

· 专家论坛 ·

## 三维可视化技术在原发性肝癌外科手术中的应用

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**摘要:**外科手术切除是目前治疗原发性肝癌的主要方法。三维可视化技术、3D 打印、虚拟现实、吲哚菁绿分子荧光影像、术中导航肝切除等技术的应用,为原发性肝癌的术前诊断、手术规划及术中导航等方面提供了全新的方法。其中,三维可视化技术对原发性肝癌的诊断、治疗方案选择、术前规划、术中导航及肝移植等方面表现出无可比拟的优越性,本文主要总结近年来三维可视化技术在原发性肝癌外科手术中的应用进展。

**关键词:**肝肿瘤; 成像, 三维; 外科手术

### Application of three – dimensional visualization in surgical operation for primary liver cancer

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**Abstract:** Surgical resection is currently the main method for the treatment of primary liver cancer. The appearance of new techniques, such as three – dimensional visualization, 3D printing, virtual reality, indocyanine green molecular fluorescence imaging, and hepatectomy with intraoperative navigation, has provided new methods for the preoperative diagnosis, surgical planning, and intraoperative navigation of primary liver cancer. Among these techniques, three – dimensional visualization shows incomparable advantages in the diagnosis of primary liver cancer, the selection of treatment regimen, preoperative planning, intraoperative navigation, and liver transplantation. This article summarizes the recent advances in the application of three – dimensional visualization in surgical operation for primary liver cancer.

**Key words:** Liver Neoplasms; Imaging, Three – Dimensional; Surgical Procedures, Operative

原发性肝癌(以下简称肝癌)是全世界范围内常见的恶性肿瘤之一,在2018年全球恶性肿瘤发病率中排名第6位,是第4位肿瘤致死原因<sup>[1]</sup>。我国肝癌发病人数和死亡人数均占全球一半以上<sup>[2]</sup>。随着近些年来以外科手术为主的综合治疗的不断发展,肝癌患者的预后取得明显改善<sup>[3]</sup>。肝脏的脉管系统(肝动脉、肝静脉、门静脉和胆道系统)十分复杂,以往外科医师需要依靠CT、MRI等非立体的断层影像信息,在头脑中整合立体的三维印象,然而受限于个人临床经验和三维重构能力不同,往往存在不确定性。1998年,Marescaux等<sup>[4]</sup>首次使用三维可视化技术描绘肝脏脉管系统。此后,三维可视化技术不断推广与发展,革命性实现术前即可清晰、直观掌握肝癌的三维解剖和形态特征的诊疗模式<sup>[5]</sup>。以三维可视化、3D打印、虚拟现实(virtual reality, VR)、增强现实(augmented reality, AR)、吲哚菁绿(indocyanine green, ICG)分子荧光影像、多模图像实时融合导航肝切除术等

技术为代表的数字智能化技术的出现,为肝癌精确诊断、术前规划、术中导航的实施提供了全新的方法。

### 1 三维可视化技术在肝癌术前规划中的应用

肝脏具有复杂的脉管系统,术前准确判断肝血管、胆管的变异能够影响手术决策、减少术中重要管道的损伤以及降低术后并发症。方驰华等<sup>[6]</sup>研究纳入我国7家医疗中心的1665例肝癌手术患者,通过三维可视化分析显示肝血管变异率高达53.2%,且术中所见肝动脉、门静脉及肝静脉的变异情况与术前三维可视化一致。三维可视化技术还可准确、直观地评估门静脉变异情况<sup>[7]</sup>,确定断肝平面,规划门静脉重建,提高手术安全性。三维可视化技术可进行术前残肝体积计算及虚拟仿真手术,通过充分而详实的术前规划,有效减少肝切除术后并发症。研究<sup>[8-9]</sup>显示,1025例应用三维可视化技术的肝癌肝切除患者的术后肝衰竭发生率为3.7%,围手术期病死率为0.59%;5家医疗中心876例应用三维可视化技术的肝癌肝切除患者的术后肝衰竭发生率为1.5%,围手术期病死率为4.1%。Okuda等<sup>[10]</sup>发现肝内胆管癌患者行术前三维重建,有利于提高术中切缘的阴性率。结合新兴的3D打印技术,可将三维可视化图像通过逐层打印的方式构

造出个体化的立体物理模型,实现空间维度跨越式转变。2013年,Zein等<sup>[11]</sup>首次报道3D打印技术在肝癌手术中的应用。3D打印模型最实质性的优点在于可以带入手术室,在手术过程中与真实肝脏进行比较,并调整最佳解剖位置以识别肝内管道结构<sup>[12]</sup>。Xiang等<sup>[7]</sup>报道3D打印技术能够准确识别门静脉的变异,进行保留来自门静脉右前支的IV段分支的右半肝切除术,有效防止术后IV段缺血,避免术后肝功能失代偿。对于需行血管重建的复杂性肝脏手术,3D打印最大的优势是血管重建关键区域的立体可视化、血管浸润需切除长度的预估和重建方案的制订<sup>[13]</sup>。近年研究<sup>[14]</sup>显示,最新的3D生物打印模型由生物材料和肝细胞共同组成,具有生物相容性、可扩展性和成本较低的优势。这些模型将在肝生物工程,甚至模拟人工肝等方面发挥至关重要的作用,为肝衰竭患者带来新的曙光。

## 2 VR技术在肝癌术前规划中的应用

VR技术是计算机软硬件技术、传感技术、人机接口技术及人工智能等科学领域飞速发展的结晶。在三维可视化技术的基础上,VR技术可创建一个虚拟的三维立体环境,手术医师可在术前通过头戴式眼镜对虚拟环境中的3D模型进行全方位、多角度观察,再对模型进行缩放、旋转、透视化、删减处理,使术者能够立体、清晰、精准地了解肿瘤的位置及其周围血管的关系,实现对肝内外病灶的精确定位<sup>[15]</sup>。VR技术提供的虚拟手术场景,使术者可以在模拟真实手术,反复练习,寻求最佳的手术路径,同时有助于手术组成员进一步熟悉手术步骤,从而缩短手术时间,减少术中出血及损伤。Sampogna等<sup>[16]</sup>研究显示,术前行VR模拟手术的肝癌患者,术中出血量、手术时间明显减少。Mise等<sup>[17]</sup>研究发现,术前行三维重建及VR虚拟肝切除的肝癌患者,解剖性肝段切除率高于对照组,虽然整体上两组的5年总生存期及无进展生存期无统计学差异,但是在肝功能储备差(ICG 15 min滞留率>10%)的肝癌患者中,行VR虚拟肝切除患者的无进展生存期明显优于对照组。也有报道<sup>[18]</sup>针对巨块型肝癌患者术前行三维重建并转化为VR模型,能够最大程度防止术中血管损伤,预防术后残肝不足所致的肝衰竭。然而,在临床现实中,患者的呼吸运动、术中体位等因素均可能引起术中形变。因此,仅仅依靠VR技术无法实现术中精确实时导航。

## 3 AR技术在肝癌术中导航的应用

AR技术由VR技术的基础上发展而来,主要包括三维重建、显示、跟踪和配准技术,与前述技术的主要区别是配准技术。配准是将虚拟图像和真实图像中的相应数据点链接到一个坐标系中的过程,是一种将真实世界信息和虚拟世界信息“无缝”集成的技术<sup>[19-20]</sup>。2014年,

Beat Müller-Stich教授团队<sup>[21]</sup>首次利用腹腔镜技术结合AR术中导航切除肝肿瘤,AR图像与腹腔镜图像匹配较好,手术进展顺利,患者无术后并发症出院。Phutane等<sup>[22]</sup>基于AR技术的手术导航系统,使外科医生通过佩戴光学透视式头戴式显示器(optical see-through head-mounted displays, OST-HMD)获得融合图像,将虚拟解剖结构与术中真实场景相结合,精确定位肝内肿瘤及关键部位,从而减少术中出血,缩短手术时间。与骨科和神经外科的刚性手术导航不同,肝脏为非刚性结构,腹腔镜术中气腹、呼吸运动、心跳和手术操作导致的术中形变均显著影响AR术中导航的准确性<sup>[23-24]</sup>。为此,近年来国内外专家在该领域付出不懈探索和努力。在开放手术方面,Okamoto等<sup>[25]</sup>通过增加3D摄像机、立体显示器和OST-HMD的运用,完成了包括右半肝切除术、尾状叶切除术、胆总管切除术及肝管-空肠吻合术,实际切除线与术前预设切除线之间的误差约为5 mm,极大改善了手术准确性的手术时间。Tang等<sup>[26]</sup>应用基于AR的术中导航系统及肝脏3D打印模型,完成1例肝门部胆管癌的肝切除及淋巴结清扫术,术中导航系统能够精确定位手术区域,提高手术安全性与准确性。而腹腔镜手术及机器人手术相比开放手术具有更宽广的视野及更少的术中形变,使AR术中导航运用的更加广泛。Bertrand等<sup>[27]</sup>使用新兴的AR软件——Hepataug,将一个可变形的术前模型半自动地覆盖到腹腔镜图像上,能够有效减少术中形变,已顺利开展了17例腹腔镜肝切除手术。Zhang等<sup>[28]</sup>通过自主研发的3DLARN(腹腔镜AR导航系统),通过融合术前3D模型实现了腹腔镜解剖性肝切除的实时导航,将85例患者分为术中导航组及非术中导航组,结果证实前者出血量、输血率及住院时间均较后者明显减少。最近一项研究<sup>[29]</sup>表明,在腹腔镜半或Ⅷ段肝切除术中采用可变形的模型重合实现AR术中导航,可精确定位肿瘤,此外AR导航系统还发现2例腹腔镜超声无法显示的微小肿瘤。相比腹腔镜手术,机器人肝切除具有3D成像、多倍放大和显著提高的灵活性等优点,联合AR术中导航更是如虎添翼。Pessaux等<sup>[30]</sup>在机器人肝切除术中使用AR的透明可视化功能行Trocar孔设置,每个Trocar孔均根据患者的解剖、变异和目标病灶设置,争取达到最合适操作平面,同时AR术中导航能够协助在整个手术过程中准确、安全地识别肝内血管、胆管;研究中所有病例均未使用第一肝门阻断,且均无围手术期输血。此后,Bari等<sup>[31]</sup>也报道了类似结果,AR术中导航在机器人的腹腔镜视野中可以清晰显示肿瘤的安全切缘,术前重建的三维模型的覆盖也有助于在切肝过程中识别血管和胆管,最终所有病例的肿瘤切缘宽度均达到1 cm,且术后均无并发症。

#### 4 ICG 分子荧光成像技术在肝癌术中的应用

ICG 作为一种理想、高效的成像介质,利用其荧光特性,可以使癌组织与正常组织形成光强对比,以识别肝表面病灶,同时也能检测到切缘残留小病灶和静脉癌栓,有利于降低术后肿瘤复发及转移的风险<sup>[32]</sup>。Meta 分析<sup>[33]</sup>显示,与使用传统手术方式的对照组相比,ICG 分子影像技术组输血率、术后并发症发生率降低,切缘阴性率提高。三维可视化技术与 ICG 分子荧光成像技术相结合,应用于肝癌术前诊断和术中导航,可以真正实现解剖性、功能性和根治性肝切除术<sup>[34]</sup>。三维可视化技术提高 ICG 染色满意度的优势主要是由于其可以清晰显示肝内脉管走向,有利于术者确定癌灶的累及范围,直观了解肿瘤肝段门静脉的分布,也能更精准地选择计划穿刺点,进而提高染色满意度<sup>[35]</sup>。王晓颖等<sup>[36]</sup>利用三维可视化技术引导门静脉穿刺 ICG 荧光染色,结合腹腔镜超声,共同完成腹腔镜解剖性肝段切除术,有效提高了肝切除的安全性和精确性。方驰华教授团队<sup>[37-38]</sup>结合 AR 技术,选择肝上下腔静脉窝和胆囊底部,同时结合肝边缘形状作为导航图像配准的标记点,较好地改善了术中形变和气动的问题,实现将三维可视化技术、ICG 分子荧光成像技术和 AR 术中融合的精准确肝切除术。研究结果显示,相比于对照组,导航组在减少手术出血量、降低术中输血率和缩短术后住院天数方面具有明显的优势。

#### 5 三维可视化技术在肝移植中的应用

肝移植是肝癌根治性治疗手段之一,尤其适用于肝功能失代偿、不适合手术切除及局部消融的早期肝癌患者。对于儿童肝移植,由于基础供肝短缺以及大部分因病逝捐献的供肝肝体对儿童受者而言相对较大,导致儿童肝移植等待时间较长,死亡风险也相应增加,因此,活体肝移植一直是儿童肝移植领域的重点研究方向。在活体肝移植中,对移植物的尺寸匹配以及对供受者肝血管解剖的精确评估是保证手术成功及供者安全的关键因素。研究<sup>[39]</sup>显示,活体肝移植前应用三维可视化技术行病肝体积计算、肝前后径测量,结合供者肝脏三维重建情况综合制订供者移植切取方案,能够最大程度避免出现移植受者不匹配问题。在活体肝移植中使用 3D 打印的物理模型来模拟供、受者手术,可以帮助术者掌握移植物的尺寸、厚度以及血管解剖,缩短手术时间,提高手术成功率<sup>[40]</sup>。Mise 等<sup>[17]</sup>提出在供体选择上可根据 3D 成像信息进一步优化,包括根据供体血管解剖变异进行相应的静脉重建,从而提高手术的安全性。三维可视化技术结合前述的 ICG 分子荧光成像技术,一方面可用于胆道成像,经胆囊管断端注射 ICG,可获得清晰的胆道解剖图像,指导供者和受者的胆管-胆管吻合,以降低术后胆漏、胆管狭窄等并发症发生率<sup>[41]</sup>;另一方面可用于评

估重建后血管通畅性及移植肝功能的恢复情况,因 ICG 经静脉注射后可迅速与血浆蛋白结合而分布于全身血管,有助于评估重建后血管的通畅情况。肝移植术中经外周静脉注入 ICG,术后如在肝外胆管检测到 ICG 近红外光影像,则表明移植肝肝细胞开始正常分泌胆汁<sup>[42]</sup>。

#### 6 小结与展望

随着数字智能化时代的发展,三维可视化技术在肝癌的诊断、治疗方案的选择、术前规划、术中导航及肝移植等方面体现了无可比拟的优越性。然而,三维可视化技术仍存在一定局限性,例如在一些复杂病例中,巨块型肝癌常推挤、压迫第二肝门,导致对应的肝静脉在薄层 CT 扫描时显示不全,原始数据的缺失也将影响术前评估及术中导航的准确性。未来可在人工智能大数据的算法下,补全缺失数据,提示静脉可能的走行路径,实现精准化、智能化肝切除。目前,AR 术中实时导航的形变及气动也是亟待解决的难点问题,未来有望通过增加配准标记点<sup>[25]</sup>、升级处理软件<sup>[27,43]</sup>、术中联合 CT 建模<sup>[44]</sup>等方式,进一步推动 AR 术中导航的应用与发展。总而言之,以三维可视化技术为代表,联合 AR、ICG 分子荧光成像技术可实现多模式、相互验证、互补不足的手术导航方式,将彻底改变传统二维图像指导下的手术方式,进一步推动肝胆外科个体化、微创化、精准化发展。

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