

Advances in pediatric cardiovascular MR and CT technology: Toward low-sedation and low-dose

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[Abstract] Pediatric cardiovascular imaging faces unique challenges due to poor patient cooperation, fast heart rates and complex disease anatomy. This article focuses on the latest advancements in cardiovascular MR (CMR) and cardiovascular CT (CCT) technologies, elaborating on the technologic breakthroughs for achieving low-/no-sedation, low-/ultra-low-dose imaging, also the value for detection of anatomical abnormalities and quantitative functional evaluation of complex pediatric cardiovascular diseases, in order to provide evidences for early intervention and lifelong management, and looking forward to an intelligent future centered on artificial intelligence.

[Keywords] child; cardiovascular system; magnetic resonance imaging; tomography, X-ray computed; artificial intelligence

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儿科心血管 MR 与 CT 技术进展:迈向低镇静与低剂量

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[摘要] 儿科心血管影像因患儿配合差、心率快及疾病解剖复杂而面临独特挑战。本文聚焦心血管 MR(CMR)与心血管 CT(CCT)最新进展, 阐述其为实现低镇静/无镇静、低剂量/超低剂量成像而实现的技术突破及其用于检出复杂儿童心血管解剖及定量评估功能的价值, 旨在为早期干预和全周期管理提供依据, 并对以人工智能为核心的智能化未来方向进行展望。

[关键词] 儿童; 心血管系统; 磁共振成像; 体层摄影术, X线计算机; 人工智能

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儿科心血管影像对于诊断与管理先天性心脏病(先心病)、心肌病等至关重要, 但其发展面临患儿配合度差、心率快及解剖结构复杂等独特挑战。作为两大无创技术, 近年来心血管 MR (cardiovascular MR, CMR) 与心血管 CT (cardiovascular CT, CCT) 在快速成像、定量分析与辐射控制等方面取得一系列突破, 推动了儿科心血管影像进入“低镇静、低剂量、高精度”的新阶段。

1 CMR 最新进展: 从定性到定量全周期管理

凭借其无电离辐射、卓越的软组织分辨率及强大的多参数定量能力, CMR 确立了其在儿童心血管疾病诊疗中的核心地位。

1.1 快速成像技术 实现自由呼吸与“低镇静”成像 针对儿童心率快、配合度差及对镇静/麻醉的需求, CMR 技术加速发展。自由呼吸序列结合压缩感知 (compressed sensing, CS) 与并行成像 (parallel

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imaging, PI)等加速技术能大幅缩短三维全心电影(Cine)、钆对比剂延迟强化(late gadolinium enhancement, LGE)等的成像时间,使在自然睡眠或浅镇静条件下对学龄前儿童完成高质量扫描成为可能^[1-3]。在评估胎儿心脏方面,初步研究^[4-5]结果显示,结合心电/脉搏门控技术的胎儿CMR可在无电离辐射前提下详细评估胎儿复杂心脏结构。

1.2 定量组织与功能评估技术 早期发现与综合评估CMR定量技术已趋成熟,T1 mapping、T2 mapping及细胞外容积(extracellular volume, ECV)可无创早期检测心肌水肿、纤维化及铁过载等病变^[6-7]。为检出儿童心肌炎,无需采用对比剂进行增强扫描,基于T1/T2值升高即可进行定量评估,显著提升了诊断敏感性,尤其适用于不符合Lake Louise标准或存在钆禁忌证患儿^[8]。对于川崎病,CMR可无创评估冠状动脉瘤,弛豫时间mapping联合LGE能定量评估瘤体远段缺血/梗死及心肌水肿,为远期管理提供关键信息^[9]。利用ECV可非侵入性评估川崎病患儿心肌纤维化程度^[10],并适用于长期随访法洛四联症等复杂先心病,ECV升高有利于早期识别心肌弥漫性纤维化,且与患者心室功能不全、心律失常风险及不良预后显著相关^[11]。T2* mapping仍是诊断地中海贫血铁过载的金标准,可指导调整螯合剂^[12]。需要特别指出,现已初步确立了6岁以上儿童在1.5T场强下的T1/ECV参考范围^[13],而对0~3岁患儿及3.0T设备则缺少多中心标准,加之婴幼儿心率快、配合度差,推广弛豫时间mapping有待标准化。除定量静态组织外,负荷心肌灌注CMR是儿科领域的另一关键进展,攻克了快心率和药物负荷等技术壁垒,实现了无创评估心肌血流储备,现已证实其用于检出6个月以上儿童川崎病冠状动脉后遗症^[10]、先天性冠状动脉异常^[14]、心肌病^[15]及心脏移植后评估^[16]等多个场景均安全可行。

1.3 四维血流MRI(4D Flow MRI) 全方位透视血流动力学 4D Flow MRI可通过一次扫描而获取整个心脏和大血管的三维时相分辨血流信息,提供丰富的血流动力学参数,在评估复杂先心病(如Fontan循环、法洛四联症术后肺动脉反流/狭窄)^[17]、定量与可视化瓣膜病反流^[18]、血管异常(如主动脉缩窄、侧支血流)^[19]等方面表现突出。

1.4 评估心肌应变 深化功能评估CMR特征追踪(CMR-feature tracking, CMR-FT)可于标准Cine图像中自动追踪心肌运动而实现应变分析,在射血分数(ejection fraction, EF)下降前检出心肌亚临床损伤,

对于早期诊断肥厚型心肌病^[20]、迪谢内(Duchenne)肌营养不良^[21-22]及川崎病^[23]等具有重要临床意义。

1.5 人工智能(artificial intelligence, AI)驱动提升效率与洞察力 AI、特别是深度学习(deep learning, DL)正在加速儿科CMR从研究向临床渗透,实现效率和分析能力的双重飞跃:①加速采集与重建,DL重建用于儿科CMR可缩短约80%扫描时间,显著提高检查效率^[24],结合生成式AI等前沿技术,未来将可于“单次心跳”完成自由呼吸电影成像^[25],为彻底解决婴幼儿因呼吸、心律不齐导致的成像困难提供了可能;②自动化分析,实现自动分割心腔/心肌,并能秒级输出EF、心肌质量等关键参数^[26];③赋能亚临床功能评估,赋能CMR-FT,实现全面自动化心肌应变分析,突破技术壁垒而使亚临床心功能评估触手可及^[27];④建立临床预测模型,如基于多模态CMR数据的AI模型用于预测心肌病、Fontan循环衰竭预后等已进入临床验证阶段^[28]。

2 CCT革新:迈向超低剂量与零镇静

目前CCT仍是精细评估儿童心脏和大血管解剖结构的主要手段,正在围绕“辐射剂量最小化”和“运动伪影控制”向更安全、普适的精准评估平台演进。

2.1 持续巩固解剖学评估与功能融合 凭借其极高的空间分辨率和快速采集能力,CCT对于显示儿童心血管解剖结构具有不可替代的优势。①术前一体化评估复杂先心病解剖与功能:对于肺动脉闭锁伴体肺侧支循环、血管环等复杂畸形,CCT能提供精准的解剖“外科路线图”,清晰显示血管形态、空间关系及伴发异常;同时,双能CT(dual-energy CT, DECT)肺灌注成像功能可在一次检查中同步获得肺实质血流灌注信息;这种一站式“形态+功能”评估对于制定手术策略、评估肺血管发育及体肺侧支循环状况至关重要^[29];②评估冠状动脉异常:通过生成低能量虚拟单能图像(40~70 keV),DECT利用碘的K边缘效应显著提升血管(尤其是细小冠状动脉)对比度与可视性^[30],可在确保图像质量的同时有效降低辐射剂量^[31],已成为无创评估冠状动脉起源与走行异常的关键工具;③术后长期随访与评估:CCT是法洛四联症、Fontan术后等患者长期管理的核心影像学手段,可精准评估管道通畅度、肺动脉发育及吻合口状况^[32]。

2.2 超低剂量与“零镇静”成像成为现实 新技术的突破正在彻底改变儿科CCT应用模式。作为革命性技术,光子计数CT(photon-counting detector CT, PCD-CT)在采用前瞻性心电触发、低管电压(如80 kV)及超短采集时间窗条件下可将辐射剂量降至

亚 mSv 级,同时实现超高空间分辨率,为婴幼儿安全成像树立了新标准^[33]。对于实现“零镇静”成像,超高螺距扫描与宽体探测器技术同为核心手段。利用大螺距双源 CT 技术(螺距可达 3.2~3.4 mm)能实现亚秒级全身数据采集,前瞻性研究^[34]证实了其用于“零镇静”对清醒婴幼儿进行胸腹部检查的可行性,为在自由呼吸状态下实现快速、无伪影心脏及大血管成像奠定了基础。凭借 16 cm 的探测器宽度,宽探测器 CT 可在 1~2 次旋转内覆盖全心或全胸部,革新了儿科成像流程,使检查可在无需镇静和自由呼吸状态下快速完成,显著提升了安全性、舒适性与成像质量^[35]。

3 小结与展望

CMR 与 CCT 的技术进步,使儿科心血管影像能在最低限度镇静与辐射风险下对于宏观解剖和微观组织、静止形态和动态功能进行精准的定量评估。未来,以 AI 为核心的技术融合与数据分析将进一步提升检查效率、标准化程度与诊断洞察力,推动儿科心血管病诊疗向智能化、个体化全周期管理迈进。

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