



Review of the Latest Research Directions and Clinical Application Advances in Cardiac CT

Kaining Yang¹, Jilong Jin²

¹ Changzhi Medical College, Changzhi, Shanxi, China

² Department of Radiology, Jincheng General Hospital, Jincheng, Shanxi, China

Abstract: Objective: To systematically review the latest research findings on cardiac computed tomography (CT) in terms of hardware innovation, intelligent technology integration, and expanded clinical applications. This review emphasizes its value in precision diagnosis and treatment for conditions such as atrial fibrillation and aortic valve stenosis, providing reference for the advancement of precision medicine in cardiovascular diseases. Methods: We retrieved data from core domestic and international journals, multicenter clinical trials, and authoritative guidelines (ESC, ACC/AHA, Chinese Medical Association Radiology Branch) published between 2021 and 2025. Analyses focused on technological breakthroughs in cardiac CT and disease-specific assessments through AI integration. Results: Dual-slice dual-source CT and photon-counting detector CT (PCD-CT) achieved the integration of low dose and high resolution, while AI technology revolutionized the entire image reconstruction workflow. CT demonstrates critical value in pre-ablation assessment for atrial fibrillation and throughout transcatheter aortic valve replacement (TAVR) for aortic stenosis. Left atrial appendage volume >9.25 ml serves as an independent predictor of post-ablation recurrence (HR=1.160, 95% CI: 1.095–1.229, P<0.001). An independent predictor of post-ablation recurrence (HR=1.160, 95% CI: 1.095–1.229, P<0.001). Pre-TAVR CT assessment achieves over 95% accuracy in valve selection. Recommendations for CCT differ between the 2024 ESC and ACC/AHA guidelines, with ACC/AHA's Class COR-IIa recommendation rate (51.9%) significantly higher than ESC's (35%) (P=0.04). Conclusion: Cardiac CT has evolved into an integrated diagnostic and therapeutic platform characterized by "intelligence, precision, and comprehensive care." Future efforts should focus on advancing technical standardization and improving accessibility at the primary care level to enhance its role in early disease screening and personalized treatment.

Keywords: cardiac CT; photon-counting detector; artificial intelligence; atrial fibrillation; aortic valve stenosis; transcatheter aortic valve replacement; low-dose imaging; clinical guidelines

1. Introduction

Cardiac computed tomography (CCT) has evolved from a purely anatomical imaging tool to a comprehensive platform integrating structure, function, and biological information. Recent breakthroughs hinge on photon-counting detector technology, artificial intelligence (AI)-driven workflow optimization, and radiomics-based risk stratification. These advancements enhance spatial resolution, reduce radiation doses, and enable precise assessment of vulnerable plaques and myocardial function. With global guideline updates and domestic innovation gaining traction, CCT is reshaping cardiovascular diagnosis, prognostic evaluation, and personalized treatment strategies, marking a paradigm shift toward noninvasive precision medicine.

2. Technological Innovation: Dual-Driven by Hardware Upgrades and Intelligent Empowerment

2.1 Disruptive Breakthroughs in Hardware Equipment

(1) Dynamic Imaging Capabilities of Dual-Slice Dual-Source CT: The world's first dual-slice dual-source CT achieves whole-heart dynamic imaging within a single cardiac cycle at 8ms temporal resolution. The second-generation dual-source CT employs dual-step triggering technology that dynamically adjusts current output intervals based on heart rate[1]. A clinical study of 53 cases demonstrated a 97.76% diagnostic segment coverage rate in coronary arteries, with a radiation dose of only 3.33±0.65 mSv. Left ventricular function parameters showed high correlation with cardiac MRI (r values ranging from 0.89 to 0.97), significantly improving examination success rates for patients with arrhythmias[2]. This technology is recommended in the Chinese Expert Consensus on Coronary CT Angiography for Diagnosis and Management of Coronary Artery Disease (2025) for coronary assessment in patients with poor heart rate control, classified as a Class COR-I recommendation (LOE-B).

(2) Clinical Applications of Photon-Counting Spectral CT: PCD-CT achieves ultra-high spatial resolution of 0.2 mm through direct photon conversion. Studies by Lemmens et al. confirmed its capability to perform coronary artery assessment and myocardial late enhancement imaging in a single scan [3-5]. In myocardial fibrosis assessment, using LGE-MRI as the gold standard, diagnostic accuracy reached 85.2% at the patient level and 90.7%–91.1% at the segment level (κ values 0.63–0.70). Its virtual non-contrast scanning technology reduces contrast agent usage by 50%–75% [6]. The 160ms high-pitch scan expands indications for unstable patients. The 2025 Chinese Expert Consensus on Operational Procedures and Image Analysis for Dynamic CT Myocardial Perfusion Imaging recommends its use for myocardial perfusion assessment in patients with renal insufficiency (COR-IIa, LOE-B) [7].

2.2 Deep Integration of Artificial Intelligence Throughout the Imaging Workflow

AI technology establishes an end-to-end "scan-reconstruction-diagnosis" solution: Algorithms like CardioBoost balance low-dose and high-resolution imaging, while motion artifact correction engines reduce heart rate control requirements [8, 9]. Diagnostic quality variation among technicians with differing experience levels is minimized to 0.3%, achieving a 99% examination success rate. A graph neural network-based registration algorithm achieves high-precision matching between preoperative CTA and intraoperative contrast images, with an average error of only 1.52 mm, supporting interventional planning. This technology is listed as a Class COR-IIa recommendation (LOE-B) for preoperative coronary intervention assessment in the ACC/AHA 2024 guidelines.

3. Clinical Application Expansion: Precision Navigation Throughout the Diagnostic-Therapeutic Continuum

3.1 Precision Assessment of Coronary Artery Disease

Cardiac CT has achieved integrated anatomical and functional assessment. The German Society of Cardiology's standardized protocol proposes that 128-slice or higher CT can quantify calcification density (≥ 635 HU indicates the necessity for rotational atherectomy), with CT-SYNTAX scores guiding interventional strategy formulation. CT-FFR technology has undergone multicenter validation. The DISCOVER-FLOW study (103 patients) demonstrated diagnostic accuracy of 84.3% (AUC 0.90), significantly outperforming CCTA alone (58.5%) [10, 11]; The DeFACTO international multicenter study (252 patients) achieved an AUC of 0.79 in moderately stenotic lesions with a negative predictive value of 90%, reducing unnecessary angiography by 77% [12]. The 2025 Chinese Guidelines for Percutaneous Coronary Intervention explicitly state that for lesions with 50%–90% stenosis, CT-FFR or CT myocardial perfusion (CTP) must provide evidence of ischemia before revascularization is indicated (COR-I, LOE-A). PCD-CT clearly visualizes coronary stents < 3 mm, enhancing the accuracy of post-procedural restenosis assessment. The 2024 ESC guidelines recommend its use for follow-up after small vessel stenting (COR-IIa, LOE-B).

3.2 Comprehensive Guidance for Interventional Treatment of Structural Heart Disease

(1) Aortic Stenosis (AS) and TAVR Evaluation: AS, a valvular disease causing left ventricular-aortic outflow obstruction, has TAVR as its primary treatment modality, with CT serving as the gold standard for preoperative assessment. Preoperative CT precisely evaluates aortic valve morphology (Hasan classification accuracy $> 90\%$), annular circumference/area, and calcification distribution [13]. For patients with bicuspid aortic valve (BAV), CT identifies fusion ridge characteristics and ascending aortic dilatation, optimizing surgical strategies. Full cardiac cycle scanning protocols predict left ventricular outflow tract obstruction risk, achieving 93% accuracy in predicting TAVR-related coronary obstruction risk and 95% accuracy in selecting left atrial appendage occluder size. The ACC/AHA 2024 guidelines recommend CCT for VHD at a significantly higher rate (18.5%) than the ESC (2.5%) ($P=0.02$). Six Class I recommendations involve preoperative TAVR CT assessment, including critical components such as annular measurement and coronary ostium distance evaluation. Postoperative CT enables assessment of paravalvular leakage, stent positioning, and coronary patency, providing evidence for prognostic evaluation. The Chinese Expert Consensus on Standardized CT Assessment for Transcatheter Aortic Valve Replacement (2025) specifies postoperative CT scanning parameters and evaluation criteria.

(2) Mitral Valve Intervention: CT three-dimensional reconstruction introduced the "Neo-LVOT" concept, enabling anatomical parameter quantification to optimize device selection [14]. Multimodal fusion technology enhances precision in critical procedures like atrial septal puncture, reducing surgical complications. This technique is listed as a COR-IIa recommendation (LOE-B) for complex mitral valve interventions in the 2024 ESC guidelines.

3.3 Matrix visualization in electrophysiological surgery

(1) Core Value in AF Management: AF patients exhibit significant cardiac structural remodeling, and CT precisely

quantifies left atrial appendage (LAA) anatomy. A study of 83 AF patients showed a 32.53% recurrence rate after radiofrequency ablation[15]. The recurrence group had significantly larger left atrial volume, LAA volume, and LAA opening diameter compared to the non-recurrence group (all $P < 0.05$). Left atrial appendage volume >9.25 ml predicted recurrence with a sensitivity of 85.2% and specificity of 67.9% (AUC 0.82), serving as an independent predictor of recurrence (HR=1.160, $P<0.001$). The combination of low tube voltage (100 kVp) + low-concentration contrast agent (300 mg I/mL) with 70%–80% ASIR-V reconstruction protocol reduces radiation dose by 37.4% and iodine uptake by 29.9% while maintaining the display rate of left atrial and pulmonary vein anatomical variations, thereby supporting ablation pathway planning. This protocol is recommended by the Chinese Expert Consensus on CT Examination and Diagnosis of Coronary Heart Disease (2025) for pre-ablation assessment in atrial fibrillation (COR-I, LOE-B). The ESC and ACC/AHA guidelines show no significant difference in recommended CCT proportions for arrhythmia management (7.5% vs. 9.3%, $P=0.73$), both recognizing CT as an alternative imaging modality for evaluating structural heart disease[16, 17].

(2) Myocardial Scarring and Target Localization: CT delayed iodinated contrast enhancement can detect myocardial scars <1 mm, with an 82% matching rate to electroanatomical mapping low-voltage zones. Preoperative 3D reconstruction increased detection of pulmonary vein variations by 40%, aiding in the avoidance of anatomical obstacles, optimizing ablation pathways for atrial fibrillation, and reducing complication risks[18]. The 2024 ESC guidelines list this as a Class IIa recommendation (LOE-B) for complex atrial fibrillation ablation.

4. Cutting-Edge Exploration and Technical Bottlenecks

4.1 Emerging Technological Directions

(1) Low-Dose Dynamic Functional Imaging: The 4D-CT protocol combines AI with PCD-CT advantages to achieve coronary CTA at an ultra-low dose of 1.72 mGy. The radiation dose for ULD-PCT is only 10%–20% of standard low-dose CT while still meeting clinical diagnostic requirements[19]. The 2025 Chinese Expert Consensus on Dynamic CT Myocardial Perfusion Imaging Technology Operation and Image Analysis recommends its use for screening high-risk populations (COR-IIa, LOE-B).

(2) Quantitative assessment of myocardial function: ECV values derived from PCD-CT iodine concentration maps show high correlation with cardiac MRI, providing noninvasive evaluation of microscopic lesions such as myocardial fibrosis and edema. The 2024 ACC/AHA guidelines list it as an alternative for patients with MRI contraindications (COR-IIa, LOE-B) [20].

(3) Technological Accessibility and Standardization: "One-click" AI-CT lowers technical barriers for primary-care hospitals through standardized workflows. The "technology transfer" initiative of National Regional Medical Centers promotes load CT adoption. The Chinese Expert Consensus on Coronary Artery Disease CT Examination and Diagnosis (2025) establishes standardized scanning protocols feasible for primary-care hospitals[21].

4.2 Current Challenges

PCD-CT operations are highly complex, requiring precise selection among multiple scanning modes and reconstruction parameter combinations, resulting in significant learning costs. High-resolution modes increase image noise, with single-case data volumes reaching 3000MB, imposing stringent demands on storage and transmission systems. The absence of unified imaging parameter standards limits comparability between different devices. Discrepancies in CCT recommendations between ESC and ACC/AHA guidelines (e.g., in congenital heart disease, ACC/AHA has an 11.1% COR-I recommendation while ESC lacks formal guidance) underscore the urgency for standardization ($P=0.04$). Regarding functional assessment, CT-FFR carries a risk of false negatives in lesions within the 0.75–0.80 "gray zone," and its reliance on specialized software limits clinical adoption. Calcification artifacts still compromise assessment accuracy in 10–15% of cases, necessitating further optimization of spectral imaging and AI-based de-artifactation algorithms.

5. Conclusions and Outlook

Recent advances in cardiac CT embody the trends of "intelligence, precision, comprehensive coverage, and accessibility." Dual-slice dual-source CT and PCD-CT enable unified dynamic functional imaging and ultra-low dose acquisition. AI technology is transforming imaging workflows. Functional assessments like CT-FFR, validated through multicenter studies, extend from diagnosis to the entire therapeutic chain in conditions such as atrial fibrillation and aortic stenosis, becoming a core pillar of precision cardiovascular medicine. Differences between the 2024 ESC and ACC/AHA guidelines reflect regional and evidence disparities in CCT clinical application. Future large-scale multicenter studies are needed to advance unified recommendation standards. Further refinement of AI-powered real-time image fusion systems is required to enhance

multimodal data integration capabilities and advance technical parameter standardization. Key priorities include addressing functional assessment accuracy and accessibility in primary care settings to achieve integrated early screening, personalized treatment decision-making, and prognostic evaluation for cardiovascular diseases. This will ultimately realize the goals of universal access to diagnostics and precision medicine.

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Author Bio

Kaining Yang: Male; Han Nationality; Born in 1997; Master Candidate (Class 2503); Resident Physician; Research Direction: Radiology.