Modern Health Science; Vol. 8, No. 1; 2025
ISSN 2576-7291 E-ISSN 2576-7305
https://doi.org/10.30560/mhs.v8n1p79

Cardiac Computed Tomograpy Technology in Interventions Related to Atrial Fibrillation

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Received: February 13, 2025; Accepted: March 6, 2025; Published: March 8, 2025

Abstract

Atrial fibrillation represents the predominant cardiac arrhythmia encountered in the elderly population clinically. In recent years, the use of cardiac interventional therapy for atrial fibrillation has become increasingly prevalent. Cardiac computed tomograpy(CT) plays a important rolesin interventional therapy, particularly demonstrating significant importance in preoperative assessment and planning. This article reviews the applications of cardiac CT in assisting transseptal puncture, catheter radiofrequency ablation, ethanol infusion into the vein of marshall, and left atrial appendage occlusion procedures.

Keywords: atrial fibrillation, Cardiac CT, transseptal puncture, percutaneous catheter radiofrequency ablation, ethanol infusion into the vein of marshall, left atrial appendage occlusion

1. Introduction

Atrial fibrillation (AF), a common cardiac arrhythmia marked by rapid, irregular atrial activation and impaired atrial contraction, is among the most frequently encountered persistent arrhythmias in clinical settings, affecting approximately 2% to 4% of the population [1] This condition is associated with a significant increase in all-cause mortality, elevating the risk by 15-20% in affected patients.

The incidence and prevalence of AF continue to rise steadily in contemporary clinical practice. With advancements in cardiac intervention techniques, various therapeutic approaches for AF have gained widespread clinical application, including catheter-based radiofrequency ablation, left atrial appendage closure, Marshall vein ethanol ablation, and atrial septal puncture for left atrial access establishment. Substantial evidence demonstrates that percutaneous catheter ablation significantly reduces both cardiovascular and all-cause mortality in AF patients [2], while the combination of ethanol infusion into the vein of marshall with catheter ablation effectively decreases postoperative recurrence rates in persistent AF cases [3]

Despite the widespread adoption and technological maturation of AF-related interventions, clinical challenges persist, including procedural failures, postoperative arrhythmia recurrence, pericardial tamponade, and major vascular complications. Cardiac computed tomography (CT) has emerged as an indispensable noninvasive imaging modality for comprehensive structural and functional cardiac assessment, providing high-resolution cardiac imaging that has revolutionized noninvasive cardiac evaluation [4] This advanced imaging technique offers crucial individualized and validated diagnostic information throughout the perioperative period, enabling operators to obtain detailed preoperative cardiac anatomical data for informed intraoperative decision-making. Consequently, cardiac CT has become increasingly integral to AF-related interventions.

This article aims to comprehensively review the evolving role of cardiac CT technology in guiding AF-related interventions, highlighting its clinical applications and procedural implications.

2. Atrial fibrillation

2.1 Diagnostic Criteria and Classification of Atrial Fibrillation

The diagnosis of atrial fibrillation primarily relies on characteristic electrocardiographic findings: disappearance of P waves replaced by fibrillatory waves (f waves) that exhibit irregular amplitude, morphology, and timing, with a frequency ranging from 350 to 600 beats per minute (bpm). the ventricular rate is irregular and the morphology of the QRS wave is normal, and when the ventricular rate is too fast and intraventricular differentiated conduction occurs, the QRS wave can be widened and deformed.

Clinically, AF manifests with symptoms including palpitations, fatigue, dyspnea, and dizziness. Physical examination typically reveals irregularly irregular rhythm (absolute arrhythmia), variable intensity of the first heart sound, and pulse deficit.

AF is classified into four distinct categories based on duration and response to treatment. Paroxysmal AF, Self-terminating episodes lasting less than 7 days, typically resolving within 48 hours either spontaneously or with intervention. Persistent AF, Episodes continuing beyond 7 days that require pharmacological or electrical cardioversion for termination and restoration of sinus rhythm. Long-standing persistent AF, Continuous AF sustained for more than 1 year, where catheter ablation may be considered as a therapeutic option. Permanent AF, Established AF that is refractory to cardioversion or recurs despite therapeutic interventions, where rhythm control is no longer pursued [5]

2.1 Complications

The most prevalent and significant complication of atrial fibrillation is the formation of thrombi in the left atrial appendage or within the left atrium itself. The pathogenesis of thrombus formation involves several mechanisms: during AF episodes, the electrical activity of the atria becomes disorganized, resulting in irregular and often accelerated heart rhythms. This leads to impaired cardiac pumping function and subsequent blood stasis within the atrial chambers, creating a prothrombotic environment. These intracardiac thrombi are prone to dislodgement during cardiac contractions and may embolize to various systemic locations through the bloodstream, potentially causing embolic events in critical organs such as the brain (cerebral embolism), kidneys (renal infarction), gastrointestinal system (mesenteric ischemia), and extremities (peripheral arterial embolism) [6]

Furthermore, AF is associated with additional complications resulting from chronic cardiac rhythm disturbances. The persistent irregular rhythm leads to compromised cardiac output, increasing the myocardial workload and potentially resulting in heart failure [6] The abnormal electrical activity and impaired contractile function may also cause myocardial ischemia due to inadequate blood supply. Moreover, sustained atrial dysrhythmias can induce structural remodeling and fibrosis of atrial myocardium, potentially progressing to arrhythmia-induced cardiomyopathy.

2.3 Treatment of Atrial Fibrillation

The therapeutic principles for atrial fibrillation management encompass three key aspects. Restoration of sinus rhythm, control of ventricular rate, and prevention of thromboembolic complications [5,6] AF treatment modalities can be broadly categorized into pharmacological and non-pharmacological approaches.1.Pharmacological Treatment: Antiarrhythmic drugs for AF management are classified into two categories: a) Rhythm control agents: These medications aim to convert AF to sinus rhythm and prevent recurrence, including:Class IA agents (e.g., quinidine, procainamide). Class IC agents (e.g., propafenone). Class III agents (e.g., amiodarone), b) Rate control agents: These medications regulate ventricular rate, including: β-blockers (e.g., bisoprolol, metoprolol) ,Non-dihydropyridine calcium channel blockers (e.g., verapamil, diltiazem), Digitalis preparations. Additionally, anticoagulation therapy is essential for AF patients undergoing conservative management to prevent thromboembolism. Options include: Vitamin K antagonists (e.g., warfarin), Novel oral anticoagulants (NOACs) (e.g., dabigatran, rivaroxaban), Non-pharmacological Treatment: Interventional approaches include: Percutaneous catheter ablation, Marshall vein ethanol ablation, Left atrial appendage closure, Electrical cardioversion.

3. Cardiac CT

Cardiac computed tomography is a non-invasive diagnostic modality that utilizes X-ray technology and advanced computer algorithms to reconstruct detailed cardiac anatomy and functional information. This imaging technique employs three-dimensional reconstruction technology to generate comprehensive and intricate three-dimensional datasets of the heart, which are reconstructed from raw data files based on specific phases of the cardiac cycle. Cardiac CT enables comprehensive examination of cardiac structures through axial images in any orientation (coronal, sagittal, and transverse planes) and multiplanar reconstruction images [7] Currently, cardiac CT has gained widespread clinical application, with numerous studies utilizing its three-dimensional imaging capabilities to investigate various cardiac parameters, including aortic stiffness and motion [8], coronary artery bifurcation angles [9], pericardial diseases, and left atrial appendage thrombi.

The advantages of cardiac CT technology include: Superior Imaging Resolution, High spatial resolution: Enables clear visualization of cardiac chambers, valves, arteries, and myocardium. High temporal resolution: Effectively reduces cardiac motion artifacts, resulting in clearer images [10] Advanced Reconstruction Capabilities: Multiplanar reconstruction and three-dimensional visualization: Allows conversion of two-dimensional scan images into three-dimensional reconstructions, providing clinicians with intuitive, multi-angle views of cardiac structures. Clinical Efficiency: Non-invasive nature: Minimizes patient discomfort, Rapid examination: Short scanning time with high diagnostic efficiency, Precise measurement: Enables accurate and reproducible quantification of three-dimensional thoracic structures, including various distances and angles [11]

4. Cardiac CT Guides Interventions Related to Atrial Fibrillation

4.1 Transseptal Puncture

Transseptal Puncture (TSP) is a critical technique in various cardiac interventional therapies, widely used in left heart catheterization, atrial fibrillation ablation, and mitral valve interventions. It serves as an essential pathway to access the left atrium. Currently, atrial septal puncture techniques are quite mature. However, challenges remain when patients have morphological abnormalities of the atrial septum (such as thickening, fibrosis, or aneurysms) or abnormalities in surrounding tissues (such as atrial enlargement or reduction, aortic dilation), which can increase the incidence of adverse events. Severe and potentially fatal complications include cardiac tamponade and perforation of adjacent large vessels [12] Traditional atrial septal puncture relies on X-ray fluoroscopy for guidance, but its two-dimensional imaging has limitations, especially in patients with anatomical variations. Cardiac computed tomography, with its high-resolution three-dimensional imaging capabilities, has evolved into a valuable tool for determining device sizes and planning transseptal punctures [14] Yan Wang et al. have demonstrated that a three-step method guided by cardiac CT image analysis is safe and feasible for transseptal puncture, helping to reduce the need for left atrial angiography and the likelihood of cardiac perforation [15] Tan Ming et al. used left atrial CT to assess the anatomical location, angle, and height of the fossa ovalis relative to the coronary sinus, guiding X-ray fluoroscopy for atrial septal puncture. This approach effectively improved the efficiency and safety of transseptal puncture (TSP), reduced the risk of complications, and provided anatomical support for understanding atrial septal puncture [16] Cardiac CT can preoperatively assess the thickness and morphology of the atrial septum and locate the fossa ovalis, aiding in the selection of the optimal puncture site during the procedure and avoiding damage to important structures around the atrial septum. Furthermore, by utilizing cardiac CT three-dimensional imaging, it is possible to integrate preoperative 3D images with intraoperative 2D images to guide real-time atrial septal puncture. During the procedure, the puncture angle and depth can be adjusted in real-time based on the fused images, enhancing the precision and safety of the puncture.

4.2 Percutaneous Catheter Radiofrequency Ablation

Radiofrequency ablation (RFA) is one of the primary methods for treating atrial fibrillation. It involves puncturing the femoral vein, femoral artery, or subclavian vein to deliver an electrode catheter to specific locations within the cardiac chambers. Radiofrequency energy is then released to generate a thermal effect in the tissue, leading to cellular dehydration, protein denaturation, and coagulative necrosis, thereby eliminating abnormal electrical signals and restoring normal cardiac rhythm. The success rate of radiofrequency ablation for atrial fibrillation is significantly higher than that of pharmacological therapy alone. The initial success rate of AF ablation is approximately 80%, though some patients may experience AF recurrence post-procedure [17] The primary objectives of AF ablation include electrical isolation of the pulmonary vein ostia and mitral isthmus ablation. Golnoush Asaeikheybari highlighted a potential correlation between radiological features of the pulmonary veins and AF recurrence following ablation [15] Due to the complex and variable anatomy of the left atrium and pulmonary veins among individuals, preoperative cardiac CT imaging is critical for understanding the anatomical structures of the pulmonary veins, mitral valve, and other regions. This aids in precise planning of ablation pathways, ensuring accurate catheter placement in target areas, and improving procedural precision and safety.

Cardiac CT three-dimensional imaging technology can clearly delineate the anatomical structures of the left atrium and pulmonary veins, including the number, diameter, and vascular course of the pulmonary vein ostia. It also helps identify the anatomical position of the esophagus to avoid esophageal perforation during the procedure [18] By analyzing cardiac anatomy preoperatively, clinicians can optimize catheter access routes, select appropriate ablation strategies, reduce procedure-related complications, and enhance surgical success rates.

4.3 Ethanol Infusion into the Vein of Marshall

Ethanol infusion into the vein of marshall has emerged as a powerful adjunctive approach in non-paroxysmal atrial fibrillation ablation. Its efficacy and safety, when combined with percutaneous catheter ablation for AF, have been validated, leading to increasing clinical adoption. This technique involves percutaneous injection of absolute ethanol into the Marshall vein, where the ethanol damages distal capillaries of the vein, inducing localized aseptic necrosis of atrial tissue. This effectively ablates the entire atrial myocardium in regions supplied by the vein of Marshall (VOM) and its branches, disrupts epicardial connections at the mitral isthmus, and terminates AF. Studies have demonstrated that combining ethanol infusion into the vein of marshall with radiofrequency catheter ablation significantly reduces postoperative recurrence rates in persistent atrial fibrillation [3] Ning Zhu et al. confirmed the safety and efficacy of a one-stop strategy integrating ethanol infusion into the vein of marshall, radiofrequency ablation, and left atrial appendage closure for AF treatment [19]

Takamitsu Takagi et al. compared conventional CT scans with optimized VOM-CT protocols, revealing a VOM detection rate of 35% with conventional CT versus 63% with optimized VOM-CT ($P<0.001$). Their findings demonstrated that VOM-CT-guided procedures substantially reduced radiation exposure time, procedural duration, contrast agent volume, and injection frequency, while improving VOM visualization and simplifying catheter insertion [20] Given the small diameter of the VOM and intraoperative localization challenges, preoperative cardiac CT assessment of VOM anatomical characteristics enables personalized evaluation of potential intraoperative scenarios.

Integrating cardiac CT technology into ethanol infusion into the vein of marshall could enhance its clinical utility, analogous to the preoperative assessment and interventional planning using multi-detector computed tomography (MDCT) in coronary artery disease. Cardiac CT three-dimensional imaging provides detailed visualization of cardiac anatomy and VOM ostium structures. Preoperative cardiac CT evaluation of Marshall vein anatomy offers multiple advantages, including reduced intraoperative radiation exposure, shorter procedural time, and minimized contrast agent dosage.

4.4 Left Atrial Appendage Occlusion

The most common complication of atrial fibrillation is thrombus formation in the left atrial appendage (LAA) and subsequent embolic events in various organs. The LAA is a narrow, elongated structure protruding outward from the left atrium, characterized by slow blood flow and multiple endocardial folds, which predispose it to thrombus formation [21] Over 90% of intracardiac thrombi in non-valvular AF patients originate in the LAA. Transcatheter left atrial appendage occlusion (LAAO) serves as an effective alternative to lifelong anticoagulation therapy for non-valvular AF patients who are ineligible for long-term anticoagulation, effectively preventing thromboembolism in AF patients at high risk of stroke. This procedure involves placing an occlusion device at the LAA ostium to isolate blood flow between the LAA and the left atrium, thereby reducing stasis and vortex formation during AF and minimizing thrombus formation and systemic embolism. Currently, transesophageal echocardiography (TEE) is the most common imaging modality for preoperative evaluation and intraoperative guidance in LAAO [22], offering high sensitivity and specificity as the clinical gold standard for detecting LAA thrombi [23]. Despite rapid growth in LAAO procedures, technological advancements, and accumulated clinical experience, LAAO remains one of the interventional procedures with the highest reported rates of adverse events [14].

In AF patients, thrombus formation in the left atrium and LAA is one of the most frequent complications. Cardiac CT demonstrates high sensitivity for detecting LAA thrombi, though its specificity is limited due to challenges in distinguishing between reduced contrast opacification caused by slow blood flow and actual thrombus presence [15] With advancements in CT technology and postprocessing techniques, CT has shown improved efficacy in detecting LAA or left atrial thrombi. Studies indicate that combining contrast-enhanced cardiac CT with coronary CT angiography (CTA) achieves diagnostic consistency with TEE in identifying LAA thrombi, enhancing diagnostic accuracy for thrombus detection in non-valvular AF patients [23] Cheng Cheng et al. confirmed that preoperative cardiac CT three-dimensional imaging can measure LAA parameters, evaluate optimal atrial septal puncture sites, significantly shorten procedural time for septal puncture and device deployment, and reduce contrast agent dosage and radiation exposure [24] Preoperative cardiac CT assessment of LAA thrombus formation provides critical guidance for anticoagulation therapy planning, thereby reducing surgical risks. Additionally, cardiac CT technology clearly delineates the anatomical structures of the left atrium and LAA, assisting clinicians in selecting appropriate occlusion devices, ensuring effective closure, and improving procedural success rates.

5. Conclusion

The application of cardiac CT technology in the preoperative assessment of atrial fibrillation -related cardiac interventions serves as an effective supplementary tool for understanding cardiac conditions. Cardiac CT can evaluate surgical exclusion criteria, guide the selection of interventional device sizes and sheaths, and assist in planning atrial septal puncture [22]. Additionally, cardiac CT is valuable for postoperative evaluation and follow-up of AF interventions. By comparing pre- and postoperative CT images, physicians can assess surgical outcomes, such as the formation of ablation lesions and blood flow status after left atrial appendage closure, while monitoring structural changes and detecting potential complications like device displacement or thrombus formation. Studies indicate that increased left atrial wall thickness and enlarged atrial volume are associated with poor surgical outcomes and AF recurrence [25, 26] Pulmonary vein morphology and orientation have also been linked to AF recurrence [27]. Advances in MDCT imaging have significantly improved the accuracy of identifying fibrotic tissue, localizing arrhythmogenic substrates, and guiding targeted ablation therapy [15].

As a non-invasive, reliable, and efficient imaging modality, cardiac CT plays a crucial role in guiding AF-related interventions. By enabling precise thrombus screening, providing detailed anatomical information, optimizing surgical planning, and evaluating treatment efficacy, cardiac CT enhances the success rate and safety of AF interventions while reducing complication risks. With ongoing technological advancements and expanded clinical applications, the role of cardiac CT in AF management is expected to grow substantially.

In summary, cardiac CT serves as a valuable diagnostic tool for cardiovascular diseases. Accurate segmentation of cardiac structures from CT images is essential for diagnosing functional abnormalities, formulating treatment plans, and managing cardiovascular conditions [4]. Beyond AF thrombus screening, cardiac CT provides critical anatomical guidance for AF-related interventions, enabling optimized surgical strategies. As an indispensable tool in AF intervention, cardiac CT will significantly advance the quality of AF treatment.

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