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· 述评 ·

数智赋能胰腺外科：技术创新及临床实践

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摘要

胰腺外科因其解剖复杂、手术风险高而被视为外科领域的“高地”。近年来，三维重建、荧光导航、增强现实（AR）、混合现实（MR）与人工智能（AI）等数智化技术的引入，为胰腺外科的精准、安全与智能化发展提供了新的解决方案。本文系统梳理了数智化技术在胰腺外科“术前规划-术中导航-术后监测”全流程中的创新应用与临床实践。术前，通过基于深度学习的nnU-Net框架实现胰周血管与胆胰管的高精度三维重建，辅助个体化手术规划；术中，结合吲哚菁绿荧光成像、AR/MR及多模态影像融合技术，实现血管、胆管与肿瘤边界的实时可视化与动态定位，提高解剖识别精度与操作安全性；术后，AI结合可穿戴设备与多模态数据监测，推动并发症风险的智能预测与早期干预。数智化技术的系统性融合正重塑胰腺外科诊疗范式，助力实现从经验驱动到数据驱动、从术者依赖到智能决策的转变。未来，随着算法优化与循证证据积累，数智赋能将持续推动胰腺外科向个体化、精准化、智能化迈进。

关键词

胰腺切除术；手术导航系统；数字技术；成像，三维；人工智能

中图分类号：R657.5

Digital intelligence empowering pancreatic surgery: technological innovation and clinical practice

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Abstract

Pancreatic surgery remains one of the most challenging fields in general surgery due to its complex anatomy and high risk of complications. In recent years, the integration of digital intelligent technologies—such as three-dimensional (3D) reconstruction, fluorescence navigation, augmented/mixed reality (AR/MR), and artificial intelligence (AI)—has provided new strategies for achieving precision, safety, and intelligence in pancreatic surgery. This review summarizes the innovations and clinical applications of these technologies throughout the full perioperative process, including preoperative planning, intraoperative navigation, and postoperative monitoring. Preoperatively, the deep learning-based nnU-Net framework enables high-precision 3D reconstruction of peripancreatic vessels and pancreaticobiliary ducts for individualized surgical planning. Intraoperatively, multimodal image fusion combining indocyanine green fluorescence imaging with AR/MR navigation allows real-time visualization and spatial localization of key anatomical structures, enhancing surgical accuracy and safety. Postoperatively, AI-driven models integrated with wearable sensors and multimodal data support intelligent risk prediction and early intervention for complications. The systematic application of digital intelligence is reshaping the paradigm of pancreatic surgery, driving the transition from experience-based to data-driven and from surgeon-dependent to intelligent decision-making. With continuous algorithmic refinement and accumulation of clinical evidence, digital empowerment will further advance pancreatic surgery toward personalization, precision, and intelligence.

Key words

Pancreatic Neoplasms; Surgical Navigation Systems; Digital Technology; Imaging, Three-Dimensional; Artificial intelligence

CLC number: R657.5

胰腺手术难度大,并发症发生率高,主要原因在于:(1)胰腺及其周围解剖结构复杂,血管变异多见,二维(2D)CT/MRI影像在多维度评估病灶与血管及胆胰管空间解剖关系方面存在局限,导致术前精确规划制定难;(2)胆胰管和胰周细小血管在术野中往往缺乏可识别的视觉特征,尤其是在肿瘤侵袭、炎症水肿等区域,使得术中精准解剖难;(3)术后胰瘘、出血等严重并发症的发生往往具有延迟性和隐蔽性,导致术后并发症发生及时预警和早期干预难^[1-2]。因此,精确的手术规划制定、精准的术中解剖识别和精细的术后监测管理是保障胰腺手术安全实施的关键及难点。

随着医工交叉研究的不断深入,三维(3D)可视化、吲哚菁绿(indocyanine green, ICG)荧光成像、多模态影像手术导航和人工智能(artificial intelligence, AI)等数智化诊疗技术逐步应用于胰腺外科,为解决上述难点提供了新策略^[3]。ICG荧光可以实时显影血管、胆管以及富血供肿瘤的边界范围,在胰腺动脉网络精确评估、胆管保护及肿瘤剝除实时导航中具有优势。增强现实(augmented reality, AR)技术通过将胰腺3D模型与

真实术野融合,为医生提供可“透视”的胰腺解剖视野,辅助术中解剖识别。混合现实(mixed reality, MR)技术则通过可穿戴设备将胰腺3D模型全息投影至术者视野并实现交互,更具有沉浸感,有利于增强医生术中解剖认知,提高决策精度与效率。随着AI技术的发展,利用机器学习和深度学习(deep learning, DL)算法可建立有效的术后胰瘘风险分层预测,识别高风险群体并强化监测与管理。结合可穿戴设备和计算机视觉等技术,对患者生命体征、引流液情况等进行动态监测和实时分析,更有助于早期识别指标异常,及时预警并引导干预。笔者总结了数智化诊疗技术在胰腺外科的关键应用及临床实践进展,探讨其在推动胰腺围术期全流程诊疗向精准化、智能化转型的潜力与发展方向。

1 胰周血管及胆胰管精细3D重建及可视化手术规划

胰腺位置深在,毗邻诸多腹腔重要血管,胆胰管穿行其中且胰周细小血管变异多见,为精确

胰腺手术常常涉及胆胰管的解剖与保护,对胆胰管的精细3D重建也是精确手术规划的关键之一^[14]。磁共振胆胰管成像(magnetic resonance cholangiopancreatography, MRCP)通过重T2加权成像强化静止液体信号,可以清晰展示胆胰管结构^[15-18]。但MRCP仍为2D影像,对胆胰管空间关系的显示能力不足,也无法融合肿瘤等信息进行手术演练。已有多位学者尝试利用MRCP影像进行3D重建:Goldfinger等^[19]运用Otsu阈值算法和智能路径搜索算法,结合操作员人工识别,可以半自动重建出胆胰管3D模型;Becq等^[20]利用手动分割以及基于阈值、区域生长算法对MRCP的胆道结构进行半手动分割方法,平均Dice系数分别为 0.79 ± 0.05 和 0.75 ± 0.08 。上述这些分割方法依赖于专家级医生经验手动或半自动描述感兴趣区域,其效率难以保证,重建精确度也有限。针对这一问题,

笔者团队基于多中心3D-MRCP影像数据,开发了一种AI驱动的胆道系统自动分割模型,在达到专家级分割精度的同时显著提升了效率,实现了胆胰管整体结构的高精度重建(图2)。但需要指出的是,胰周解剖结构十分复杂,尤其在胰头区域,仅依靠胆胰管3D模型仍不足以实现术中精准决策,还需结合胰腺病灶位置与周围血管信息进行综合量化分析。因此,将从CT影像中获取的血管、病灶模型与基于MRCP重建的胆胰管3D模型进行配准融合具有重要临床意义。随着AI图像处理技术的不断发展,未来可基于肝内门静脉与胆道伴行的解剖规律,探索以门静脉为引导的胆道图像生成与形变推断方法,从而实现CT与MRCP数据的高精度非刚性融合,有望显著提升术前规划的准确率与临床适用性。

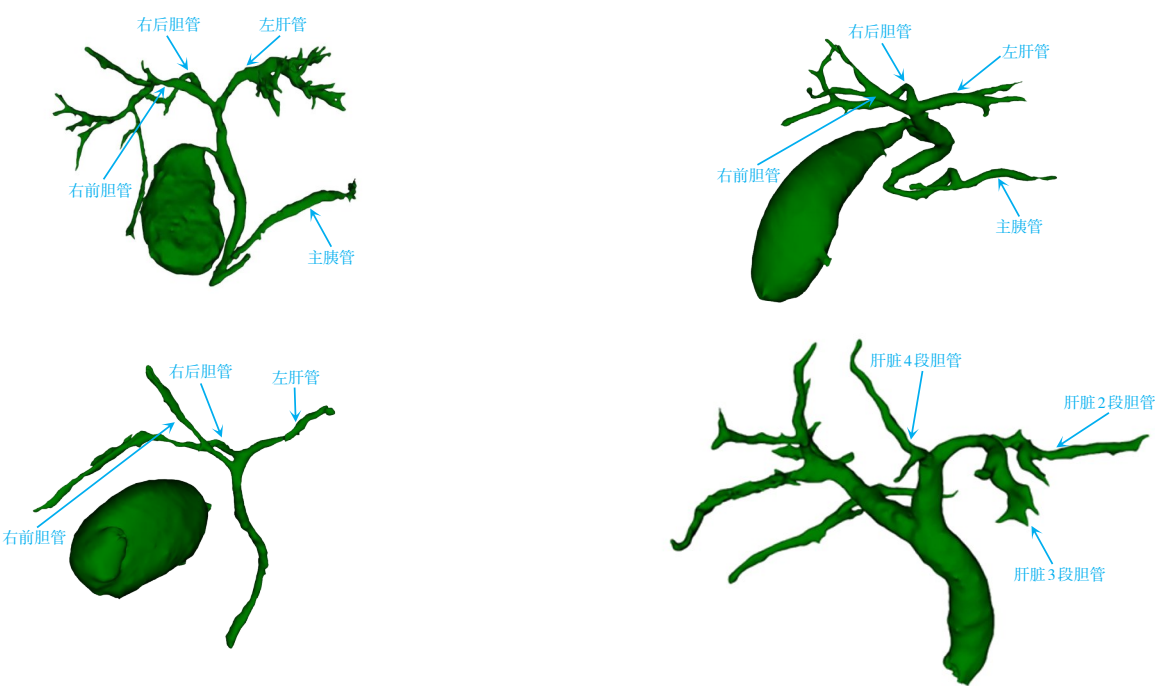


图2 基于AI重建的胆胰管三维可视化模型

Figure 2 Three-dimensional model of biliary and pancreatic ducts based on AI reconstruction

2 多模态影像融合胰腺手术导航

有了精确的可视化手术规划,术中精准识别肿瘤边界、血管及胆胰管等重要解剖结构也是提升胰腺手术安全性的关键^[21-22]。由于实际手术与术前规划存在时间和空间上的分离;微创视野下触觉反馈减弱甚至缺失;加之胆胰管和胰周细小血

管在术中往往缺乏可识别的视觉特征,若仅依赖医生经验进行解剖操作,难以满足精准手术的要求,手术安全性必然面临挑战。笔者团队与中国科学院深圳先进技术研究院合作,在ORB-SLAM2和Go-ICP框架基础上,通过视觉定位和形变配准算法,融合ICG荧光成像、术中超声、AR/MR等多模态影像导航技术^[23-25],能够在不同维度协同实现

术中关键解剖信息的可视化和空间定位,为胰腺手术的精准执行提供了强有力的决策支持^[26]。

ICG经外周静脉注射后与血清白蛋白结合,随着血液循环快速到达各级动脉,从而实现动脉血管网络的增强显示^[27]。基于这一原理,ICG可被应用于判断动脉弓完整性、评估吻合口血流灌注情况及识别富血供肿瘤边界。经肝脏摄取后通过胆道排泄的特性,使得ICG在显影胆道方面发挥着重要作用。保留十二指肠的胰头切除术(laparoscopic duodenum-preserving pancreatic head resection, LDPHR)的关键难点在于胆管的保护以及胰头动脉弓完整性确认^[28]。笔者团队开展的一项随机对照临床试验^[29]结果证实:麻醉诱导时注射极低剂量(0.05 mg) ICG的方案能够实时增强显影胆道,同时降低周围组织背景荧光的干扰。基于此,笔者团队采用“双阶段荧光”方法辅助LDPHR实

施:第一阶段在麻醉诱导时注射0.05 mg ICG用于胰头切除过程中实时显影胆总管,避免胆管损伤;第二阶段在胰头完整切除后静脉注射5 mg ICG,增强显影胰头动脉弓走行,实现了器官功能保护的安全性(图3)。肿瘤精准定位和实时边界引导是胰腺肿瘤局部切除的关键^[30-31]。笔者团队根据胰岛素瘤血供丰富特点,先经外周静脉注射ICG,辅助肿瘤定位;随后在胰岛素瘤包膜下注射ICG,为胰岛素瘤切除术提供了稳定、有效的3D立体切除界面引导^[32]。吻合口及残余胰腺组织的缺血是导致胰痿的关键病理生理机制,而血流灌注不足是其直接原因^[33-35]。ICG实时显影动脉血管网络的特性为评估组织血流灌注提供了新方法, Ghimire等^[36]使用ICG荧光观察胰腺断端的血流灌注情况,对灌注不良的胰腺断端进行切除修剪以改善灌注,有效降低了胰十二指肠切除术后胰痿发生率。

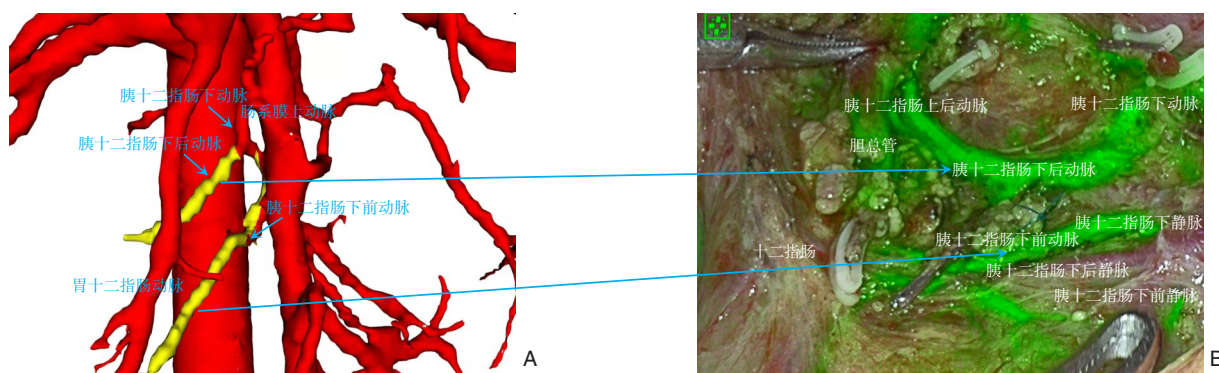


图3 1例行“双阶段荧光”方法辅助LDPHR患者资料 A: 术前精细3D动脉重建,显示IPDA弓完整形态; B: 术中场景胰头完整切除后ICG荧光清晰呈现胰十二指肠后动脉弓,与术前3D模型一致

Figure 3 Clinical data of a patient undergoing LDPHR assisted by the two-stage fluorescence imaging A: Preoperative fine 3D reconstruction of peripancreatic arteries showing the complete morphology of the IPDA arch; B: Intraoperative scene after complete resection of the pancreatic head, with ICG fluorescence clearly delineating the posterior pancreaticoduodenal arterial arch, consistent with the preoperative 3D model

尽管ICG荧光能够实时增强显示肿瘤、血管及胆管,但受限于荧光的穿透深度,无法显影“透视”深部解剖。术中对胰腺3D模型的复习也能够强化外科医生对肿瘤、血管及胆管空间解剖关系的理解,有助于对上述结构的预判和辨识^[37]。AR技术可以将术前胰腺3D模型与术中场景进行精准融合,辅助外科医生在术中进行关键解剖结构识别和肿瘤定位^[38](图4A)。Onda等^[39]使用AR手术导航技术,成功在术中识别肠系膜上动脉、空肠动脉和IPDA,显示出导航技术的可行性与安全性。笔者团队^[40]将AR手术导航技术应用于腹腔镜

胰十二指肠切除术,结果显示该技术可以更快速、更准确地定位血管、胰管和肿瘤位置,从而保障了围手术期安全性。AR手术导航技术还可用于胰腺异物去除术,快速定位鱼刺等异物位置,避免对胰腺大范围探查带来的副损伤^[41]。此外,MR技术的兴起也为术中可视化带来新突破。借助可穿戴式显示设备,能够将患者个体化3D模型以全息投影方式与术野图像融合,通过手势交互实现自由缩放、旋转与拆分组合,避免频繁切换视图,提高术中决策精度与效率。笔者团队将MR导航技术用于全腹腔镜联合腹腔干切除的胰体尾癌根治

术^[42],辅助外科医生对术中复杂解剖进行多维度理解和认知(图4B)。多模态影像融合手术导航技术通过不同模态影像间的信息互补显著提高了导航系统的性能,但不同模态的影像数据差异极大,提取和整合信息所需的计算负荷显著增加,难以

同时保证配准融合精度和效率,限制了导航技术的进一步推广应用。更精准高效的软组织变形补偿、运动补偿和感知适应等算法的开发与优化仍然是未来研究工作的重点。



图4 多模态影像融合导航技术术中场景 A: 手术过程中医生视角; B: 术者佩戴MR导航设备,通过手势将胰腺3D模型与术中场景进行交互

Figure 4 Intraoperative application of multimodal image fusion for surgical navigation A: Surgeon's view during the procedure; B: The surgeon wearing a mixed-reality navigation device interacts with the preoperative 3D pancreatic model through gesture control to achieve intraoperative fusion and spatial alignment

随着计算机视觉技术的快速发展,AI已具备对术野图像与视频进行理解和解析的能力,能够自动识别术中关键解剖结构,为提升外科医生的术中决策提供支持。笔者团队^[43]基于DeepLab v3+与nnU-Net模型,对多中心标准化腹腔镜肝切除术视频中肝内血管结构进行精确分割,对肝静脉、肝蒂等重要脉管结构的识别精度不亚于专家级医生。Shi等^[44]利用HRNet-FCN模型成功识别了腹腔镜远端胰腺切除术中的肠系膜上静脉、门静脉与脾静脉。AI解剖结构识别的实现还为多模态影像融合导航的动态配准难题提供了新的解决路径。利用AI实时识别的解剖结构与边界信息为配准提供特征点,使得原本的静态配准转变为动态配准与实时追踪校正,有望解决导航过程中因器官、组织等位移和形变导致的配准失效,进一步提高导航精度。

3 AI驱动的术后并发症监测与预警

由于胰瘘、术后出血等严重并发症的发生往往具有延迟性和隐蔽性,建立精细、智能化的术后监测管理体系对并发症早期干预、避免严重后果发生具有重要意义^[45]。而传统的术后监测主要

依赖外科医生对引流液流量多少、性状的观察与淀粉酶测定、临床体征及常规生化指标,难以做到实时监控和及时预警。可穿戴设备的应用为实现连续的生理参数监测提供了解决路径。有研究发现连续温度监测设备与常规定时测量方法相比能够更早识别患者术后的体温升高以及呼吸频率改变^[46]。未来结合电化学传感器的可穿戴设备有望对胰腺术后引流液进行实时检测,及早发现引流液淀粉酶等指标的改变和前哨出血的发生。而来自多源、多模态的大量定性与定量信息需要外科医生投入更多的精力整合分析以作出综合判断。如何从复杂、海量的临床数据中快速提取关键性信息,成为术后风险预测的核心难题。

近年来,随着AI技术的不断发展,逻辑回归、随机森林、支持向量机和朴素贝叶斯等机器学习模型能够利用医疗数据,整合并提取巨量多维数据特征构建预测模型,在胰腺术后并发症预测方面展现出巨大潜力^[47-49]。一项研究利用机器学习算法分析术前和术中变量,有效预测了胰瘘的发生风险,其预测效能优于传统单一的风险因子评估。笔者团队^[50]利用3D可视化技术对残余胰腺组织体积进行量化,并作为特征加入机器学习预测模型,有效提高了胰瘘风险模型预测精度。然而,传统

机器学习通常模型结构较为简单、依赖专家手工设计特征,难以有效整合图像等非结构化信息,预测能力有限。

为了进一步增强预测模型的泛化能力和准确率,DL技术正逐渐应用于胰腺术后风险的预测中。相较于传统统计学方法,DL凭借其独特的多层神经网络架构,能够自主从原始文本、影像等多元数据中学习并提取高维语义特征,大幅降低了对人工特征工程的依赖。这不仅赋予了DL更强大的复杂数据建模能力,也使其在整合跨模态信息方面展现出显著优势^[51-52]。例如,Mu等^[47]利用多中心513例患者的术前CT影像训练了卷积神经网络模型,构建了用于预测胰十二指肠切除术后的胰肠吻合口漏的评分系统,其预测效能已超越现有的传统胰瘘评分体系。胰腺外科手术中涉及的术中操作过程作为直接影响术后结果的核心因素,因其具有高度的动态性、连续性与复杂性,使得对其进行系统化、量化的建模异常困难。鉴于此,如何对术中操作过程进行科学、精准地评估与量化,并将其有效融入预测模型,已成为提升胰腺术后风险预测能力的关键突破口与当务之急。数智化技术的加入正逐步将胰腺术后监测从被动、延迟向主动、实时转变。如何将复杂的AI预测结果转化为简明易懂的临床决策,仍是未来研究与实践的重点。展望未来,结合可穿戴监测设备与传感器、更丰富的多组学数据(如蛋白质组学、代谢组学)、个体化的生理响应模式与DL,有望构建更为精准、实时的胰腺术后风险监测预警系统,提升术后管理水平,最终改善患者预后。

4 小结与展望

数智化诊疗技术在胰腺外科的应用正从单一技术的零散探索,逐渐形成覆盖“术前规划-术中执行-术后监测”的系统性解决方案。终端侧算力提升、高精度配准算法、多模态数据融合技术等关键难点的进一步突破,以及更多更高级别的循证医学证据的积累,将推动数智化诊疗技术的临床推广与规模化应用,进一步加速胰腺外科迈向“个体化、精准化、智能化”的进程,最终赋能数智胰腺外科新范式,造福更多患者。

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料,撰写和修改文章;陶海粟负责选题与设计;方驰华负责指导论文修改并负责文章的总体质量控制;杨剑负责选题与设计,指导论文修改并负责文章的总体质量控制。

利益冲突:所有作者均声明不存在利益冲突。

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