动脉与门静脉、胆管之间存在相对稳定的空间分布模式; 肝内分析进一步发现, 右后肝管与门静脉右支的空间位置与肝右动脉走行方式具有显著相关性。

结论: 三维可视化技术可在术前准确识别肝脏脉管的变异类型及其复杂空间构型, 揭示脉管解剖特征与肝叶体积分布之间的内在联系, 为精准肝切除、活体肝移植及复杂肝胆外科手术的安全实施提供可靠的解剖学依据。

关键词

成像, 三维; 肝; 血管; 胆管; 解剖变异; 空间构型

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Clinical application of three-dimensional visualization technology in assessing the spatial configuration of major hepatic vessels and liver lobar volume distribution

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Abstract

Background and Aims: The hepatic vascular and biliary systems exhibit substantial anatomical variability and complex spatial relationships, posing challenges for precise surgical planning based on conventional two-dimensional imaging. This study aimed to evaluate the clinical value of three-dimensional visualization in characterizing the spatial architecture of hepatic vasculature and bile ducts and to explore its association with hepatic volumetric distribution.

Methods: A total of 610 living liver donors and 158 patients with bile duct dilatation were retrospectively analyzed. Three-dimensional models of the hepatic artery, portal vein, hepatic veins, and bile ducts were reconstructed from contrast-enhanced CT images. Vascular and biliary anatomical patterns, spatial relationships, and their correlations with hepatic lobe and segmental volumes were systematically assessed.

Results: Three-dimensional visualization enabled intuitive and comprehensive depiction of hepatic vascular and biliary anatomy. Distinct portal vein configurations were associated with significant differences in regional liver volume distribution, with an increased proportion of the right posterior lobe observed in patients with specific portal vein branching patterns. The presence of an inferior right hepatic vein with a diameter ≥ 5 mm was also associated with a larger right posterior lobe volume. Analyses of extrahepatic and intrahepatic spatial relationships revealed relatively consistent positional patterns between the right hepatic artery, portal vein, and bile ducts, and a significant correlation was observed between the spatial courses of the right hepatic artery and the right posterior bile duct.

Conclusion: Three-dimensional visualization provides accurate preoperative assessment of hepatic vascular and biliary anatomy and clarifies complex spatial relationships and their volumetric implications. This technique offers critical anatomical support for precision hepatobiliary surgery and liver transplantation.

Key words

Imaging, Three-Dimensional; Liver; Blood Vessels; Bile Ducts; Anatomic Variation; Spatial Configuration

CLC number: R657.3

三维可视化技术是数字医学的核心技术，它能够将CT、MRI等二维医学影像，通过计算机处理，重建为立体的人体器官模型。该技术不仅实现了从二维到三维的“重建”，还能融合不同期相或检查类型的影像进行“配准”和“重组”，为临床提供全面的立体洞察。目前，该技术已在肝胆胰外

科等领域成熟应用，成为疾病精准诊断与手术规划的关键工具^[1-4]。

肝脏脉管系统（肝动脉、门静脉、胆管和肝静脉）解剖结构复杂、变异繁多，尤其在第一肝门区相互交错，是肝胆外科手术高风险和不确定性的主要来源^[5-8]。以三维可视化技术为核心的精

准外科，通过实现“可视化、可量化、可控化”，正逐步克服传统手术的局限^[9-12]。该技术能立体、直观地显示肝脏形态与脉管结构，尤其在识别复杂和罕见变异方面优势显著，为手术规划和解剖研究提供了关键依据。

目前，三维可视化技术在全球肝胆外科诊治中的应用已日趋成熟，并通过多项专家共识形成了规范化指导。它已成为术前评估围肝门解剖结构、规划手术路径不可或缺的工具，对推动精准肝胆外科发展具有重要价值。本研究基于增强多排螺旋CT检查数据进行三维重建和三维可视化评估（three-dimensional visualization evaluation, 3DVE），探究其在肝脏脉管解剖结构评估中的独特价值及其临床意义。

1 资料与方法

1.1 研究对象资料

本部分研究采用回顾性横断面研究方法，分别纳入血管模型组和胆管扩张模型组两组患者。收集上海交通大学医学院附属仁济医院2013年1月—2017年10月接受活体肝移植手术的血管模型组患者（ $n=610$ ）和2014年5月—2019年12月接受手术治疗的胆管扩张模型组患者（ $n=158$ ）的术前增强多排螺旋CT检查、3DVE结果和临床病例资料。本研究已获得本机构伦理审查委员会批准（编号：KY2022-075-B），并鉴于其回顾性研究性质，免除知情同意要求。

1.2 纳入标准和排除标准

血管模型组的纳入标准为：接受儿童活体肝移植供体且临床资料完整者；病理学检查证实肝

脏组织完全正常者；接受术前上腹部增强多排螺旋CT检查和3DVE者。胆管扩张模型组的纳入标准为：存在胆管扩张（胆总管直径 ≥ 10 mm）且接受手术治疗的初治的胰腺癌患者；接受术前上腹部增强多排螺旋CT检查和3DVE者；增强多排螺旋CT检查显示肝脏结构正常且胆道系统扩张明显，可显示左、右两侧三级肝管者；胰腺肿瘤未累及胰腺上缘以上的胆道系统者。两组患者共同的排除标准为：上腹部增强多排螺旋CT检查影像质量不良影响评估者。

1.3 影像采集方法

所有768例患者均行上腹部多排螺旋CT平扫和CT增强检查，CT增强包含动脉期、静脉期和平衡期三个相。常规采用64排螺旋CT扫描仪（LightSpeed™ VCT; GE Healthcare, Milwaukee, Wisconsin, USA），扫描层厚为1.25 mm。常规平扫时，患者取仰卧位和头足方向，控制呼吸，由膈顶扫描至肝脏下缘，扫描条件为120 kV、250 mA；采用0.625 mm \times 64排探测器组合，层厚1.25 mm，间隔1.25 mm，螺距0.984，球管旋转一周时间0.5 s。静脉注射非离子型碘对比剂（碘帕醇® 370 mg/mL；上海伯莱克信谊制药公司，上海，中国），动脉期扫描延时为20~25 s，门静脉期延时为60~65 s。扫描结束后，增强多排螺旋CT检查数据会自动上传至院内PACS系统，下载至本地电脑储存为DICOM格式。

1.4 3DVE 路径

1.4.1 CT检查数据的导入 将院内PACS系统下载的增强多排螺旋CT检查数据，导入三维可视化工作站 IQQA®-LIVER（EDDA Technology, Princeton, New Jersey, USA）（图1）。

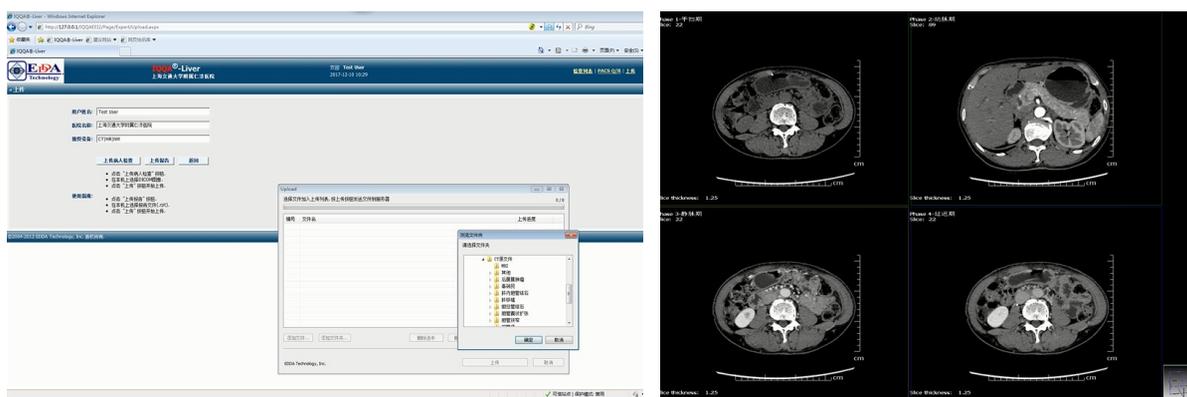


图1 将CT检查数据导入工作站和半自动化处理（IQQA®-LIVER半自动化处理患者多排螺旋CT检查数据的操作页面）
 Figure 1 Import the CT data into the workstation and perform semi-automatic processing (the operational interface of IQQA®-LIVER for the semi-automatic processing of patient multi-slice spiral CT scan data)

1.4.2 脏器轮廓重建 三维可视化工作站 IQQA[®]-LIVER 依据半自动区域生成等方法自动识别并还原肝脏轮廓,评估人员在此基础之上再次手动调整各个扫描层面的肝脏轮廓边界,减少肝脏轮廓的重建误差(图2)。

1.4.3 脉管的分割和标注 三维可视化工作站 IQQA[®]-LIVER 依据阈值分割方法,根据动脉期、静

脉期和延迟期的脉管阈值特征半自动分割出肝动脉、门静脉和肝静脉及扩张的胆管轮廓。评估人员在此基础之上对照多排螺旋CT的二维图像人工核对和调整肝脏脉管轮廓。最后,根据肝静脉和门静脉的形态特征人工标注和分割肝静脉与门静脉(图3)。

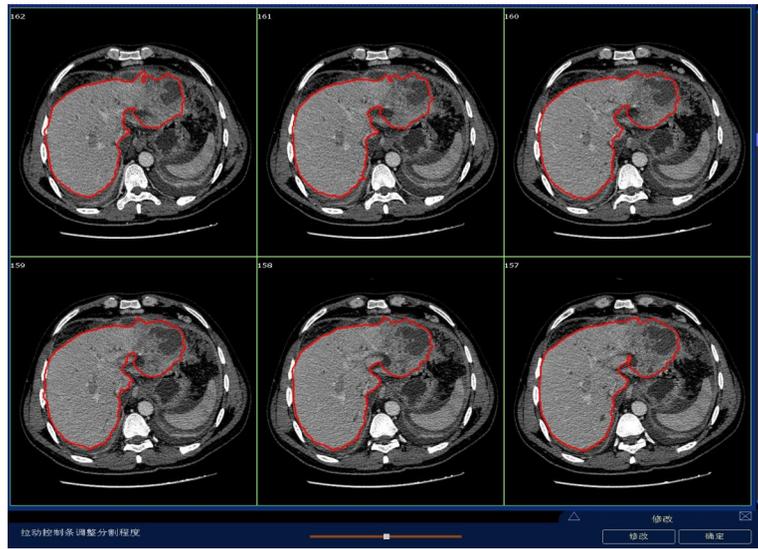


图2 手动调整肝脏轮廓边界[逐层手动修正肝脏边界(红色),以减少三维重建误差]

Figure 2 Manual adjustment of liver contour boundaries [layer-by-layer manual correction of the liver boundary (red) to reduce errors in three-dimensional reconstruction]

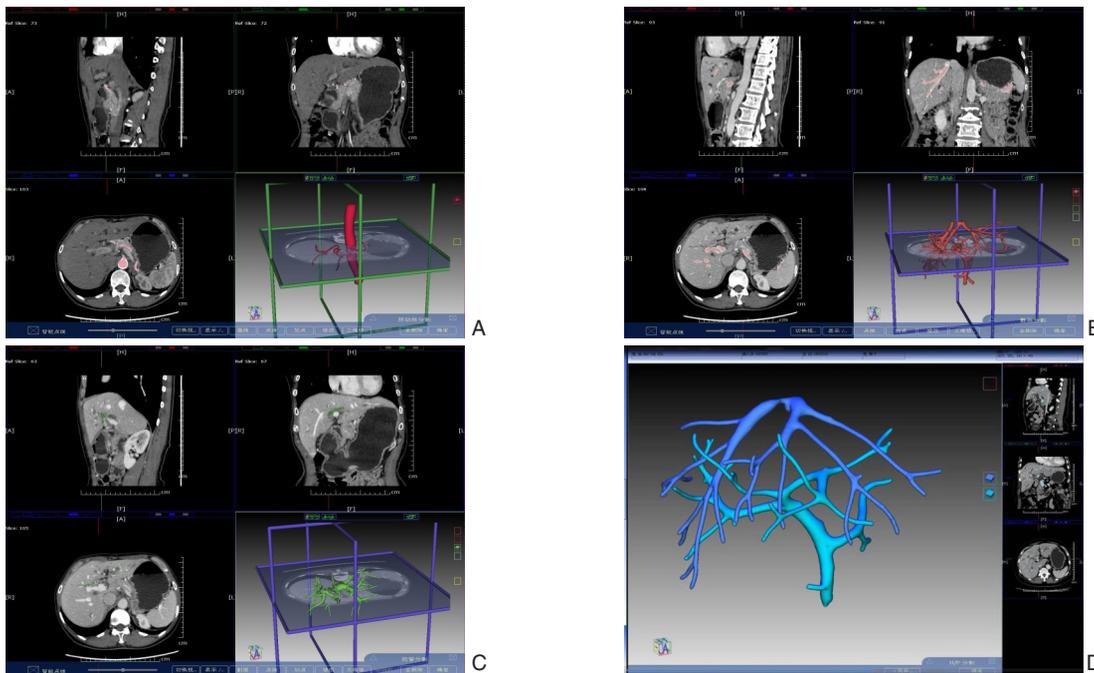


图3 肝动脉、门静脉、肝静脉和胆管的分割与标注 A: 还原肝动脉轮廓; B: 还原门静脉与肝静脉轮廓; C: 还原胆管轮廓; D: 人工分割和标注门静脉和肝静脉

Figure 3 Segmentation and annotation of the hepatic artery, portal vein, hepatic veins, and bile ducts A: Reconstruction of the hepatic artery contour; B: Reconstruction of the portal vein and hepatic veins; C: Reconstruction of the bile duct contour; D: Manual segmentation and annotation of the portal vein and hepatic veins

1.4.4 门静脉流域分析测量肝叶体积 依据 Couinaud 肝段划分法, 标注和分割门静脉左支和右支, 以肝右静脉为标志, 标注和分割门静脉右前支和右后支, 以门静脉矢状部为标志, 分割门静脉左内支和左外支, 三维可视化工作站

IQQA[®]-LIVER 通过拓扑流域和几何分析方法计算出肝脏左内叶 (left medial lobe, LML)、左外叶 (left lateral lobe, LLL)、右前叶 (right anterior lobe, RAL) 和右后叶 (right posterior lobe, RPL) 区域范围和肝体积^[13] (图4)。

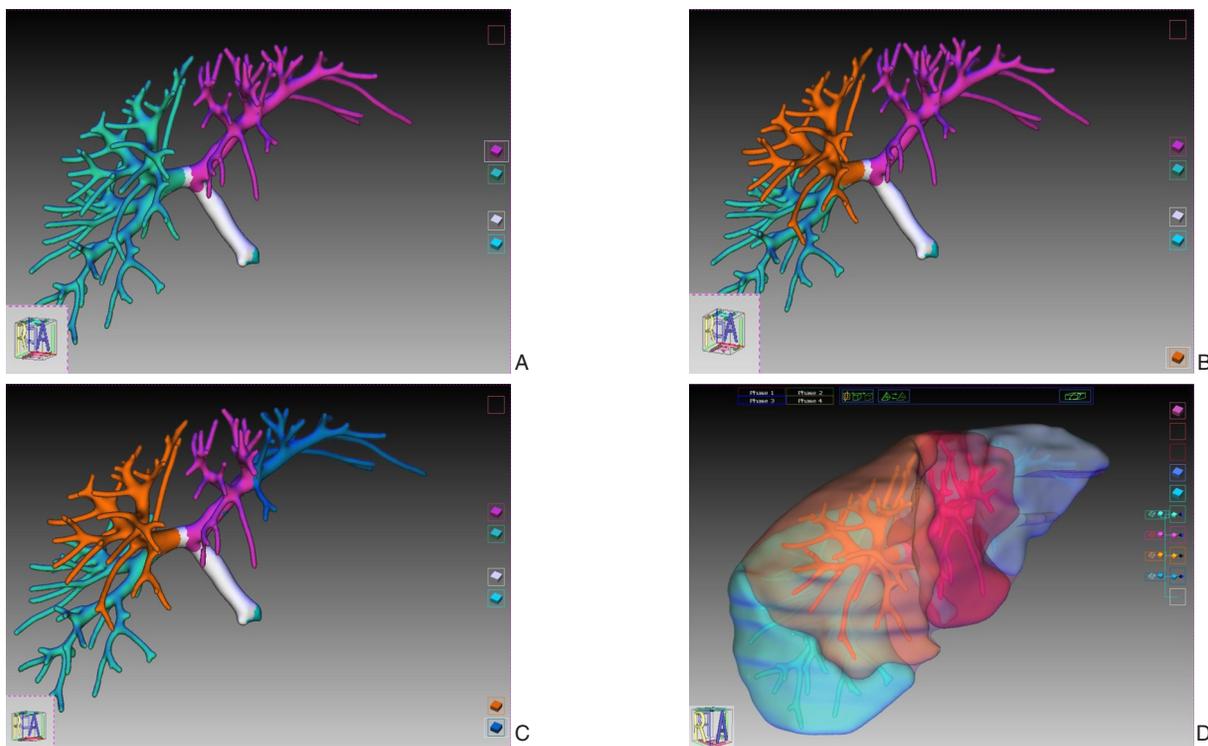


图4 门静脉流域与几何分析还原及测量肝叶体积 A: 标注分割门静脉左支和右支; B: 标注分割门静脉右前支和右后支; C: 标注分割门静脉左内支和左外支; D: 根据门静脉分支进行肝脏分区

Figure 4 Reconstruction of portal venous territories and geometric analysis for hepatic lobe volumetric measurement

A: Segmentation and labeling of the left and right portal vein branches; B: Segmentation and labeling of the right anterior and right posterior portal vein branches; C: Segmentation and labeling of the left medial and left lateral portal vein branches; D: Hepatic lobe partitioning based on portal vein branching

1.4.5 三维可视化操作与测量 基于三维可视化技术, 可进行肝脏轮廓、肝动脉、门静脉、肝静脉和胆管及病灶等结构的单独和组合显示, 同时能进行肝脏模型的旋转、分割、缩小、放大、点与点距离测量、模拟手术切除与残余肝体积测量等操作。

1.5 影像评估方法

多排螺旋 CT 检查图像通过院内 PACS 系统获得和阅览, 评估由本院放射科 2 名肝胆胰外科方向的放射科医师共同完成, 图像评估内容包括肝动脉、门静脉、肝静脉、胆管的基本结构类型和空间构象。3DVE 由 1 名肝胆胰外科医师和 1 名放射科医师共同完成, CT 检查数据导入三维可视化工作站 IQQA[®]-LIVER 进行阅览和评估, 评估内容除上述内容, 还包括各肝叶体积与占比。两种影像学

评估方法相互独立, 互不干扰。

1.6 统计学处理

使用 SPSS 19.0 软件进行统计分析。分类变量比较采用 χ^2 检验或 Fisher 精确检验, 连续变量比较采用非配对 t 检验。显著性水平设定为 $P=0.05$ 。

2 结果

2.1 门静脉解剖分型及其与肝叶体积分布的关系

根据 Germain 分型^[14]标准, 通过对 610 例儿童肝移植供体的 3DVE 分析, 将肝门部门静脉构型分为五型。其中 I 型 (门静脉主干分左、右支) 占 85.6% (522/610), 为主要类型; 其余 II、III、IV、V 型及其他类型的占比分别为 3.4%、9.2%、0.2%、

0.3%和1.3% (图5) (表1)。通过门静脉拓扑流域与几何分析发现,不同门静脉分型供体的肝区体积分布存在显著差异。与I型相比,III型供体的肝脏RAL、LML及LLL体积占比均明显降低 (均 $P < 0.001$),而RPL体积占比明显增加 ($P < 0.001$)。II型供体的RPL体积也明显大于I型 ($P < 0.001$) (图6)。

2.2 肝静脉构型特征及其对肝区体积分布的影响

基于610例儿童肝移植供体的3DVE结果,本研究参照Nakamura分型^[15]标准,将肝中静脉(middle hepatic vein, MHV)与肝左静脉(left hepatic vein, LHV)的汇入方式分为两型:1型为二者分别汇入下腔静脉(inferior vena cava, IVC),占69.5% (424/610);2型为二者形成共同干后汇入IVC,占30.5% (186/610) (图7) (表2)。根据门静脉拓扑流域和几何分析,MHV与LHV汇入类型

(1型与2型)供体间的肝脏RAL、RPL、LML及LLL体积占比均无明显差异 (均 $P > 0.05$),表明二者的汇合方式不影响各肝区体积分布 (图8)。参照Nakamura分型^[15]标准,依据肝右后下静脉(inferior right hepatic vein, IRHV)直径将其分为三型:I型(未见IRHV)占30.7% (187/610);II型(直径 < 5 mm)最常见,占47.7% (291/610);III型(直径 ≥ 5 mm)占21.6% (132/610) (图9) (表3)。根据门静脉拓扑流域和几何分析,IRHV直径显著影响肝脏RAL与RPL体积:随IRHV直径增大,RAL体积占比降低(I型37.8% \rightarrow III型33.7%),而RPL体积占比升高(I型25.3% \rightarrow III型29.5%),差异均有统计学意义 (均 $P < 0.001$)。LML与LLL体积占比在不同分型间则无明显变化 (均 $P > 0.05$) (图10)。

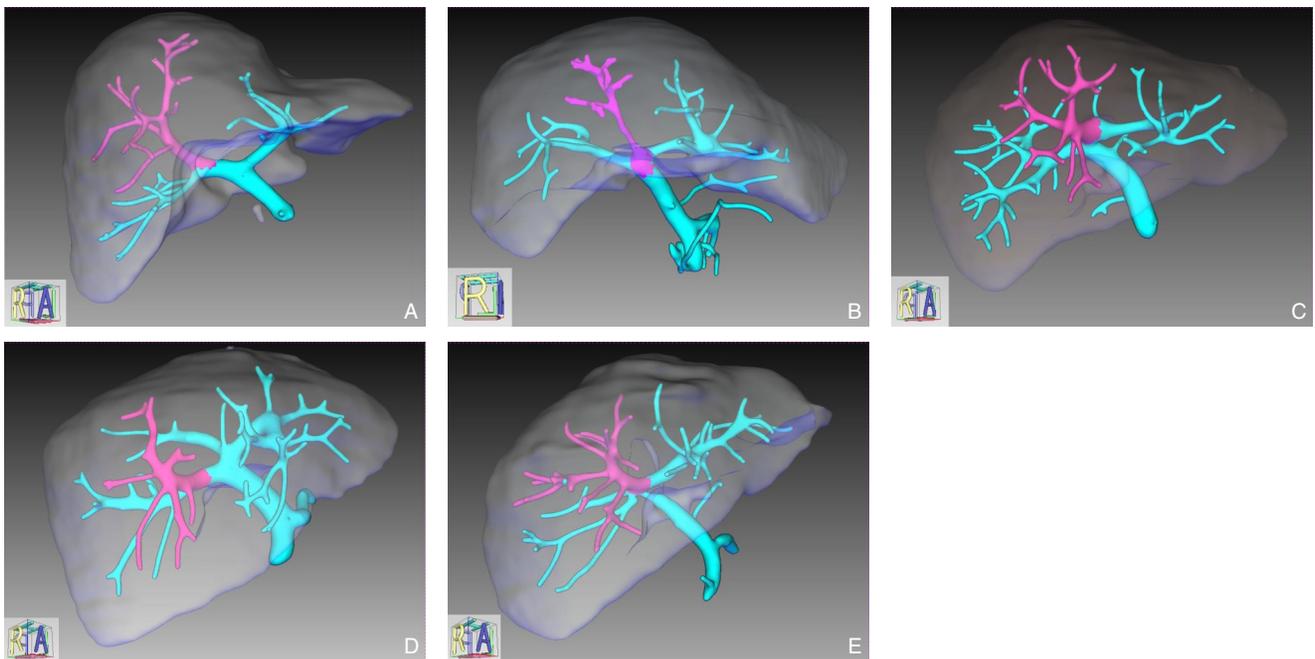


图5 门静脉分型三维可视化模型图 A: 门静脉I型; B: 门静脉II型; C: 门静脉III型; D: 门静脉IV型; E: 门静脉V型
 Figure 5 Three-dimensional visualization models of portal vein classifications A: Type I portal vein; B: Type II portal vein; C: Type III portal vein; D: Type IV portal vein; E: Type V portal vein

表1 610例活体肝移植供体的肝门部门静脉构型[n (%)]

Table 1 Portal vein configurations at the hepatic hilum in 610 living liver donors [n (%)]

类型(肝门部门静脉构型)	数值
I型(门静脉主干分为左、右两支,分别注入左、右半肝)	522(85.6)
II型(门静脉分为三叉型,分别为右前支、右后支和左支)	21(3.4)
III型(门静脉右前支来自左支)	56(9.2)
IV型(门静脉右后支来自左支)	1(0.2)
V型(门静脉分为四叉型,分别为左支、右前支、6段分支和7段分支)	2(0.3)
其他	8(1.3)
总计	610(100.0)

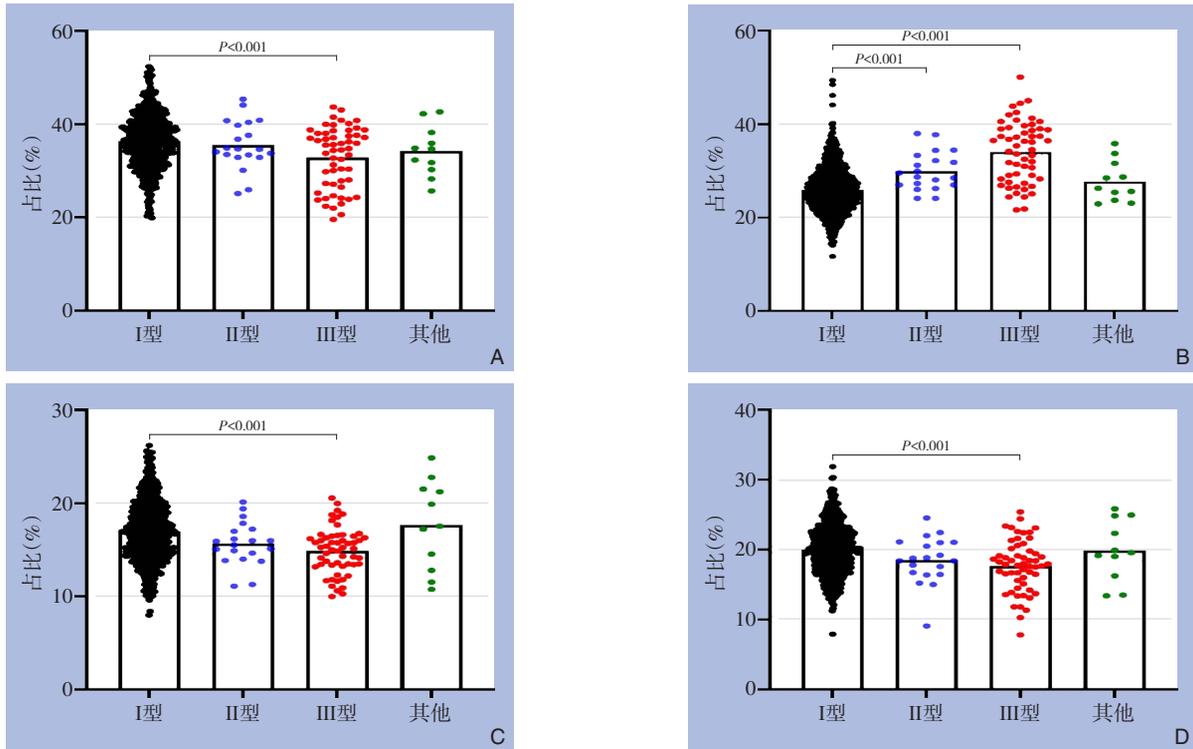


图6 不同肝门部门静脉构型供者肝脏各肝叶体积比 A: RAL 体积占比; B: RPL 体积占比; C: LML 体积占比; D: LLL 体积占比

Figure 6 Proportions of hepatic lobe volumes in donors with different portal vein configurations at the hepatic hilum

A: Proportion of RAL volume; B: Proportion of RPL volume; C: Proportion of LML volume; D: Proportion of LLL volume

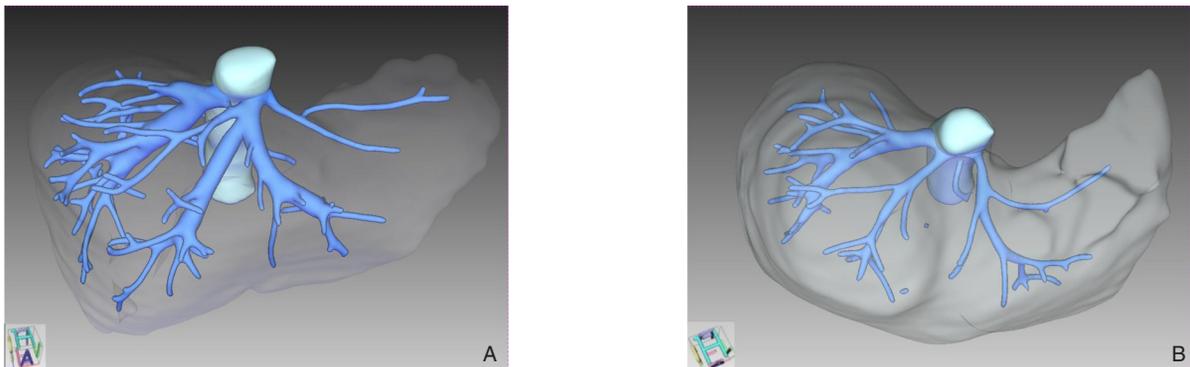


图7 MHV和LHV汇入IVC类型三维可视化模型图 A: 1型; B: 2型

Figure 7 Three-dimensional visualization models of MHV and LHV drainage into the IVC A: Type 1; B: Type 2

表2 610例活体肝移植供体的MHV和LHV汇入IVC类型[n (%)]

Table 2 Drainage patterns of the MHV and LHV into the IVC in 610 living liver donors [n (%)]

类型(汇入IVC方式)	数值
1型(独立汇入型, MHV和LHV分别独立汇入IVC)	424(69.5)
2型(共干汇入型, MHV和LHV汇合成主干后再汇入IVC)	186(30.5)
合计	610(100.0)

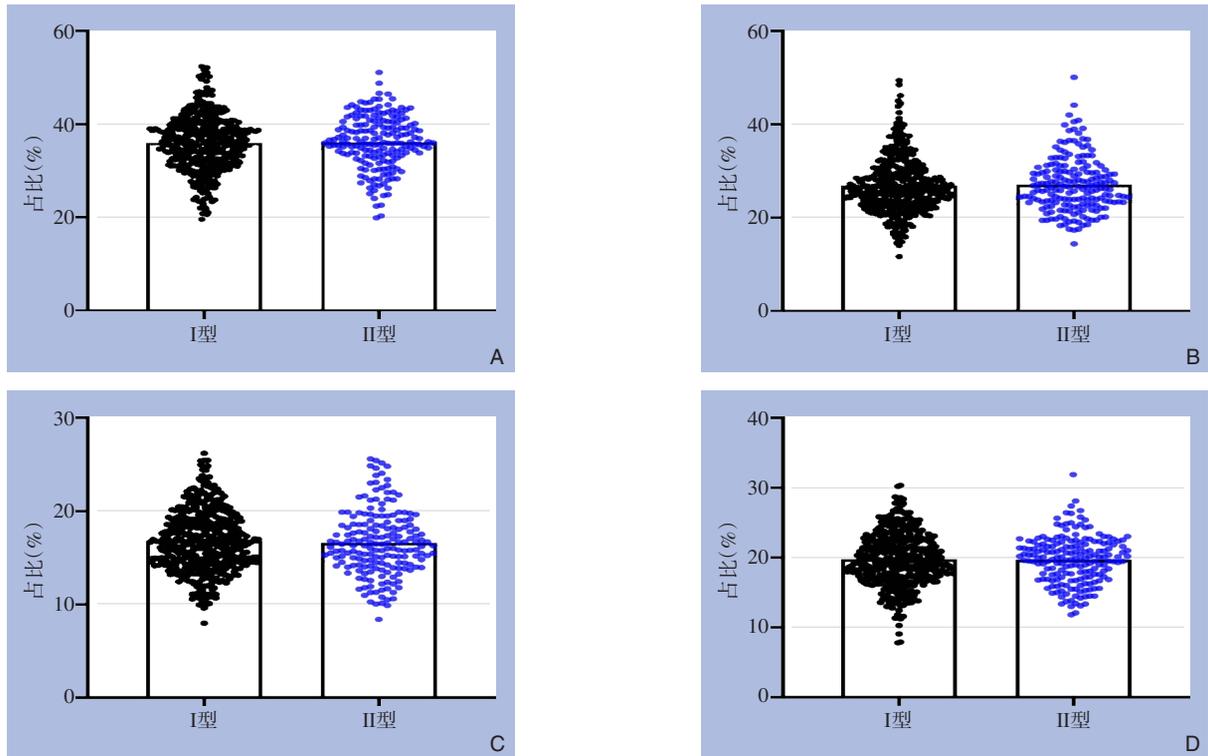


图8 不同MHV和LHV汇入IVC方式供体肝脏各肝叶体积占比 A: RAL体积占比; B: RPL体积占比; C: LML体积占比; D: LLL体积占比

Figure 8 Proportions of hepatic lobe volumes in donors with different MHV and LHV drainage patterns into the IVC A: Proportion of RAL volume; B: Proportion of RPL volume; C: Proportion of LML volume; D: Proportion of LLL volume

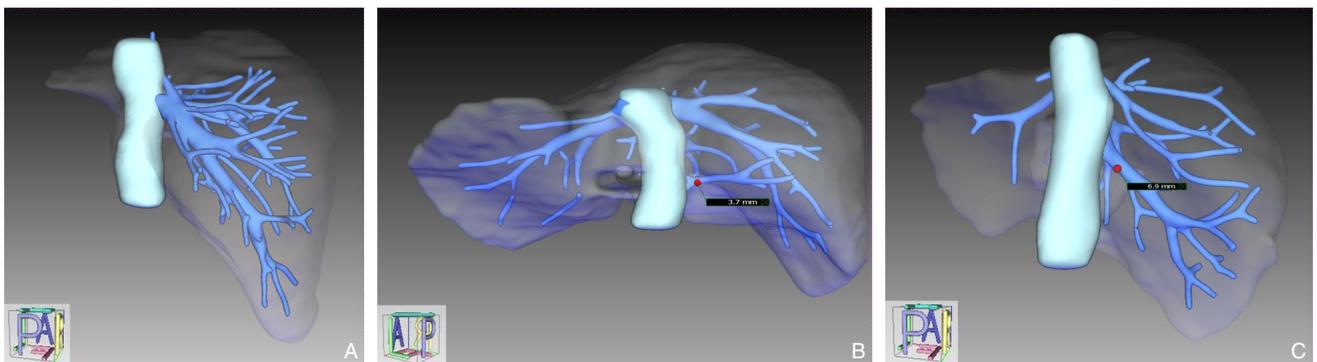


图9 不同IRHV类型三维可视化模型图 A: I型; B: II型; C: III型

Figure 9 Three-dimensional visualization models of different IRHV types A: Type I; B: Type II; C: Type III

表3 610例活体肝移植供体的IRHV类型[n (%)]
Table 3 IRHV types in 610 living liver donors [n (%)]

类型(影像特征)	数值
I型(影像学上未发现IRHV)	187(30.7)
II型(IRHV直径<5 mm)	291(47.7)
III型(IRHV直径≥5 mm)	132(21.6)
总计	610(100.0)

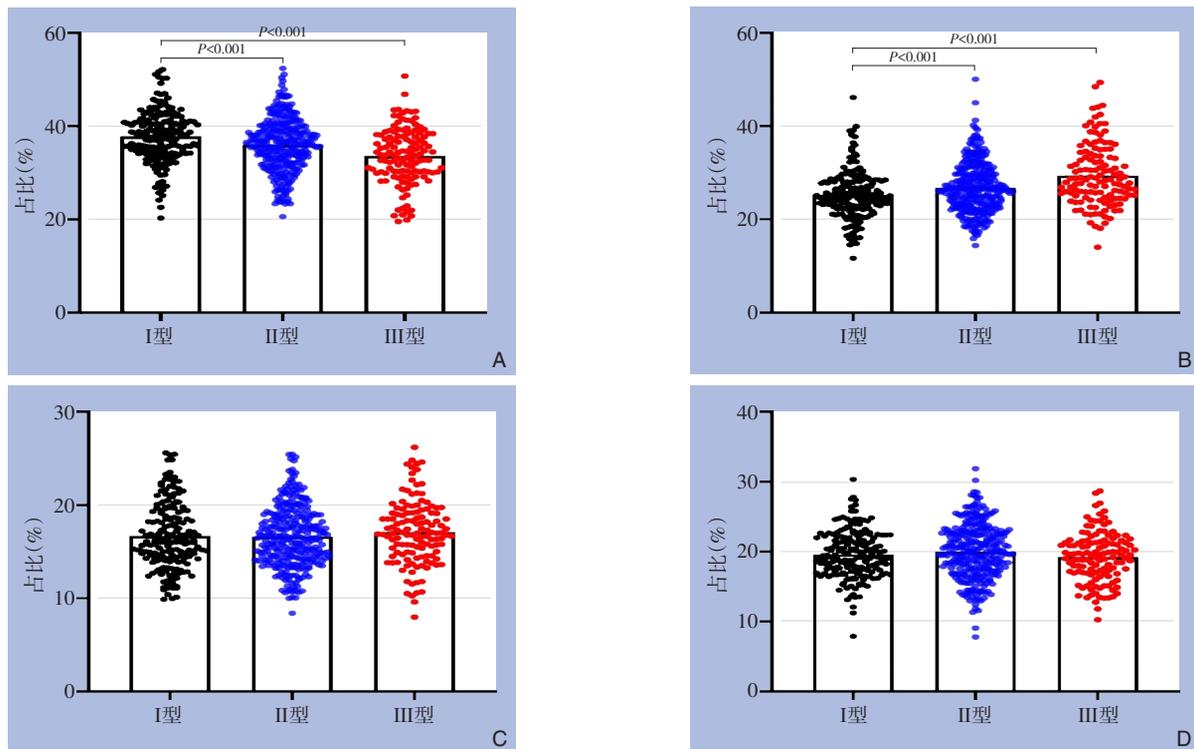


图10 不同IRHV类型供体肝脏各肝叶体积占比 A: RAL体积占比; B: RPL体积占比; C: LML体积占比; D: LLL体积占比

Figure 10 Proportions of hepatic lobe volumes in donors with different IRHV types A: Proportion of RAL volume; B: Proportion of RPL volume; C: Proportion of LML volume; D: Proportion of LLL volume

2.3 胆管解剖分型特征及其与肝区体积分布的关系

基于158例胆管扩张患者的3DVE结果,本研究参照Varotti分型^[16]将右肝管汇合方式分为四型:1型[右前肝管(RABD)、右后肝管(RPBD)先汇合]最常见,占66.5%(105/158);2型(三叉型汇合)占7.6%(12/158);3型(RABD异常汇入)占8.2%(13/158);4型(RPBD异常汇入)占17.1%(27/158);另有0.6%(1/158)为其他类型[B6段胆管汇入肝总管(common hepatic duct, CHD)](图11)(表4)。门静脉拓扑及几何分析显示,不同右肝管汇合分型(I~IV型)患者的各肝区(RAL、RPL、LML及LLL)体积占比均无明显差异

(均 $P>0.05$)(图12)。参照Cho分型^[17]将左肝管汇合方式分为三型:I型(左外上叶B2与左外下叶B3段胆管先汇合,再与左内叶B4段胆管汇合)最为常见,占80.4%(127/158);II型(B3、B4段胆管先汇合,再与B2段胆管汇合)占18.4%(29/158);III型(B2、B3、B4段胆管三叉型汇合)占1.3%(2/158)(图13)(表5)。门静脉拓扑及几何分析显示,不同左肝管汇合分型(I型 vs. II/III型)患者的各肝区(RAL、RPL、LML及LLL)体积占比差异均无统计学意义(均 $P>0.05$),表明左肝管汇合方式不影响各肝区体积分布(图14)。

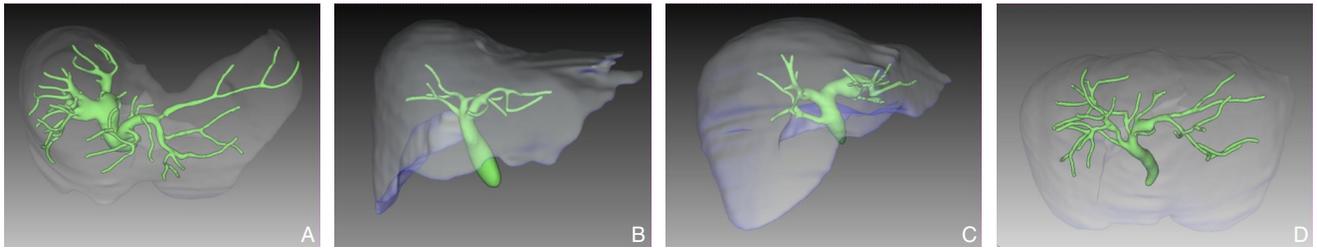


图11 不同右肝管汇合方式 A: 1型; B: 2型; C: 3型; D: 4型

Figure 11 Different confluence patterns of the right hepatic duct A: Type 1; B: Type 2; C: Type 3; D: Type 4

表4 158例胆管扩张患者右肝管解剖汇合分型[n (%)]

Table 4 Anatomical confluence patterns of the right hepatic duct in 158 patients with bile duct dilatation [n (%)]

分型(汇合方式)	数值
1型(RABD和RPBD汇合为右肝管,然后与左肝管汇合为CHD)	105(66.5)
2型(RABD、RPBD和左肝管呈三叉型汇合为CHD)	12(7.6)
3型(RABD汇入左肝管或RPBD直接汇入CHD)	13(8.2)
4型(RPBD汇入左肝管或RABD直接汇入CHD)	27(17.1)
其他	1(0.6)
合计	158(100.0)

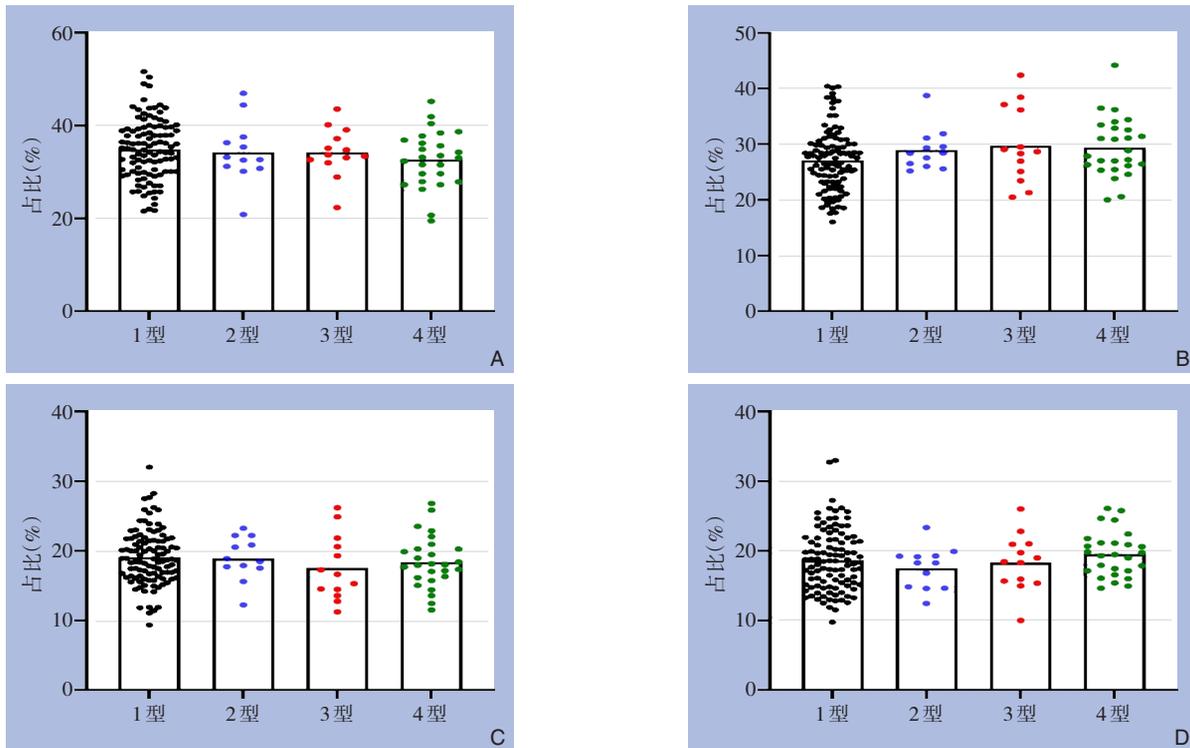


图12 不同右肝管汇合方式患者的肝脏各肝叶体积占比 A: RAL 体积占比; B: RPL 体积占比; C: LML 体积占比; D: LLL 体积占比

Figure 12 Proportions of hepatic lobe volumes in patients with different right hepatic duct confluence patterns A: Proportion of RAL volume; B: Proportion of RPL volume; C: Proportion of LML volume; D: Proportion of LLL volume

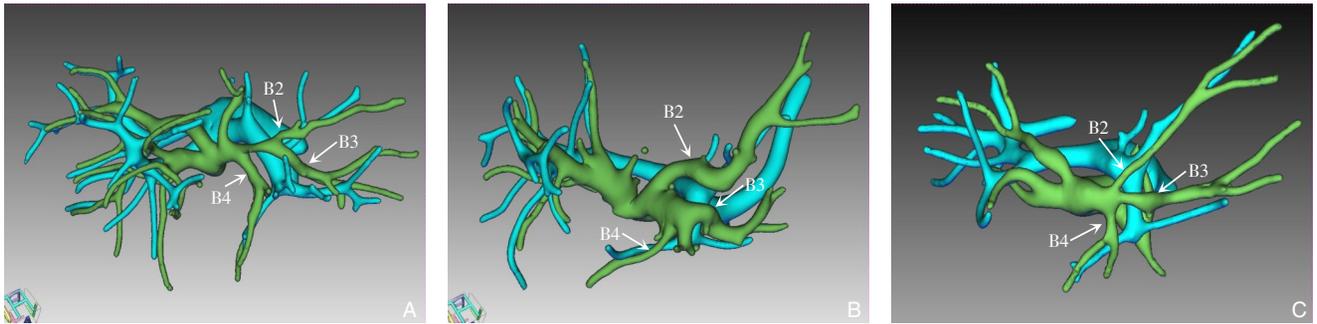


图 13 不同左肝管汇合方式 A: I型; B: II型; C: III型

Figure 13 Different confluence patterns of the left hepatic duct A: Type I; B: Type II; C: Type III

表 5 158例胆管扩张患者的左肝管汇合方式[n (%)]

Table 5 Confluence patterns of the left hepatic duct in 158 patients with bile duct dilatation [n (%)]

类型(左肝管汇合方式)	数值
I型(B2和B3胆管汇合后其主干再与B4汇合)	127(80.4)
II型(B3与B4胆管汇合后其主干再与B2汇合)	29(18.4)
III型(B2、B3和B4胆管呈三叉型汇合)	2(1.3)
合计	158(100.0)

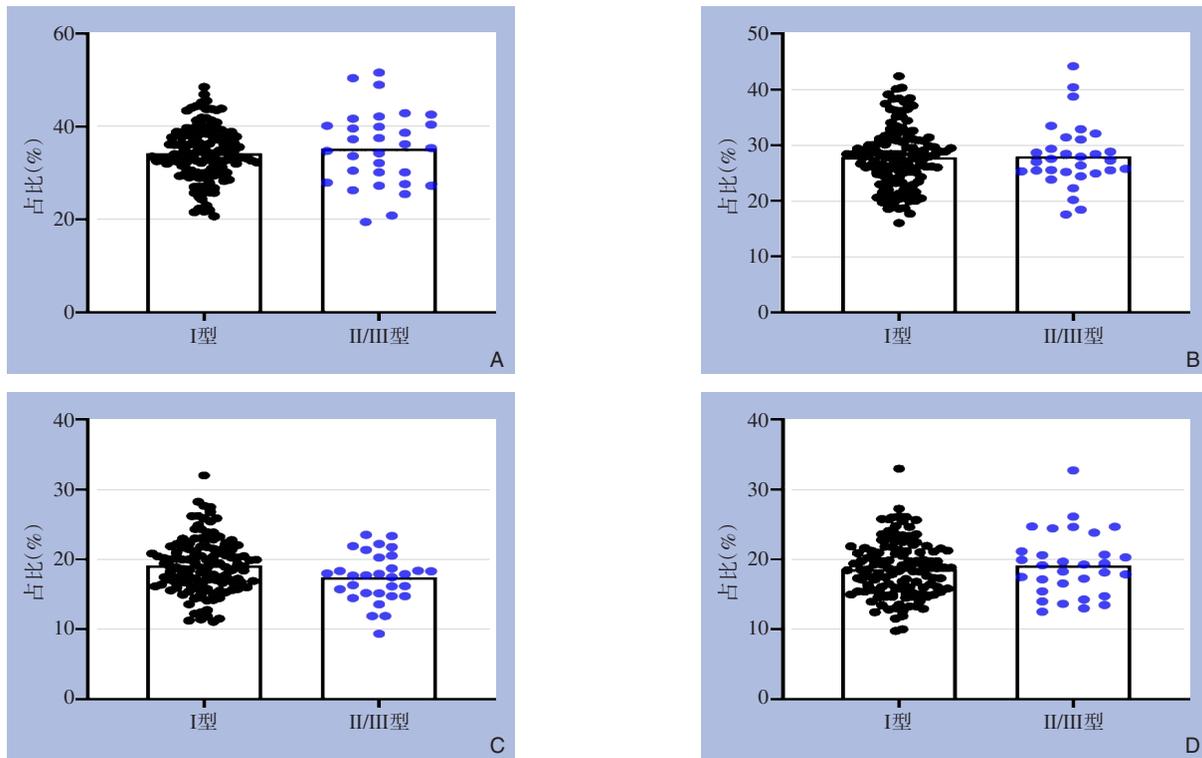


图 14 不同左肝管汇合方式患者的肝脏各肝叶体积占比 A: RAL 体积占比; B: RPL 体积占比; C: LML 体积占比; D: LLL 体积占比

Figure 14 Proportions of hepatic lobe volumes in patients with different left hepatic duct confluence patterns A: Proportion of RAL volume; B: Proportion of RPL volume; C: Proportion of LML volume; D: Proportion of LLL volume

2.4 肝外肝动脉、门静脉及胆管的空间构型特征

本研究基于 158 例胆管扩张患者的 3DVE 结果，将肝外肝动脉与门静脉的空间关系分为两型：门

静脉前型（动脉跨前方）占 91.8%（145/158），为最常见类型；门静脉后型（动脉绕后方）占 8.2%（13/158）（图 15）（表 6）。将肝外肝右动脉

(right hepatic artery, RHA) 与 CHD 的空间关系分为三型: CHD 后型 (动脉经后方) 占 91.1% (144/158), 为绝对主导类型; CHD 前型 (动脉跨前方)

占 8.2% (13/158); 混合型 (动脉分前后两支) 占 0.6% (1/158) (图 16) (表 7)。

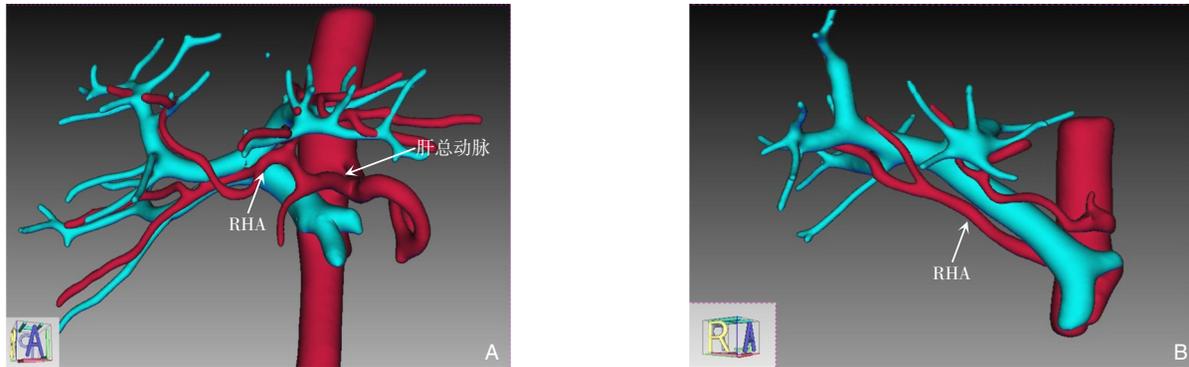


图 15 肝外肝动脉和门静脉主干空间关系三维可视化模型图 A: 门静脉前型肝外肝动脉; B: 门静脉后型肝外肝动脉
 Figure 15 Three-dimensional visualization models of the spatial relationship between the extrahepatic hepatic artery and the main portal vein trunk A: Extrahepatic hepatic artery anterior to the portal vein; B: Extrahepatic hepatic artery posterior to the portal vein

表 6 158 例胆管扩张患者肝外肝动脉与门静脉的空间关系特征 [n (%)]

Table 6 Spatial relationship characteristics between the extrahepatic hepatic artery and the portal vein in 158 patients with bile duct dilatation [n (%)]

类型(肝外肝动脉与门静脉空间关系)	数值(%)
门静脉前型(RHA 或肝总动脉横跨于门静脉前方)	145(91.8)
门静脉后型(RHA 或肝总动脉绕行于门静脉后方)	13(8.2)
合计	158(100.0)

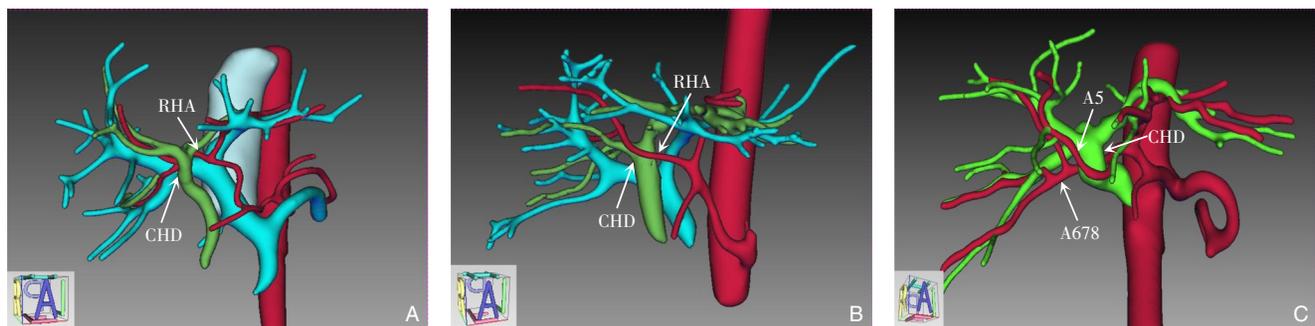


图 16 肝外肝动脉和 CHD 空间关系三维可视化模型图 (A5: 肝脏 5 段动脉; A678: 肝脏 6、7、8 段动脉) A: CHD 后型; B: CHD 前型; C: 混合型

Figure 16 Three-dimensional visualization models of the spatial relationship between the extrahepatic hepatic artery and the CHD (A5: segment V hepatic artery; A678: segment VI, VII, and VIII hepatic arteries) A: CHD-posterior type; B: CHD-anterior type; C: Mixed type

表 7 158 例胆管扩张患者肝外肝动脉与 CHD 的空间关系特征 [n (%)]

Table 7 Spatial relationship characteristics between the extrahepatic hepatic artery and the CHD in 158 patients with bile duct dilatation [n (%)]

类型(肝外肝动脉与 CHD 空间关系)	数值
CHD 后型(RHA 横跨于 CHD 后方)	144(91.1)
CHD 前型(RHA 横跨于 CHD 前方)	13(8.2)
混合型(RHA 分为两支,分别横跨于 CHD 的前方和后方)	1(0.6)
合计	158(100.0)

2.5 肝内肝动脉、门静脉及胆管的空间构型特征

基于 158 例胆管扩张患者的 3DVE 结果，将 RHA 与门静脉右支的空间关系分为三型：门静脉下型最为常见，占 75.9% (120/158)；门静脉上型占 19.6% (31/158)；混合型占 4.4% (7/158) (图 17) (表 8)。

将右肝管与门静脉右支的空间关系分为三型：门静脉上型占 88.6% (140/158)，为绝对主导类型；门静脉下型占 6.9% (11/158)；混合型占 4.4% (7/158) (图 18) (表 9)。

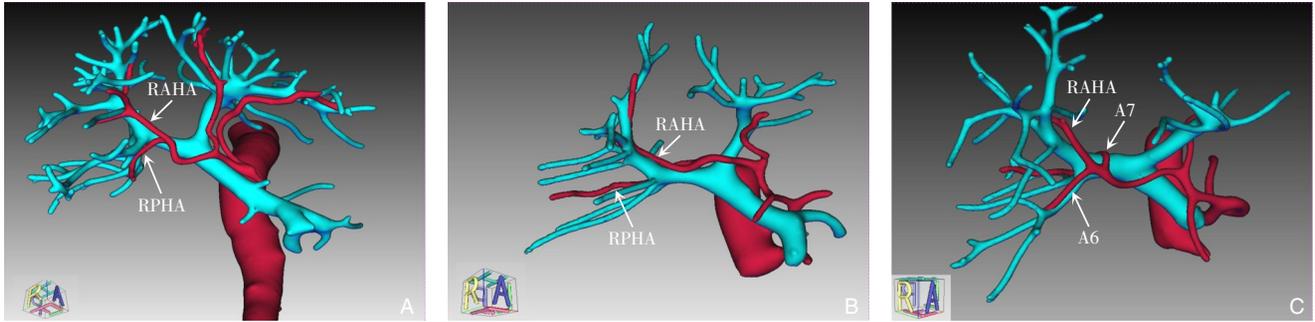


图 17 RHA 与门静脉右支空间关系三维可视化模型图 (RAHA: 肝右前动脉; RPHA: 肝右后动脉; A6: 肝脏 6 段动脉; A7: 肝脏 7 段动脉) A: 门静脉下型; B: 门静脉上型; C: 混合型

Figure 17 Three-dimensional visualization models of the spatial relationship between the RHA and the right portal vein branch (RAHA: right anterior hepatic artery; RPHA: right posterior hepatic artery; A6: segment VI hepatic artery; A7: segment VII hepatic artery) A: Infraportal type; B: Supraportal type; C: Mixed type

表 8 158 例胆管扩张患者的 RHA 与门静脉右支的空间关系特征 [n (%)]

Table 8 Spatial relationship characteristics between the RHA and the right portal vein branch in 158 patients with bile duct dilatation [n (%)]

类型(RHA 与门静脉右支空间关系)	数值
门静脉下型(RPHA 从门静脉右支下方经过, 支配肝脏 RPL)	120(75.9)
门静脉上型(RPHA 从门静脉右支上方绕过, 支配肝脏 RPL)	31(19.6)
混合型(RPHA 分为两支, 一支从门静脉右支下方经过, 另一支从门静脉右支上方绕过, 共同支配肝脏 RPL)	7(4.4)
合计	158(100.0)

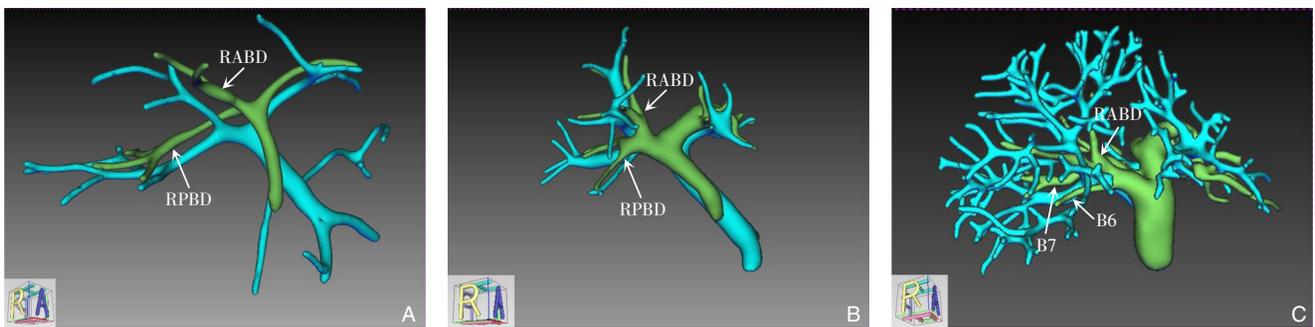


图 18 右肝管与门静脉右支空间关系三维可视化模型图 A: 门静脉上型; B: 门静脉下型; C: 混合型

Figure 18 Three-dimensional visualization models of the spatial relationship between the right hepatic duct and the right portal vein branch A: Supraportal type; B: Infraportal type; C: Mixed type

表9 158例胆管扩张患者的右肝管与门静脉右支的空间关系特征[n (%)]

Table 9 Spatial relationship characteristics between the right hepatic duct and the right portal vein branch in 158 patients with bile duct dilatation [n (%)]

类型(右肝管与门静脉右支空间关系)	数值
门静脉上型(RPBD从门静脉右支上方绕过,引流肝脏RPL的胆汁)	140(88.6)
门静脉下型(RPBD从门静脉右支下方经过,引流肝脏RPL的胆汁)	11(7.0)
混合型(B6和B7胆管分别从门静脉右支下方和上方绕过,引流肝脏RPL的胆汁)	7(4.4)
合计	158(100.0)

2.6 RHA-门静脉与RPBD-门静脉空间关系间的相关性

基于158例胆管扩张患者的3DVE结果,分析右肝管-门静脉右支和RHA-门静脉右支空间关系的相关性。结果显示,发现两种空间关系具有相关性(Fisher精确检验, $P < 0.001$),门静脉下型

RHA和门静脉上型RPBD为主导组合,占75.0%(105/140);术前影像提示胆管扩张,RPBD与门静脉右支呈门静脉下型走行,RHA亦全部位于门静脉右支下方(11/11)(表10)。该解剖对应关系明确,可作为术前预判胆管扩张不明显患者脉管空间关系的重要解剖路标。

表10 RHA-门静脉与RPBD-门静脉空间关系间的相关性分析(n)

Table 10 Correlation analysis between the spatial relationships of the RHA-portal vein and the right posterior hepatic duct-portal vein (n)

RPBD与门静脉右支空间关系	RHA与门静脉右支空间关系			
	门静脉下型	门静脉上型	混合型	合计
门静脉上型	105	30	5	140
门静脉下型	11	0	0	11
混合型	4	1	2	7
合计	120	31	7	158

3 讨论

肝脏外科的精准化体现在术前解剖评估上的核心,在于对个体化脉管解剖的深刻理解与术前精准评估。本研究表明,三维可视化技术在此领域展现出显著优势,它不仅能够高精度地揭示脉管变异与复杂的空间关系,更能将解剖学信息与功能性评估相结合,为手术决策提供超越传统影像的全面依据。

本研究团队前期已系统应用三维可视化技术,深入剖析了肝动脉与肝静脉的解剖结构并提出了分型方案^[8],并将其应用于肝门部胆管癌、胆囊癌、医源性胆管损伤等疾病的临床诊疗,充分展现了该技术在肝胆精准解剖与疾病诊治中的重要价值^[1,3,18-29]。在本研究中,3DVE能够直观、完整地重建肝动脉、门静脉及胆管的解剖走行及其空间关系,为复杂脉管变异的术前识别提供了可靠手段。相比常规腹部CT的二维或多平面重建,3DVE在呈现脉管立体结构及相互毗邻关系方面具

有明显优势,从而弥补了传统影像学评估在复杂解剖结构分析中的不足。尤其对于肝动脉,其解剖变异被认为是术中医源性损伤、术后缺血性胆道病变、肝移植血管并发症以及肿瘤栓塞不彻底的重要风险因素^[29-37],术前精准评估具有重要临床意义。

3DVE的价值远不止于形态学显示。通过其独有的门静脉拓扑流域与几何分析技术,本研究首次在大样本健康肝脏中揭示了脉管构型与肝叶体积分布的内在规律。研究发现,当门静脉右前支起源于左支(III型变异)时,其RAL体积占比显著减小而RPL增大^[14];同样,IRHV的直径也有粗细变异^[30]。这一发现将“形态变异”与“功能容积”直接关联,对于精准肝切除手术规划具有根本性指导意义。例如,在涉及上述变异的半肝切除中,切除平面的确定必须综合考虑流域边界,而非机械地遵循肝静脉平面,从而在保证根治性的同时,最大限度地保护功能性肝体积并避免剩余肝叶的流域性缺血^[13,38]。

胆管汇合方式的变异是肝门部手术的关键不确定性因素。RPL肝管（B6、B7段）若异常汇入左肝管（如3型或4型）或呈三叉型汇合（2型），在行标准半肝切除时，按常规平面离断易损伤此类“迷途”胆管，导致目标肝区胆汁引流障碍，引发胆汁漏或肝段萎缩。术前通过三维可视化明确胆管构型，可预判解剖风险点，制定安全离断策略^[38-39]。在活体肝移植中，胆管变异直接影响受体预后。若供肝RABD、RPBD分别独立汇入，切取时将形成多个细小胆管开口，显著增加受体胆道重建难度，并提升术后狭窄与胆汁漏风险^[40-41]。因此，术前精确评估胆管构型对供体离断点选择与受体重建方案规划至关重要。

3DVE在解构肝门区“血管-胆管”三维空间关系上具有不可替代的价值。本研究系统分析了RHA与门静脉右支、右肝管与门静脉右支的三种空间关系类型（门静脉上型、下型与混合型），并发现RHA-门静脉与RPBD-门静脉空间关系之间存在显著相关性。这种关联性为术中导航提供了关键路标：例如，门静脉下型的RPBD几乎总是伴随门静脉下型的RHA。在肝门部胆管癌根治术等高风险手术中，此类认知能有效预判“危险区”。对于门静脉上型的RPHA，其在行左三区切除时因位置深在、重建困难而构成技术挑战^[42]；而对于门静脉下型的RPBD，其表浅位置则允许进行更彻底的胆管切除并获得更理想的胆肠吻合效果^[43-46]。术前通过3DVE明确这些关系，是规避血管误伤、实现肿瘤根治性切除的前提。

综上所述，3DVE技术实现了从二维影像到三维构型、从静态解剖到动态流域、从形态描述到功能预测的跨越，是推动精准肝脏外科发展的核心工具。未来，将3DVE与术中导航、荧光染色技术及人工智能辅助规划进一步整合，有望构建一个从术前诊断、手术模拟到实时引导的完整精准外科体系，最终改善患者预后。

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