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四维血流磁共振成像在肝硬化门脉高压评估与并发症管理中的研究进展

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摘　要

肝硬化门脉高压(**portal hypertension, PH**)及其并发症因传统影像技术功能信息不足，难以精准评估与干预。四维血流磁共振成像(**Four-Dimensional Flow MRI, 4D Flow MRI**)可无创量化门静脉系统流速、流量及方向，成为**PH**并发症管理的革新工具。本文综述其研究进展：技术层面，整合了速度编码与呼吸导航技术，实现自由呼吸下快速扫描；临床层面，通过该技术无创获取血流动力学特征，可估算门体压力梯度，也可以对门脉血流、并发症及支架通畅性进行动态监测及评估，指导个体化治疗。然而，低流速敏感度不足及标准化流程缺失仍是瓶颈，未来需通过速度编码(**Velocity Encoding, VENC**)序列优化与人工智能建模提升效能，并建立多中心血流–代谢多组学决策体系。本综述旨在阐明**4D Flow MRI**的临床转化潜力，推动其成为肝硬化全周期管理的核心技术，以改善肝硬化门脉高压并发症预后。

关键词

四维血流磁共振成像，肝硬化门脉高压，门脉高压并发症管理，血流动力学评估

Research Advances in Four-Dimensional Flow MRI for the Evaluation and Complication Management of Portal Hypertension in Liver Cirrhosis

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Abstract

Portal hypertension (PH) and its complications in liver cirrhosis remain challenging to assess and manage precisely due to the lack of functional information from traditional imaging techniques. Four-dimensional flow magnetic resonance imaging (4D Flow MRI), which non-invasively quantifies velocity, flow volume, and directional characteristics of the portal venous system, has emerged as a revolutionary tool for PH-related complication management. This review highlights recent advancements: Technologically, 4D Flow MRI integrates velocity encoding and respiratory navigation techniques, enabling rapid scanning under free-breathing conditions. Clinically, the modality non-invasively acquires hemodynamic characteristics to estimate the portosystemic pressure gradient, dynamically monitor portal venous flow, assess complications (e.g., variceal bleeding, hepatic encephalopathy), and evaluate stent patency, thereby guiding personalized interventions. However, challenges persist, including insufficient sensitivity to low-velocity flows and the lack of standardized protocols. Future directions involve enhancing performance through multi-VENC sequence optimization and artificial intelligence modeling, as well as establishing multicenter hemodynamic-metabolic multi-omics decision-making systems. This review elucidates the clinical translational potential of 4D Flow MRI, advocating its adoption as a core technology for whole-cycle management of liver cirrhosis to improve outcomes in end-stage liver disease.

Keywords

Four-Dimensional Flow MRI, Portal Hypertension in Liver Cirrhosis, Complication Management of Portal Hypertension, Hemodynamic Evaluation

1. 引言

肝硬化门脉高压(portal hypertension, PH)的并发症严重威胁患者生存质量与预后。肝性脑病(hepatic encephalopathy, HE)作为肝硬化患者最常见的神经认知障碍，发病率超过 30%，其导致的医疗负担加重与生活质量恶化已成为临床管理难点[1]。在 PH 相关并发症中，胃食管静脉曲张破裂出血(variceal hemorrhage)致死风险最高，6 周内死亡率可达 20%，而高 Child-Pugh 评分或内镜下活动性出血患者预后尤差[2]。此外，腹水与肝肾综合征(hepatorenal syndrome, HRS)等并发症形成的恶性循环，进一步加速疾病进展并显著降低患者生存率[3]。

当前门脉血流动力学评估面临传统影像学技术的双重挑战。超声虽能检测门脉血流速度，但其结果受操作者经验及患者体型影响显著，且难以实现三维血流分布的全量化分析[4]。CT 血管造影虽可清晰显示血管解剖结构，却无法提供动态血流功能信息，并伴有电离辐射风险[5]。常规 2D 相位对比 MRI (2D cine phase-contrast MRI)虽突破单一时间点测量限制，但受制于单平面成像技术，难以同步解析多血管间复杂的血流交互作用[4]。值得注意的是，非侵入性血液标志物(如 APRI、FIB-4)虽被用于肝硬化并发症风险评估，但对门脉系统血流动力学细微变化的敏感性仍显不足[6]。在此背景下，四维血流磁共振成像(Four-Dimensional Flow MRI, 4D Flow MRI)通过三维时间分辨血流成像技术，实现了全腹部血管系统血流速度、流量及方向参数的同步精准量化，为突破传统方法局限提供了新范式[4]。本研究系统综述 4D Flow MRI 在肝硬化 PH 评估与并发症管理中的研究进展。

2. 4D Flow MRI 技术原理及现状

2.1. 原理及特点

4D Flow MRI 以三维时间分辨相位对比成像(3D cine phase-contrast MRI)为技术基础，通过三维速度编码技术实现全容积覆盖的血流动力学参数量化[7]。其核心技术创新在于：① 速度编码(Velocity Encoding, VENC)，通过预设速度敏感梯度场动态调整，精准匹配目标血管流速范围，从而避免信号混叠[8] [9]；② 生理运动补偿，采用心电门控同步采集联合呼吸导航技术(如膈肌位置追踪或自导航算法)，显著抑制呼吸运动伪影，确保腹部血流数据的时空一致性[10] [11]。相较于传统 2D 相位对比 MRI，该技术通过全腹部容积扫描实现“一站式”血流评估，支持任意平面血流参数的回顾性分析，并同步获取血流速度、流量及方向三维矢量信息[4]。值得注意的是，通过整合 k-t 加速技术(如 k-t GRAPPA 或 k-t SPARSE)，可在保持血流参数精度的前提下，将扫描时间缩短至自由呼吸条件下的 3~5 分钟，显著提升临床可行性[12]。

2.2. 应用现状

近年来，随着成像技术的迭代，4D Flow MRI 在心血管疾病评估领域(如主动脉瓣狭窄血流动力学分析、先天性心脏病复杂分流评估)已逐步形成标准化应用方案[13]。然而在腹部疾病尤其是肝硬化 PH 研究中，其临床应用仍面临双重挑战。当前研究瓶颈主要受限于低流速敏感度不足(门静脉流速常低于 20 cm/s)及呼吸运动伪影干扰，这在肝功能失代偿患者中尤为突出。此外，缺乏统一的后处理软件标准化流程(包括血管分割算法和涡流分析模块)，成为制约其临床推广的关键技术障碍[14]。

3. 血流动力学监测与 PH 评估

4D Flow MRI 凭借其三维动态血流成像优势，能够无创性获取肝硬化患者门静脉系统全定量血流动力学参数，为 PH 的精准评估提供重要影像学依据。近年来，多项前瞻性研究验证了该技术在监测门静脉主干(main portal vein, MPV)、脾静脉(splenic vein, SV)及肠系膜上静脉(superior mesenteric vein, SMV)多维血流参数中的有效性。Hu 等人[15]的队列研究显示，静脉曲张组患者 MPV、SV 血流速率较健康对照组显著增加，证实了这些参数作为无创生物标志物的临床潜力。Hyodo 等人[16]创新性提出相对驻留时间(relative residence time, RRT)这一动态参数，发现 RRT 平均值延长是门静脉血栓(portal vein thrombosis, PVT)的独立预测因子，联合血小板计数可显著提升 PVT 预测效能，曲线下面积(area under the curve, AUC)从 0.77 提升至 0.84，揭示了 4D Flow MRI 在评估血流淤滞及血栓前状态中的独特价值。Hyodo 等人[17]还发现门脉栓塞术后门脉左支血流量增加反映门静脉血流重新分布，可能驱动未来肝残余体积代偿性增生。值得关注的是，通过整合 4D Flow MRI 原始数据与计算流体动力学(computational fluid dynamics, CFD)模拟，Riedel 等人[18]成功实现了门体压力梯度(portosystemic pressure gradient, PSPG)的无创估算，其与有创导管测量的相关系数 r 达 0.77 ($P < 0.001$)，标志着该技术在门脉压力定量评估中的突破性进展。

4. 肝硬化 PH 并发症管理

4.1. 静脉曲张出血风险的预测与分层

作为肝硬化患者最致命的急性并发症，静脉曲张出血的精准风险分层对改善预后具有关键意义。4D Flow MRI 通过量化门静脉系统分流量及侧支循环三维血流特征，为无创性血流动力学分层提供了新模态。Motosugi 等人[5]的前瞻性研究表明，奇静脉血流 > 0.1 L/min (100%敏感性和 62%特异性)、门静脉流量小于 SV 和 SMV 流量之和(100%敏感性，94%特异性)可作为高危静脉曲张的强预测因子。Karam 等人[19]进一步证实，SV、门静脉各项血流动力学特征的协同分析，不仅能有效区分食管静脉曲张与胃底

静脉曲张，更可减少45%的非必要内镜检查，实现精准治疗决策。更值得关注的是，Moon等人[20]通过整合4D Flow MRI参数(如门静脉峰值流速)与内镜红色征，构建多模态预测模型，使静脉曲张出血风险的预测效能从单一胃镜指标的AUC 0.762提升至0.871，显著优化了临床干预路径。

4.2. 其他并发症的早期识别

在肝硬化并发症管理的延伸领域，4D Flow MRI展现出独特的跨学科应用价值。针对HE的血流动力学监测，Higaki等人[21]通过个案报道证实4D Flow MRI可动态评估经颈静脉肝内门体分流术(Transjugular Intrahepatic Portosystemic Shunt, TIPS)术后门静脉血流恢复与血氨改善的关联。近期研究进一步扩展了其应用场景：Hyodo等人[22]利用4D Flow MRI定量分析门体分流栓塞术后肠系膜上静脉血流方向由离肝转为向肝($P < 0.05$)，并可视化三维血流特征；Hamasaki等人[23]的队列研究显示，球囊闭塞逆行静脉闭塞术后门静脉及脾静脉血流速率显著提升($P < 0.05$)，且血流方向判读准确率达70%~100%。这些数据表明，4D Flow MRI可通过多参数动态监测为HE的机制解析及疗效评估提供客观影像学依据。在脾功能亢进管理中，Keller等人[24]创新性提出的脾血流指数，公式为脾血流指数 =(脾体积 + 动脉血流量 + 静脉血流量 × 门脉分流百分比)/体表面积，可定量识别需介入治疗的严重脾亢患者，其诊断敏感性与特异性均达100%。Brunsing等人[10]则通过4D Flow MRI量化脾静脉逆向血流比例 > 15%作为介入治疗阈值，其与血小板计数 $< 50 \times 10^3/\mu L$ 的符合率达92%。此外，Nadim等人[3]在近期共识指南中强调，肝硬化相关急性肾损伤与门脉血流动力学紊乱密切相关，但当前4D Flow MRI在此领域的应用仍待探索。

5. TIPS术后监测与并发症管理

4D Flow MRI在TIPS术后血流动力学动态监测与预后评估中展现出不可替代的技术优势。Bannas等人[25]通过纵向研究发现，该技术不仅能精准量化TIPS术后门静脉血流再分布特征，还可为评估疗效(如腹水缓解)提供直接血流动力学证据。Stankovic等人[26]的里程碑式研究首次证实，TIPS术后门静脉血流量从基线562 ± 373 mL/min激增至1831 ± 965 mL/min ($P < 0.05$)，同时观察到肝动脉血流代偿性从176 ± 132 mL/min增至354 ± 140 mL/min ($P < 0.05$)，可能解释部分临床观察中异常现象(如肝功能波动或并发症)，辅助个体化术后管理。值得关注的是，Riedel等人[18]创新性整合4D Flow MRI原始数据与计算流体动力学(CFD)建模，实现了PSPG的无创评估($r = 0.77$, $P < 0.001$)，其预测TIPS支架再狭窄的准确率达80%，显著降低了传统血管造影的介入需求。此外，Zheng等[27]分析发现自发性脾肾分流与胃肾分流的解剖直径与门静脉总容积和血流体积呈显著负相关($r = -0.385$)，为临床个体化分流干预阈值的确立提供了量化标准。

6. 小结及展望

4D Flow MRI凭借其全定量三维动态血流成像优势，在肝硬化PH并发症的预测与个体化管理中展现出革命性价值。该技术通过精准量化门静脉系统流速、流量及压力梯度，已成功建立胃食管静脉曲张出血风险分层体系，实现TIPS术后血流再分布的动态监测，并在PVT前状态识别中取得突破性进展，部分前瞻性研究证实其具备替代传统侵入性检查的循证医学潜力。尽管如此，当前研究仍有一定局限：其一，肝硬化PH并发症，如HE、HRS的血流动力学证据链尚未完善，缺乏大样本系统性验证；其二，肝硬化门脉系统的特征性低流速状态受限于现有技术的时间/空间分辨率，导致血流参数截断效应显著，直接影响风险分层模型的临床转化效能。

未来研究需沿三个维度突破：首要任务在于通过多VENC融合序列优化与深度学习驱动相位误差校正技术(如三维U-Net卷积神经网络)提升低流速信号捕获能力及运动伪影抑制效能，其中深度学习技术

已展现出自动化校正背景相位误差的潜力，可显著减少人工干预并在腹部及盆腔血管中实现与手动校正相当的精度，但其依赖大量高质量训练数据且目前主要验证于特定解剖区域，而多 VENC 融合技术可能通过扩展流速动态范围减少部分容积效应对低流速信号的干扰，但需权衡扫描时间与计算复杂度的增加，同时需满足血管直径与体素大小的比例及信噪比以保障测量精度[28] [29]；建议建立标准化参数测量协议(如门静脉主干流速测量平面定位规则、呼吸运动补偿参数设置指南)，为临床实践提供可复制的技术操作框架。同时亟需整合多模态数据(血氨代谢组学、系统性炎症标志物)构建血流－代谢－炎症多组学关联模型，明确 4D Flow MRI 关键参数与临床事件的定量关联，建立基于血流动力学表型的分层管理路径；结合计算流体力学仿真明确 PH 代偿阈值，开发门静脉压力梯度无创替代指标[17]。最终目标在于开展多中心前瞻性队列研究，分三阶段建立临床应用路径：第一阶段定义门静脉高压无创分级标准，第二阶段验证肝硬化失代偿预警阈值，第三阶段制定治疗指征及评估方案；建议开发临床决策支持系统，输出个性化监测频率建议与预防性干预方案。跨学科融合人工智能与血流动力学建模，有望实现 PH 并发症的全息风险评估，填补机制研究空白，最终改善终末期肝病患者预后。

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