

左心声学造影的最新研究进展

杜利平^{1*}, 刘 涛¹, 廖志雄^{2#}

¹吉首大学医学院, 湖南 吉首

²张家界市人民医院心血管内科, 湖南 张家界

收稿日期: 2025年11月16日; 录用日期: 2025年12月9日; 发布日期: 2025年12月17日

摘 要

左心声学造影是基于声学空化原理的超声成像技术, 通过静脉注射微泡造影剂增强心脏内结构显像。本文阐述该技术在肥厚型心肌病心尖部动脉瘤检测、右向左分流定量评估、冠状动脉微血管功能障碍诊断和结构性心脏病介入治疗引导中的核心价值与应用进展。与此同时还分析了当前技术存在的显像稳定性不足与操作标准化缺失等问题, 并展望了智能造影剂开发、多模态影像融合及人工智能辅助分析等发展方向, 为提升心血管疾病的精准诊疗水平提供参考。

关键词

左心声学造影, 超声造影剂, 肥厚型心肌病

Recent Advances in Left Heart Contrast Echocardiography

Liping Du^{1*}, Tao Liu¹, Zhixiong Liao^{2#}

¹School of Medicine, Jishou University, Jishou Hunan

²Department of Cardiovascular Medicine, Zhangjiajie People's Hospital, Zhangjiajie Hunan

Received: November 16, 2025; accepted: December 9, 2025; published: December 17, 2025

Abstract

Left heart contrast echocardiography is an ultrasonic imaging technology grounded in the principle of acoustic cavitation. It enhances the visualization of intracardiac structures by intravenously injecting microbubble contrast agents. This paper expounds upon the core value and application

*第一作者。

#通讯作者。

文章引用: 杜利平, 刘涛, 廖志雄. 左心声学造影的最新研究进展[J]. 临床医学进展, 2025, 15(12): 2213-2220.
DOI: 10.12677/acm.2025.15123646

advancements of this technology in several aspects. These include the detection of apical aneurysms in hypertrophic cardiomyopathy, the quantitative evaluation of right-to-left shunts, the diagnosis of coronary microvascular dysfunction, and the guidance of interventional treatments for structural heart diseases. Meanwhile, the paper also analyzes the existing problems of the current technology, such as insufficient imaging stability and the lack of operational standardization. Moreover, it looks ahead to the development directions, including the development of intelligent contrast agents, the integration of multi-modal imaging, and the application of artificial-intelligence-assisted analysis. This aims to provide references for improving the precision diagnosis and treatment of cardiovascular diseases.

Keywords

Left Heart Contrast Echocardiography, Ultrasound Contrast Agent, Hypertrophic Cardiomyopathy

Copyright © 2025 by author(s) and Hans Publishers Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

1. 引言

左心声学造影(left heart contrast echocardiography)是无创心血管影像的重要组成部分,其通过增强心腔内膜边界显示与评估心肌灌注,提升了心脏结构与功能评估的精准度。解决了传统非对比超声存在心尖部显像盲区与诊断敏感性不足等问题,扩充了其临床应用。近些年来,随着造影剂特性优化与三维、人工智能等技术的融合,左心声学造影在复杂心脏病诊断与介入引导中也展现出优势。本文通过综述其技术原理、核心临床价值及介入应用进展,探讨当前技术瓶颈与未来演进路径,旨在推动该技术在精准心血管医学中的应用。

2. 临床应用与核心价值

左心声学造影技术基于声学空化原理,通过静脉注射含气体微泡的超声造影剂(如疏水性气体微泡),在超声波作用下产生强烈振荡和反射信号,显著增强心室内膜边界可视化,提升心室腔尺寸和功能量化准确性,克服了传统非对比超声的局限性[1]-[3]。目前研究进展包括:在肥厚性心肌病(HCM)患者中,左心声学造影检测左心室顶动脉瘤的灵敏度达 97%~98%,优于非对比超声(灵敏度 67%)和心血管磁共振(灵敏度 97%),被推荐为常规评估工具以优化风险分层[4]。心肌造影技术进一步扩展至心肌血流储备(MBFR)评估,能无创检测微循环功能障碍和心肌灌注异常(如心肌血流量化),为缺血性心脏病诊断提供新途径[5][6]。此外,结合三维和斑点追踪技术,提升了左心房和心室形态学的评估精度[7][8]。

左心声学造影技术通过在静脉注射超声对比剂,增强左心结构的可视化,显著提升了对特定心脏疾病的诊断准确性,成为现代心血管影像学的重要组成部分。以下系统阐述最新研究进展在特定疾病诊断中的核心价值,重点聚焦于提高灵敏度、优化定量分析及辅助风险分层等方面。

2.1. 在肥厚型心肌病(HCM)心尖部动脉瘤诊断中的应用核心价值

左心声学造影在检测 HCM 患者左心室心尖部动脉瘤时展现出高灵敏度,解决了传统非对比心脏超声(敏感性较低)的局限性。研究表明,左心室心尖部动脉瘤是 HCM 不良预后的重要标志物,但其真实患病率常被低估[4]。对比研究中,左心声学造影相比心血管磁共振(CMR)具有更高诊断效能:敏感性达 97% ($P = 0.0198$),远高于非对比心脏超声的 64% ($P = 0.0001$);经专家二次复核后,灵敏度进一步升至 98%,

且与 CMR 无显著差异($P = 1.00$) [4]。核心价值在于常规用于 HCM 患者的风险分层和治疗评估,例如用于识别高危患者群体,为临床决策提供可靠依据[4]。

2.2. 在右到左分流(RLS)疾病(如卵圆孔未闭)诊断中的核心价值

左心声学造影在检测 RLS 时,通过增强微泡对比剂在左心房的可视化,实现无创诊断。在卵圆孔未闭(PFO)的间接诊断中,经胸心脏超声配合造影(TTE-C)能有效捕捉对比剂通过缺损进入左房的现象,优于传统非对比方法[9]。最新进展包括开发定量技术,例如利用回声密度变化(echo density, ED)量化分流:一项分析 437 例患者的研究中,ED 测量可量化肺动静脉畸形(PAVMs)引起的 RLS,提升诊断准确性[10]。核心价值在于其作为无创筛查工具的经济性与高效性,尤其适用于替代有创的经食道超声(TEE),减少患者不适[10][11]。

2.3. 在冠状动脉微血管功能障碍(CMD)和心衰诊断中的核心价值

最新研究将左心声学造影整合到复杂疾病的诊断流程中,突出其定量和功能性价值。1) 冠状动脉微血管功能障碍(CMD)诊断:心肌对比心脏超声(MCE)结合计算机辅助技术,可量化心肌血流量和储备。例如,在一项针对胸痛患者的前瞻性研究中,MCE 通过测量冠状动脉流速储备(CFVR)识别微血管病变,辅助无创诊断 CMD,减少冠状动脉造影的需求[12][13]。2) 心力衰竭诊断:特别是在保留射血分数型心衰(HFpEF)中,左心声学造影通过测量左心房顺应性提供诊断支持。研究表明,在 225 例慢性呼吸困难患者中,运动状态下左心房顺应性降低与 HFpEF 强相关,提高了诊断特异性(尽管未直接提及造影作用,但心脏超声是核心工具)[14][15]。核心价值在于补充传统方法(如心电图)的不足,实现早期功能性评估,例如在心衰风险患者中检测左心室应变和舒张功能异常[16][17]。

2.4. 在心血管并发症监测中的核心价值

在癌症治疗相关心血管毒性的诊断中,左心声学造影发挥着关键作用。例如,经导管瓣膜修复术(TEER)后,自发回声对比(SEC)在左房的出现可预测血栓风险[18][19]。最新进展结合人工智能(AI)模型,提高诊断自动化:卷积神经网络(CNN)等深度学习技术能自动分析心脏超声图像,辅助识别左心室肥大(LVH)或瓣膜病变,减少人工判读误差(准确率达 83%~96%) [20]-[22]。核心价值在于为高危患者提供连续监测和早期预警,如用于量化左心室容积变化和心肌瘢痕对比度[3][23]。

总之左心声学造影的核心价值在于:1) 提升诊断灵敏度,如 HCM 心尖部动脉瘤检测敏感性 97%~98%;2) 推动无创定量分析,通过 ED 量化 RLS;3) 支持风险分层,在 HCM 和 CMD 中指导治疗;4) 整合 AI 技术,实现自动化诊断。最新进展强调多模态融合(如结合 ECG),但未来需优化对比剂特性以进一步提高组织特异性信号[24][25]。整体上,该技术为特定心脏疾病提供了经济、可靠的影像学解决方案,强化了个体化医疗能力。

3. 左心声学造影在多模态影像中的竞争优势

根据相关研究,左心声学造影在临床实践中与其他影像学技术的优劣势对比如下:

3.1. 对比心脏磁共振(CMR)

左心声学造影在检测左心室心尖室壁瘤(LV apical aneurysm)方面敏感性显著优于 CMR (97%~98% vs. 85%) [4],尤其适用于肥厚型心肌病(HCM)患者的常规风险分层[4]。其操作便捷、实时动态成像的优势弥补了 CMR 设备昂贵、检查时间长且禁忌症多的局限。但对于心肌组织特征分析(如纤维化定量),CMR 仍是金标准[26][27],左心声学造影需作为其补充手段提供血流动力学信息。

3.2. 对比经食道超声(TEE)与心导管

在右向左分流(RLS)诊断中, 经胸 LHCE (TTE-C)准确性接近 TEE (敏感性 96%、特异性 92%) [11], 且避免 TEE 的侵入性风险。左心耳评估方面, 新型三维左心声学造影技术的精度媲美 CT 参考标准[28], 可作为心导管检查前的无创筛查工具。但在瓣膜病细节评估或需同步介入操作时, TEE/心导管仍不可替代[6] [28]。

3.3. 对比冠脉 CTA (CCTA)与 PET

左心声学造影通过心肌灌注显像可评估冠脉微循环障碍, 其成本效益和便携性优于 CCTA/PET [29] [30], 尤其适用于无法接受辐射或肾功能不全患者。但宏观冠脉解剖显示受限, 需联合 CCTA 进行病因学诊断[31]; 而 PET 心肌代谢显像的分子层面功能评估仍是 LHCE 的技术盲区[27] [32]。

临床定位:

左心声学造影是一线筛查工具(如 HCM 室壁瘤、心肌缺血), 首选替代方案(TEE 禁用于 RLS 初筛), 以及核心补充手段(与 CMR/PET 多模态联合)。其核心价值在于无创、实时、可重复的血流动力学评估, 但在组织分辨率及分子成像层面存在技术局限[4] [11] [28]。

4. 左心声学造影在介入治疗中的应用

左心声学造影作为心脏介入治疗的关键成像技术, 近年来研究进展显著, 其应用主要集中在实时引导手术、评估血流动力学及优化治疗决策, 以提升微创介入的精度和安全性。以下详细阐述其在介入治疗中的主要应用进展。

4.1. 在结构心脏介入手术中的实时引导

经食管超声心动图(transesophageal echocardiography, TEE)结合对比增强技术, 已成为经导管二尖瓣修复(transcatheter edge-to-edge repair, TEER)和左心房附属物闭合(left atrial appendage closure, LAAO)的标配工具。研究显示, TEE 能提供高分辨率图像, 精准引导器械放置并监测器械位置, 显著减少手术并发症。例如, 在 TEER 术中, 超声可检测自发性回声对比(spontaneous echocardiographic contrast, SEC)的出现, 尽管其临床意义尚不明确, 但能提示潜在的血栓风险[18]。此外, 三维(3D)重建技术的融入, 实现了实时融合超声与荧光透视图像, 强化了空间定位能力, 便于术前规划和术中调整, 尤其对于复杂解剖如左心房附属物的形态评估[28] [33]。

4.2. 评估分流病变和介入前诊断

经胸对比超声(transthoracic contrast echocardiography, TTCE)在介入前诊断中发挥核心作用, 尤其针对右侧向左侧分流(right-to-left shunt, RLS)的筛查。例如, 在卵圆孔未闭(patent foramen ovale, PFO)的诊断中, 对比剂通过可直观显示分流, 辅助决策介入必要性, 其敏感性高于常规无对比超声[9] [11]。新方法如回声密度分析正开发用于量化分流程度, 优化了治疗筛选和预后预测[10]。

4.3. 微创介入中的功能监测与并发症评估

在微创手术中, 如经胸主动脉微创切除(transapical beating heart septal myectomy, TA-BSM), 实时超声引导允许术中多次优化切除, 以改善血流动力学和心室形态, 确保手术成功率[34]。同时, 对比增强超声用于 sonothrombolysis (声波溶栓), 能改善急性心肌梗死后的心肌灌注和心室舒张功能, 减少左心房重构, 拓展了介入后功能评估的新领域[35]。

总之,左心声学造影在介入治疗中的应用,借助技术进展如3D成像和实时融合,强化了个体化介入指导,提升了手术安全性和疗效。未来需进一步探索人工智能整合以预测治疗结局[33][36]。

5. 技术局限性与未来方向

(一) 技术局限性: 1) 解剖结构显像不足: 非增强超声对左心室心尖部细微结构(如室壁瘤)的检出存在固有缺陷,敏感性显著低于增强超声(67% vs 98%)和心脏磁共振(85% vs 97%) [4]。心尖部伪影干扰及声窗限制是主要因素[4]。2) 标准化操作缺失: 术中对比剂注射时机与机械指数调控尚缺统一规范,影响心肌灌注定量分析的可重复性[37]。尤其在急救场景下,造影操作可能延误胸外按压恢复[38]。3) 微泡特性限制: 商用微泡造影剂因粒径大($>1\ \mu\text{m}$)、半衰期短、稳定性差,难以实现持续心腔显像及组织穿透,且缺乏靶向治疗功能[2][39][40]。(二) 未来方向: 1) 多模态技术整合: 开发三维超声斑点追踪技术与增强超声的融合方案,提升左心房应变分析和右心功能评估精度[7][41][42]。探索超声与心脏磁共振的互补诊断路径,尤其针对心肌微循环障碍量化[6][7]。2) 智能造影剂开发: 研发纳米级载药微泡,通过表面修饰实现靶向递送(如抗纤维化药物),同步解决显像与治疗需求[2][39][40]。优化微泡壳层材料以延长半衰期并增强组织穿透性[2][39]。3) 术中实时监测系统: 建立经食管超声引导下的左心耳封堵术标准化造影流程,动态监测血栓形成及封堵器位置,替代部分CT检查以减少辐射暴露[38][42][43]。4) 人工智能辅助分析: 需构建深度学习模型自动识别自发超声对比(SEC)信号及微泡灌注缺损区域,减少人工判读误差[18][44][45]。结论: 当前技术瓶颈集中于显像稳定性及定量标准化,未来需通过跨尺度造影剂革新、多模态成像融合及智能算法嵌入,突破解剖-功能一体化评估的壁垒[7][39][46][47]。

6. 结论

左心声学造影在检测肥厚型心肌病(HCM)患者左心室心尖部瘤(LV apical aneurysm)方面表现出高敏感性(98%),优于非对比超声(灵敏度 67%),并与心血管磁共振(97%)相当,应作为常规评估和风险分层的工具[4]。此外,新方法量化对比注射后回声密度变化可有效评估右向左分流(RLS),如肺动静脉畸形检测[10]。在介入治疗领域,三维经食管超声和实时图像融合技术提升了精准度,用于心脏结构(如左心房)形态评估[33]。

参考文献

- [1] El Kadi, S., Porter, T.R., Verouden, N.J.W., van Rossum, A.C. and Kamp, O. (2022) Contrast Ultrasound, Sonothrombolysis and Sonoperfusion in Cardiovascular Disease: Shifting to Theragnostic Clinical Trials. *JACC: Cardiovascular Imaging*, **15**, 345-360. <https://doi.org/10.1016/j.jcmg.2021.07.028>
- [2] Wegierak, D., Nittayacharn, P., Cooley, M.B., Berg, F.M., Kosmides, T., Durig, D., et al. (2024) Nanobubble Contrast Enhanced Ultrasound Imaging: A Review. *WIREs Nanomedicine and Nanobiotechnology*, **16**, e2007. <https://doi.org/10.1002/wnan.2007>
- [3] Papachristidis, A., Queirós, S., Theodoropoulos, K.C., D'hooge, J., Rafter, P., Masoero, G., et al. (2021) The Impact of Vendor-Specific Ultrasound Beam-Forming and Processing Techniques on the Visualization of *in Vitro* Experimental "Scar": Implications for Myocardial Scar Imaging Using Two-Dimensional and Three-Dimensional Echocardiography. *Journal of the American Society of Echocardiography*, **34**, 1095-1105.e6. <https://doi.org/10.1016/j.echo.2021.05.016>
- [4] Lee, D.Z.J., Chan, R.H., Montazeri, M., Hoss, S., Adler, A., Nguyen, E.T., et al. (2021) Left Ventricular Apical Aneurysms in Hypertrophic Cardiomyopathy: Equivalent Detection by Magnetic Resonance Imaging and Contrast Echocardiography. *Journal of the American Society of Echocardiography*, **34**, 1262-1272. <https://doi.org/10.1016/j.echo.2021.07.015>
- [5] Al-Mohaisen, M.A. (2023) Echocardiographic Assessment of Primary Microvascular Angina and Primary Coronary Microvascular Dysfunction. *Trends in Cardiovascular Medicine*, **33**, 369-383. <https://doi.org/10.1016/j.tcm.2022.02.007>
- [6] Fine, N.M., Greenway, S.C., Mulvagh, S.L., Huang, R., Maxon, S.A., Hepinstall, M.J., et al. (2021) Feasibility of Real-Time Myocardial Contrast Echocardiography to Detect Cardiac Allograft Vasculopathy in Pediatric Heart Transplant

- Recipients. *Journal of the American Society of Echocardiography*, **34**, 503-510. <https://doi.org/10.1016/j.echo.2020.12.009>
- [7] Mihos, C.G., Liu, J.E., Anderson, K.M., Pernetz, M.A., O'Driscoll, J.M., Aurigemma, G.P., *et al.* (2025) Speckle-Tracking Strain Echocardiography for the Assessment of Left Ventricular Structure and Function: A Scientific Statement from the American Heart Association. *Circulation*, **152**, e96-e109. <https://doi.org/10.1161/cir.0000000000001354>
- [8] Lopez, L., Saurers, D.L., Barker, P.C.A., Cohen, M.S., Colan, S.D., Dwyer, J., *et al.* (2024) Guidelines for Performing a Comprehensive Pediatric Transthoracic Echocardiogram: Recommendations from the American Society of Echocardiography. *Journal of the American Society of Echocardiography*, **37**, 119-170. <https://doi.org/10.1016/j.echo.2023.11.015>
- [9] Song, J. (2023) Pearls and Pitfalls in the Transesophageal Echocardiographic Diagnosis of Patent Foramen Ovale. *Journal of the American Society of Echocardiography*, **36**, 895-905.e3. <https://doi.org/10.1016/j.echo.2023.05.004>
- [10] Kroon, S., Van Thor, M.C.J., Vorselaars, V.M.M., Hosman, A.E., Swaans, M.J., Snijder, R.J., *et al.* (2020) The Use of Echo Density to Quantify Pulmonary Right-to-Left Shunt in Transthoracic Contrast Echocardiography. *European Heart Journal - Cardiovascular Imaging*, **22**, 1190-1196. <https://doi.org/10.1093/ehjci/jeaa155>
- [11] Khan, R., Karim, M.N., Hosseini, F. and Fine, N. (2022) Diagnostic Accuracy of Transthoracic Echocardiography with Contrast for Detection of Right-to-Left Shunt: A Systematic Review and Meta-Analysis. *Canadian Journal of Cardiology*, **38**, 1948-1958. <https://doi.org/10.1016/j.cjca.2022.08.007>
- [12] Jiang, M., Bian, F., Zhang, J., Pu, Z., Li, H., Zhang, Y., *et al.* (2024) An Automatic Coronary Microvascular Dysfunction Classification Method Based on Hybrid ECG Features and Expert Features. *IEEE Journal of Biomedical and Health Informatics*, **28**, 5103-5112. <https://doi.org/10.1109/jbhi.2024.3419090>
- [13] Schroder, J., Michelsen, M.M., Mygind, N.D., Suhls, H.E., Bove, K.B., Bechsgaard, D.F., *et al.* (2020) Coronary Flow Velocity Reserve Predicts Adverse Prognosis in Women with Angina and No Obstructive Coronary Artery Disease: Results from the iPOWER Study. *European Heart Journal*, **42**, 228-239. <https://doi.org/10.1093/eurheartj/ehaa944>
- [14] Harada, T., Kagami, K., Shina, T., Sorimachi, H., Yuasa, N., Saito, Y., *et al.* (2023) Diagnostic Value of Reduced Left Atrial Compliance during Ergometry Exercise in Heart Failure with Preserved Ejection Fraction. *European Journal of Heart Failure*, **25**, 1293-1303. <https://doi.org/10.1002/ejhf.2862>
- [15] Rosano, G.M.C., Vitale, C. and Maltese, G. (2021) Interdisciplinary Assessment and Diagnostic Algorithm: The Role of the Cardiologist. *Diabetes Research and Clinical Practice*, **176**, Article ID: 108851. <https://doi.org/10.1016/j.diabres.2021.108851>
- [16] Potter, E.L., Rodrigues, C.H.M., Ascher, D.B., Abhayaratna, W.P., Sengupta, P.P. and Marwick, T.H. (2021) Machine Learning of ECG Waveforms to Improve Selection for Testing for Asymptomatic Left Ventricular Dysfunction. *JACC: Cardiovascular Imaging*, **14**, 1904-1915. <https://doi.org/10.1016/j.jcmg.2021.04.020>
- [17] Company Calabuig, A.M., Nunez, E., Sánchez, A., Nicolaidis, K.H., Charakida, M. and De Paco Matallana, C. (2021) Three-Dimensional Echocardiography and Cardiac Strain Imaging in Women with Gestational Diabetes Mellitus. *Ultrasound in Obstetrics & Gynecology*, **58**, 278-284. <https://doi.org/10.1002/uog.23666>
- [18] Sato, H., Cavalcante, J.L., Enriquez-Sarano, M., Bae, R., Fukui, M., Bapat, V.N., *et al.* (2023) Significance of Spontaneous Echocardiographic Contrast in Transcatheter Edge-to-Edge Repair for Mitral Regurgitation. *Journal of the American Society of Echocardiography*, **36**, 87-95. <https://doi.org/10.1016/j.echo.2022.08.010>
- [19] Dobson, R., Ghosh, A.K., Ky, B., Marwick, T., Stout, M., Harkness, A., *et al.* (2021) BSE and BCOS Guideline for Transthoracic Echocardiographic Assessment of Adult Cancer Patients Receiving Anthracyclines and/or Trastuzumab. *JACC: CardioOncology*, **3**, 1-16. <https://doi.org/10.1016/j.jacc.2021.01.011>
- [20] Edwards, L.A., Feng, F., Iqbal, M., Fu, Y., Sanyahumbi, A., Hao, S., *et al.* (2023) Machine Learning for Pediatric Echocardiographic Mitral Regurgitation Detection. *Journal of the American Society of Echocardiography*, **36**, 96-104.e4. <https://doi.org/10.1016/j.echo.2022.09.017>
- [21] Farhad, M., Masud, M.M., Beg, A., Ahmad, A., Ahmed, L.A. and Memon, S. (2023) A Data-Efficient Zero-Shot and Few-Shot Siamese Approach for Automated Diagnosis of Left Ventricular Hypertrophy. *Computers in Biology and Medicine*, **163**, Article ID: 107129. <https://doi.org/10.1016/j.compbiomed.2023.107129>
- [22] Lau, E.S., Di Achille, P., Kopparapu, K., Andrews, C.T., Singh, P., Reeder, C., *et al.* (2023) Deep Learning-Enabled Assessment of Left Heart Structure and Function Predicts Cardiovascular Outcomes. *Journal of the American College of Cardiology*, **82**, 1936-1948. <https://doi.org/10.1016/j.jacc.2023.09.800>
- [23] Caruso, S., Cannataci, C. and Romano, G. (2021) Case 288: Uhl Anomaly. *Radiology*, **299**, 237-241. <https://doi.org/10.1148/radiol.2021192475>
- [24] Huo, L., Zeng, J., Wang, Z., Sun, X., Guo, Y., Cao, Z., *et al.* (2024) Magnetic Field-Optimized Paramagnetic Nanoprobe for t_2/t_1 Switchable Histopathological-Level MRI. *ACS Nano*, **18**, 12453-12467. <https://doi.org/10.1021/acs.nano.4c01723>
- [25] Wang, J., Jin, W., Huang, S., Wang, W., Wang, S., Yu, Z., *et al.* (2024) Microbubble Biointerfacing by Regulation of

- the Platelet Membrane Surfactant Activity at the Gas-Liquid Interface for Acute Thrombosis Targeting. *Angewandte Chemie International Edition*, **63**, e202314583. <https://doi.org/10.1002/anie.202314583>
- [26] Demirkiran, A., van Ooij, P., Westenberg, J.J.M., Hofman, M.B.M., van Assen, H.C., Schoonmade, L.J., *et al.* (2021) Clinical Intra-Cardiac 4D Flow CMR: Acquisition, Analysis, and Clinical Applications. *European Heart Journal—Cardiovascular Imaging*, **23**, 154-165. <https://doi.org/10.1093/ehjci/jeab112>
- [27] Li, D., Kirberger, M., Qiao, J., Gui, Z., Xue, S., Pu, F., *et al.* (2024) Protein MRI Contrast Agents as an Effective Approach for Precision Molecular Imaging. *Investigative Radiology*, **59**, 170-186. <https://doi.org/10.1097/rli.0000000000001057>
- [28] Fiore, G., Gaspardone, C., Ingallina, G., Rizza, V., Melillo, F., Stella, S., *et al.* (2023) Accuracy and Reliability of Left Atrial Appendage Morphology Assessment by Three-Dimensional Transesophageal Echocardiographic Glass Rendering Modality: A Comparative Study with Computed Tomography. *Journal of the American Society of Echocardiography*, **36**, 1083-1091. <https://doi.org/10.1016/j.echo.2023.05.013>
- [29] Qian, L., Xie, F., Xu, D. and Porter, T.R. (2020) Long-Term Prognostic Value of Stress Myocardial Perfusion Echocardiography in Patients with Coronary Artery Disease: A Meta-Analysis. *European Heart Journal—Cardiovascular Imaging*, **22**, 553-562. <https://doi.org/10.1093/ehjci/jeaa026>
- [30] Huang, R., DeMarco, J.K., Ota, H., Macedo, T.A., Abdelmoneim, S.S., Huston, J., *et al.* (2021) Prognostic Value of Intraplaque Neovascularization Detected by Carotid Contrast-Enhanced Ultrasound in Patients Undergoing Stress Echocardiography. *Journal of the American Society of Echocardiography*, **34**, 614-624. <https://doi.org/10.1016/j.echo.2020.12.016>
- [31] Aurigemma, G.P., Gentile, B.A., Dickey, J.B., Fitzgibbons, T.P., Tighe, D.A., Kakouros, N., *et al.* (2023) Insights into the Standard Echocardiographic Views from Multimodality Imaging: Ventricles, Pericardium, Valves, and Atria. *Journal of the American Society of Echocardiography*, **36**, 1266-1289. <https://doi.org/10.1016/j.echo.2023.07.011>
- [32] Ettedgui, J., Blackman, B., Raju, N., Kotler, S.A., Chekmenev, E.Y., Goodson, B.M., *et al.* (2023) Perfluorinated Iridium Catalyst for Signal Amplification by Reversible Exchange Provides Metal-Free Aqueous Hyperpolarized [1-¹³C]-Pyruvate. *Journal of the American Chemical Society*, **146**, 946-953. <https://doi.org/10.1021/jacs.3c11499>
- [33] Gheorghe, L.L., Mobasseri, S., Agricola, E., Wang, D.D., Milla, F., Swaans, M., *et al.* (2021) Imaging for Native Mitral Valve Surgical and Transcatheter Interventions. *JACC: Cardiovascular Imaging*, **14**, 112-127. <https://doi.org/10.1016/j.jcmg.2020.11.021>
- [34] Fang, J., Chen, Y., Liu, Y., Li, R., Zhu, Y., Zhou, W., *et al.* (2025) Transapical Beating-Heart Septal Myectomy for Obstructive Hypertrophic Cardiomyopathy: Lessons Learned after the Learning Curve Period. *Circulation: Cardiovascular Interventions*, **18**, e015044. <https://doi.org/10.1161/circinterventions.124.015044>
- [35] Chiang, H.P., Aguiar, M.O.D., Tavares, B.G., Rosa, V.E.E., Gomes, S.B., Oliveira, M.T., *et al.* (2023) The Impact of Sonothrombolysis on Left Ventricular Diastolic Function and Left Atrial Mechanics Preventing Left Atrial Remodeling in Patients with ST Elevation Acute Myocardial Infarction. *Journal of the American Society of Echocardiography*, **36**, 504-513. <https://doi.org/10.1016/j.echo.2022.12.010>
- [36] Qin, Y., Zhu, Y., Lu, L., Wu, H., Hu, J., Wang, F., *et al.* (2025) Tailored Extracellular Matrix-Mimetic Coating Facilitates Reendothelialization and Tissue Healing of Cardiac Occluders. *Biomaterials*, **313**, Article ID: 122769. <https://doi.org/10.1016/j.biomaterials.2024.122769>
- [37] Albulushi, A., Olson, J., Xie, F., Qian, L., Mathers, D., Aboeata, A., *et al.* (2021) Effect of Intermittent High-Mechanical Index Impulses on Left Ventricular Strain. *Journal of the American Society of Echocardiography*, **34**, 370-376. <https://doi.org/10.1016/j.echo.2020.11.013>
- [38] Riendeau Beaulac, G., Teran, F., Lecluyse, V., Costescu, A., Belliveau, M., Desjardins, G., *et al.* (2023) Transesophageal Echocardiography in Patients in Cardiac Arrest: The Heart and Beyond. *Canadian Journal of Cardiology*, **39**, 458-473. <https://doi.org/10.1016/j.cjca.2022.12.027>
- [39] Žulpaitė, U. and Petrikaitė, V. (2025) Nanosystems for Myocardial Ischemic Injury Theranostics. *Biochemical Pharmacology*, **241**, Article ID: 117115. <https://doi.org/10.1016/j.bcp.2025.117115>
- [40] Li, L., Tong, T., Ji, Q., Xu, Z., Guan, Y., Liang, X., *et al.* (2021) Dual Ph- and Glutathione-Responsive CO₂-Generating Nanodrug Delivery System for Contrast-Enhanced Ultrasonography and Therapy of Prostate Cancer. *ACS Applied Materials & Interfaces*, **13**, 12899-12911. <https://doi.org/10.1021/acsami.1c00077>
- [41] Muraru, D. (2022) 22nd Annual Feigenbaum Lecture: Right Heart, Right Now: The Role of Three-Dimensional Echocardiography. *Journal of the American Society of Echocardiography*, **35**, 893-909. <https://doi.org/10.1016/j.echo.2022.05.011>
- [42] Smiseth, O.A., Baron, T., Marino, P.N., Marwick, T.H. and Flachskampf, F.A. (2021) Imaging of the Left Atrium: Pathophysiology Insights and Clinical Utility. *European Heart Journal—Cardiovascular Imaging*, **23**, 2-13. <https://doi.org/10.1093/ehjci/jeab191>

-
- [43] Quintana, R.A., Dong, T., Vajapey, R., Reyalde, R., Kwon, D.H., Harb, S., *et al.* (2022) Preprocedural Multimodality Imaging in Atrial Fibrillation. *Circulation: Cardiovascular Imaging*, **15**, e014386. <https://doi.org/10.1161/circimaging.122.014386>
 - [44] Linder, M., Voigtländer, L., Schneeberger, Y., Bhadra, O.D., Grundmann, D., Demal, T., *et al.* (2021) Spontaneous Echo Contrast, Left Atrial Appendage Thrombus and Stroke in Patients Undergoing Transcatheter Aortic Valve Implantation. *EuroIntervention*, **16**, 1114-1122. <https://doi.org/10.4244/eij-d-20-00743>
 - [45] Chen, C., Wu, Y., Dai, Q., Zhou, H., Xu, M., Yang, S., *et al.* (2024) A Survey on Graph Neural Networks and Graph Transformers in Computer Vision: A Task-Oriented Perspective. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **46**, 10297-10318. <https://doi.org/10.1109/tpami.2024.3445463>
 - [46] Erbe, R., Gore, J., Gemmill, K., Gaykalova, D.A. and Fertig, E.J. (2022) The Use of Machine Learning to Discover Regulatory Networks Controlling Biological Systems. *Molecular Cell*, **82**, 260-273. <https://doi.org/10.1016/j.molcel.2021.12.011>
 - [47] Croley, C.R., Pumarol, J., Delgadillo, B.E., Cook, A.C., Day, F., Kaceli, T., *et al.* (2023) Signaling Pathways Driving Ocular Malignancies and Their Targeting by Bioactive Phytochemicals. *Pharmacology & Therapeutics*, **248**, Article ID: 108479. <https://doi.org/10.1016/j.pharmthera.2023.108479>