❖综述

Application progresses of PET/CT in inflammatory heart diseases

WANG Yubo[1,2], HU Hao[1,2], DING Zhiyong[3], HE Zhengying[4], FU Yang[2], LI Jiageng[2], YANG Bin[2*]
(1. Graduate School, Kunming Medical University, Kunming 650500, China; 2. Medical Imaging Center, Kunming First People's Hospital, Kunming 650051, China; 3. Department of Radiology, Qujing Maternal and Child Health Hospital, Qujing 655000, China; 4. Department of Radiology, Diqing Tibetan Autonomous Prefecture People's Hospital, Diqing 674400, China)

[**Abstract**] Inflammatory heart diseases have critical impact in the occurrence and development of cardiovascular diseases such as atherosclerosis, myocardial infarction and heart failure, representing a leading cause of global mortality and disease burden. PET/CT enables localization and quantification of inflammation at the molecular level, providing essential references for early diagnosis and risk assessment of inflammatory heart diseases. The application progresses of PET/CT in inflammatory heart diseases, such as myocarditis, infective endocarditis, pericarditis and cardiac sarcoidosis were reviewed in this article.

[**Keywords**] myocarditis; endocarditis, bacterial; pericarditis; sarcoidosis; positron-emission tomography and computed tomography

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PET/CT 用于心脏炎症性疾病进展

王宇博[1,2],胡 皓[1,2],丁志勇[3],和正英[4],傅 洋[2],李佳庚[2],杨 斌[2*]
(1.昆明医科大学研究生院,云南 昆明 650500;2.昆明市第一人民医院医学影像中心,云南 昆明 650051;3.曲靖市妇幼保健院影像科,云南 曲靖 655000;4.迪庆藏族自治州人民医院影像科,云南 迪庆 674400)

[**摘　要**] 心脏炎症性疾病对于动脉粥样硬化、心肌梗死、心力衰竭等心血管疾病的发生、发展过程具有关键影响,是导致全球范围内死亡和疾病负担的主要原因之一。PET/CT 可实现在分子水平上定位和定量检测炎症,为早期诊断心脏炎症性疾病、评估疾病风险提供重要参考。本文围绕 PET/CT 在心肌炎、感染性心内膜炎、心包炎和心脏结节病等心脏炎症性疾病中的应用进展进行综述。

[**关键词**] 心肌炎;心内膜炎,细菌性;心包炎;结节病;正电子发射断层显像和计算机体层摄影术

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心脏炎症性疾病对于动脉粥样硬化、心肌梗死、心力衰竭等心血管疾病的发生、发展过程具有关键影响[1-2]。传统心血管成像技术(如超声、CT、MRI)可评估心脏结构和功能,但难以获取炎症相关信息,亦无法探究其机制[3-4]。PET/CT 为高分辨率分子成像技术,能有效识别和追踪炎症相关分子标志物,为早期诊断心脏炎症性疾病、评估风险和监测治疗提供依据[5]。本文围绕 PET/CT 在心肌炎、感染性心内膜炎(infective endocarditis, IE)、心包炎和心脏结节病(cardiac sarcoidosis, CS)等心脏炎症性疾病中的应用进展进行综述。

1 常用示踪剂

^{18}F-FDG 为临床应用最广泛的示踪剂,通过炎症组织高糖酵解活性而实现炎症代谢显像,可用于检测肉芽肿病、血管炎和骨髓炎等[6-8]。^{68}Ga-DOTATATE、DOTATOC 及 DOTANOC 均属生长抑素类似物示踪

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[**第一作者**] 王宇博(1997—),男,安徽宿州人,在读硕士。研究方向:肿瘤影像人工智能和诊断。E-mail: 735649680@qq.com
[**通信作者**] 杨斌,昆明市第一人民医院医学影像中心,650051。E-mail: yangbinapple@163.com
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剂，能靶向结合表达生长抑素受体（somatostatin receptor，SSTR）的炎症细胞，对部分慢性炎症性疾病具有高度特异性；而心肌对其低摄取，检查前无需复杂准备，具有潜在临床应用价值[9]。成纤维细胞活化蛋白（fibroblast activating protein，FAP）为Ⅱ型跨膜丝氨酸蛋白酶，具有二肽基肽酶和内肽酶活性，仅表达于被激活的成纤维细胞。^{18}F-FAP 抑制剂（FAP inhibitor，FAPI）可靶向结合炎症、纤维化心肌中的FAP，可用于评估心肌修复与纤维化进展、无创可视化心血管炎症及心室重构等过程[10]。

2　用于心脏炎症性疾病

2.1　心肌炎　心肌炎指心肌局限性/弥漫性炎性非缺血性疾病，其主要病理机制包括病毒感染和自身免疫反应等。利用^{18}F-FDG PET/CT 可早期识别心肌炎症。EDERHY 等[11]发现，PET/CT 能明确显示心肌炎急性期心脏特定区域高摄取^{18}F-FDG，且该表现与临床症状和心力衰竭程度密切相关，这表明^{18}F-FDG PET/CT 可较敏感地检出急性心肌炎。需要注意的是，^{18}F-FDG 可被任何葡萄糖代谢活跃的细胞所摄取，故存在假阳性、可能导致不必要的额外检测，并影响诊断心肌炎的灵敏度和特异度[12]。^{68}Ga-DOTATOC PET/CT 和 FAPI PET/CT 均可用于评估免疫治疗相关性心肌炎，前者结合免疫相关技术可达到较高灵敏度[13]，后者对于检出 MRI 阴性的早期心肌炎症更具潜力[14]。

利用新型 CD45-PET 成像技术能进一步精准监测组织特异性炎症动态变化、降低心肌活检风险[15]。YE 等[16]基于干扰素基因刺激因子开发了靶向放射性示踪剂^{18}F-FBTA，该示踪剂能在小鼠心脏炎症细胞中呈高度过表达，提示能以之观察心肌炎微环境变化。现阶段，新型示踪剂在心肌炎的应用研究有限，且多处于临床前阶段，有待未来深入探索。

2.2　IE　IE 临床表现缺乏特异性，16.8%～41.6%病例血培养呈阴性[17]。2023 年欧洲心脏病学会（European Society of Cardiology，ESC）发布的《心内膜炎管理指南》首次推荐将 PET/CT 作为辅助诊断人工瓣膜心内膜炎（prosthetic valve endocarditis，PVE）的依据（ⅠB 级证据）[18]。VURAL 等[19]研究结果显示，基于 PET/CT 视觉图像分析和半定量评估[最大标准摄取值（maximum standard uptake value，SUV_{max}）>3.5]诊断 IE 的特异度及阳性预测值分别高达 95.24%和 96.77%。另一项纳入 108 例疑似 IE 患者的研究[20]结合 4 分法与可疑瓣膜病变及肝、脾、骨髓的 SUV_{max} 和平均标准摄取值（mean standard uptake value，SUV_{mean}）诊断 IE，其灵敏度、特异度、准确率、阳性预测值及阴性预测值分别为 93%、81%、87%、84%及 91%，表明感染所致脾或骨髓高代谢活动可用于辅助诊断 IE。PET/CT 诊断自体瓣膜心内膜炎（native valve endocarditis，NVE）、PVE 及心脏植入式电子设备所致 IE 具有较高特异度，但其对于NVE 的灵敏度不及 PVE 及心脏植入式电子设备所致 IE[21]，具体机制尚未明确。在预测预后方面，PET/CT 能相对准确地预测 PVE 患者治疗后发生的主要不良事件，包括死亡、IE 复发、急性心功能不全及栓塞事件等[22]，有利于优化患者管理和指导治疗决策。RÉGIS 等[23]报道，IE 患者药物治疗结束后 C 反应蛋白和白细胞计数仍较高，此时利用^{18}FDG-PET/CT 能有效预测复发风险。

^{18}F-FDG 无法区分感染灶、无菌炎症及肿瘤。为此 SCHULTE 等[24]开发了 2-[^{18}F]F-对氨基苯甲酸（para-aminobenzoic acid，PABA）探针进行 PET 成像，发现其能准确测出 IE 模型小鼠的较大细菌赘生物，提示 PABA PET 有望为诊断 IE 提供决定性线索；但其临床转化仍面临较大困难。除开发新型示踪剂外，有学者[25]将机器学习引入 PET/CT，同时整合ESC 标准而构建 IE 诊断模型，以弥补 PET/CT 缺乏标准化视觉和定量解释标准等问题。

2.3　心包炎　心包炎是发生于心包脏层和壁层的炎症性疾病，可单独存在或由全身性疾病累及心包所致。急性结核性心包炎、细菌性心包炎和亚急性缩窄性心包炎 PET/CT 多表现为心包及纵隔淋巴结 FDG 摄取显著增高，且 SUV_{max} 高于特发性心包炎，提示 PET/CT 对于鉴别感染性心包炎与特发性心包炎具有一定价值[26-29]。PET/CT 可提供心脏及其他器官的代谢信息，有助于判断心包炎病因及评估并发症。既往病例报道[30]提示，对于胸腺癌所致缩窄性心包炎，PET/CT 可在诊断肿瘤引发心包炎的同时检出转移癌。JIANG 等[31]认为联合应用^{18}F-FDG 和^{68}Ga-FAPI PET/CT 有助于对缩窄性心包炎进行分期。此外，PET/CT 所示病灶 SUV_{max}/血池 SUV_{max} 比值有助于鉴别心包炎与心包恶性肿瘤[32]。

2025 年 ESC 与美国心脏病学会（American College of Cardiology，ACC）均发布了相关指南以推动心包炎诊疗模式更新[33-34]。ESC 指南构建了以MRI 为核心、CT 为辅助、PET/CT 为补充的多模态分层评估体系，更为侧重三维评估解剖-功能-代谢；ACC

指南更注重早期干预,强调纵向追踪代谢-炎症-治疗响应,推荐以 PET/CT 作为评估难治性心包炎的一线工具,通过动态监测炎症活动指导治疗。二者侧重不同,但对包括 PET/CT 在内的多模态影像的协同价值均给予认可,为临床实践构建了循证与个体化相结合的诊疗框架。

2.4　CS　CS 是由心肌肉芽肿性炎症引起的浸润性心肌病,临床可表现为心脏传导异常、室性心律失常及心室功能障碍等。心脏 MRI(cardiac MRI, CMRI)诊断 CS 的敏感度较高(92%～95%),但特异度不及 PET/CT。美国心脏协会(American Heart Association, AHA)指出,PET/CT 对于识别代谢活跃的 CS 炎性病变具有不可替代的价值[35-36]。另有研究[37]发现,对于 CMRI 提示的可疑 CS,补充进行 PET/CT 扫描具有重要价值;但目前对此尚未达成广泛共识。

新近研究聚焦 PET/CT 与 CMRI 诊断 CS 的互补价值[38]及 PET 新参数和成像方法在 CS 中的应用。为降低心肌本底葡萄糖摄取对 PET/CT 诊断 CS 准确性的影响,基于酮症与心肌葡萄糖摄取模式间的反比关系,VIDULA 等[39]提出较长的生酮饮食和禁食持续时间可进一步提高 CS 诊断准确性。在预测预后方面,有学者[40-41]发现连续 PET 显像所示右心室局部摄取升高可用于预测 CS 主要不良心脏事件;联合静息心肌灌注显像更能对伴高度房室传导阻滞的 CS 进行分期并预测预后。

3　小结与展望

PET/CT 可于分子水平检测炎症,在早期诊断心血管炎症性疾病、监测治疗效果和预测预后中展现出巨大应用潜力。目前 PET/CT 在此领域内仍面临挑战:①PET/CT 检测炎症的分辨率和敏感度尚未达到理想水平,尤其对于心脏微小炎症病灶(如局灶性心肌炎或微血管炎)可能存在假阴性或假阳性;②PET/CT 用于心血管疾病尚缺乏统一操作和解读标准,各医学中心之间,成像参数、示踪剂方案及图像分析方法均存在差异,可能影响结果的可比性和可靠性;③PET/CT 设备昂贵、辐射剂量高。随着新型 PET 示踪剂的研发、成像技术的进步及人工智能的应用,PET/CT 在心脏炎症性疾病中的应用前景将更加广阔;新型分子标记物的出现有望进一步提高检测特异度和敏感度。

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