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Review Article

Cardiac computed tomography: Current practice, guidelines, applications, and prospects

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Abstract

Cardiac computed tomography (CT) has evolved significantly as a critical tool in diagnosing and managing cardiac diseases, greatly facilitated by technological advancements in multidetector systems, dose-reduction techniques, and sophisticated imaging algorithms. This article discusses the historical progression and technological evolution in cardiac CT (CCT), focusing on the impact of 64-multidetector row CT and dual-energy CT systems on improving spatial and temporal resolutions and reducing radiation exposure. It explores the role of these technologies in enhancing diagnostic accuracy, such as through detailed three-dimensional reconstructions and minimized imaging artifacts. Furthermore, it highlights the integration of machine learning to automate complex imaging analysis and photon-counting CT, which promises higher resolution and further dose reduction. Prospective studies and ongoing trials such as FASTTRACK coronary artery bypass grafting also underscore the potential of advanced CT technologies in refining procedural planning and execution. The continuous advancements in detector technology, computational techniques, and image reconstruction are poised to expand the applications and efficacy of CCT, cementing its role in modern cardiology.

Keywords: *Calcium score, Computed tomography, Coronary anomaly, Coronary artery disease, Coronary computed tomography*

Introduction

The era for cardiac computed tomography

Imaging the heart with computed tomography (CT) is particularly challenging due to its rapid, involuntary movements and complex structure, which make two-dimensional imaging insufficient. Various techniques, such as electron beam CT, ECG gating, and extensive computing, have been explored to mitigate cardiac motion [1]. The advent of multidetector CT, which provides isometric voxels, has significantly enhanced the capability for three-dimensional (3D) reconstruction [2]. Currently, cardiac CT (CCT) has increasingly become vital in diagnosing cardiac diseases, evaluating postprocedural outcomes, and preventing severe cardiac events.

Another major concern in the application of CCT is the radiation dose, especially for patients undergoing multiple radiological examinations. Advances in technology with 256-row or higher scanners have significantly reduced radiation exposure compared to older 64-row CT scanners. An estimated 32% reduction in radiation dose has been documented [3], and further advances have brought the typical CCT radiation dose down to 2.7 mSv in the PROTECTION VI study across 62 countries [4], compared to 40 mSv from traditional thallium scan stress tests and 7 mSv from diagnostic coronary angiography.

In this article, we explore the historical advancements in CT technology, the diverse applications of CCT, and the promising future prospects of CCT. With continuous advancements in CT detector technology and computing capabilities, we anticipate witnessing an expansion of applications for CCT in the coming years.

Advancement in cardiac computed tomography

64-multidetector row coronary computed tomography

Spatial and temporal resolutions are paramount in CCT imaging. The emergence of 64-multidetector row CT has reduced the slice thickness to <0.625 mm, enabling the

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reconstruction of detailed coronary arteries in a precise manner [5,6]. Furthermore, radiation exposure from coronary CT has been significantly lowered due to novel developments in detector and image reconstruction technologies [7], marking the beginning of the era of cardiac, especially coronary CT [8].

Dual-energy computed tomography

Dual-energy CT (DECT) employs two energy levels of X-ray beams within a single detector setup, offering a higher temporal resolution of 125 ms [9]. Unlike single-energy X-ray tubes that emit a spectrum of X-rays, DECT provides two distinct energy levels, typically 80 and 140 kV [10]. This technology can create virtual monoenergetic images that minimize the blooming artifact from coronary stents and calcium plaques, potentially reducing the false-positive rate of coronary stenosis [11]. DECT also allows for the noninvasive analysis of the atomic number of coronary plaques, rather than just their CT density, providing insights into the composition of the plaques [12]. Recent studies show that DECT reduces beam hardening artifacts commonly seen when the superior vena cava is filled with concentrated contrast medium, thereby improving the accuracy of myocardial perfusion measurements [13].

To guarantee reliable diagnostic outcomes, CCT systems must provide comprehensive anatomical coverage of the entire heart, as well as deliver high temporal and spatial resolution and sufficient contrast differentiation among various tissues. The newly designed system tackles these requirements and the hardware constraints of 4 cm machines by offering uncompromised, high-performance cardiac imaging from the ground up.

Wide-coverage computed tomography and freeze motion correction systems

Currently, CT scanners were featured with 16 cm detectors, which include 256 detectors, enabling consistent whole-heart coverage in a single-beat acquisition, thus preventing issues such as beat-to-beat contrast banding and anatomical mis-registrations. The wide-coverage CT scanner also delivers high spatial resolution for cardiac imaging, with in-plane and longitudinal resolutions of 14.8 lp/cm and 18.2 lp/cm, respectively, aiding in assessments such as stent restenosis, vessel patency, and measurements in transcatheter aortic valve implantation. Studies indicate superior image quality with the 16 cm scanner over the 4 cm model for fast heart rates, demonstrating more frequent excellent and good quality studies and better contrast-to-noise and signal-to-noise ratios [14]. In addition, the 16 cm detector CT scanner allows for scanning at low radiation doses while maintaining excellent image quality even under high heart rate conditions [15].

Furthermore, the wide coverage CT incorporates modern image reconstruction technology, which applies intelligent coronary artery and whole-heart motion correction during reconstruction to minimize motion artifacts during scans [16,17]. With a gantry speed of 0.28 s/rotation, this technology effectively reduces motion artifacts to a level comparable to a 0.047 s gantry rotation, achieving an effective temporal resolution of 24 ms. This benefit is validated in both commercially available motion phantoms and mathematical cardiac phantoms with linear variable velocity motion. Snapshot freeze (SSF) significantly mitigates motion artifacts in the coronary artery, aortic annulus, and whole heart, thereby enhancing image quality and measurement accuracy, particularly in patients with high heart rates or during the systolic phase at a 40% R-R interval [17]. Furthermore, the use of SSF in image reconstruction technology ensures high-quality cardiac imaging in children with high heart rates [18].

Role of calcium score

The Coronary Artery Calcium Score (CACS) is a quantitative assessment of coronary artery calcifications, requiring ECG gating during scanning without the need for contrast medium delivery, thereby reducing the risk of drug allergies. The CACS serves as a crucial indicator for downgrading or upgrading the management of atherosclerotic cardiovascular disease (ASCVD), which includes both stroke and coronary heart disease [19]. According to the American Heart Association guidelines, a CACS of 0 suggests withholding statin therapy, whereas a CACS over 100 indicates the initiation of such treatment [20]. For low-risk individuals with a CACS of 0, repeating the measurement every 5–10 years is recommended to monitor changes [21]. In addition, guidelines suggest using CACS to guide aspirin therapy in individuals with a CACS over 100 who have a low bleeding risk and are not at low risk for ASCVD [22]. Emerging evidence indicates that a CACS over 220 carries similar risks to those enrolled in the Systolic Blood Pressure Intervention Trial, affecting hypertension management guidelines [23]. The increasing recognition of the CACS in stratifying ASCVD risk has led some healthcare providers such as UnitedHealthcare and Aetna to cover CACS, affirming its cost-effectiveness.

Cardiac perfusion evaluation by computed tomography angiography

CT is employed not only for anatomical assessments but also for evaluating cardiac function. Cardiac perfusion CT (CPCT) dynamically assesses myocardial perfusion status using contrast-enhanced CT. This method requires both rest and stress tests to be conducted sequentially. In case there is suspicious of myocardial scar formation, another session of CT scanning 10 min after contrast medium injection can detect delayed myocardial enhancement, which indicates the retention of iodinated contrast medium in the myocardial interstitial space, providing valuable insights into tissue viability [24]. A meta-analysis has estimated the sensitivity and specificity of CPCT to be 81% and 93%, respectively, highlighting its superior anatomical detail compared to single-photon emission computed tomography [25]. Although CPCT offers better anatomical information, concerns about radiation exposure from repeated scans remain. Nevertheless, ongoing advancements in CT technology are pushing toward greater applicability of CPCT as a standard method for cardiac perfusion studies.

Coronary computed tomography angiography

Coronary computed tomography angiography (CCTA) is noted for its high sensitivity (>95%) and negative predictive value (>95%), making it a significant noninvasive diagnostic method, particularly valuable for stable chest pain patients and reducing the likelihood of procedure-related complications compared to invasive coronary angiography [7]. Some studies suggest CCTA as the additional tool for evaluation for patients presenting with typical stable, atypical, or anginal symptoms, regardless of their coronary artery disease (CAD) history [25]. Figure 1 is the demonstration of CCTA in the diagnosis of right coronary artery stenosis (the figures are proved by the IRB committee in Hualien Tzu Chi Hospital: IRB No.: IRB112-240-B). CCTA is also indicated for investigating inconclusive cardiac functional tests or in asymptomatic patients at high risk of CAD. However, its use as a screening tool in asymptomatic or low-to-intermediate risk patients remains controversial [26].

Computed tomography-derived fractional flow reserve

Fractional flow reserve (FFRct) is a computational technique that simulates the pressure, flow, and fluid dynamics throughout the coronary tree without the need for additional medication, imaging, or radiation exposure [27]. It has been shown to result in 14% more revascularizations in stable chest pain patients compared to traditional myocardial perfusion imaging, highlighting its clinical relevance [28]. FFRct, processed from CCTA data, has demonstrated cost-effectiveness, particularly in individuals with intermediate to high risk of CAD, while proving ideal for those at low to intermediate risk [29]. Further evidence supports FFRct's utility in evaluating coronary artery conditions in patients with stable angina experiencing recurrent chest pain [30,31]. In addition, FFRct has proven effective in assessing coronary status postheart transplantation [32].

The overview of CACS, CCTA, and FFR was further illustrated in Figure 2, which describes the current indication of CACS, CCTA, and FFR in the diagnosis and screening of CAD.

Coronary anomalies by coronary computed tomography angiography

CCTA serves as the most effective noninvasive tool for diagnosing coronary artery anomalies (CAA), achieving greater spatial resolution and 3D reconstruction capabilities, which significantly improves diagnostic accuracy over invasive coronary angiography [33]. It detects CAAs such as anomalies of origin, course, and termination [34], crucial for clinical management, especially in young patients with ischemic symptoms linked to high-risk anatomical features such as interarterial courses, ostial tightness, and acute takeoff angles associated with sudden cardiac death in young athletes [35]. In addition, CCTA has been shown to identify myocardial bridging in 42.8% of cases [33], underscoring its utility in less obvious cases of CAA, which might not result in myocardial ischemia, especially in adults with possible atherosclerotic disease. In such cases, a combination of provocative tests using stress testing with electrocardiography (ECG), echocardiography, MRI, or myocardial perfusion scanning is recommended in the ESC 2020 guidelines for managing adult congenital heart disease [36].

Coronary computed tomography angiography in acute coronary syndrome

CCTA is increasingly employed in emergency departments for diagnosing non-ST elevation acute coronary syndrome (ACS), as documented in the 2023 ESC guidelines [37]. Although not routinely used as a first-line diagnostic tool in acute settings due to its inability to alter inhospital mortality or hospital stay lengths significantly, CCTA can effectively exclude ACS in patients with nondiagnostic electrocardiograms and ambiguous biomarker results [38]. Its high negative predictive value is crucial for ruling out coronary etiologies in acute chest pain scenarios, guiding further diagnostic and therapeutic strategies [39,40]. Moreover, it should be noted that increased levels of high-sensitivity troponin I are not necessarily indicative of coronary artery stenosis [41]. CCTA's high negative predictive value aids physicians in excluding atherosclerotic causes of myocardial injury, although its utility may be limited in scenarios such as tachycardia, established CAD, prior stents, and extensive coronary artery calcification per the 2023 ESC guidelines due to potential nondiagnostic results.

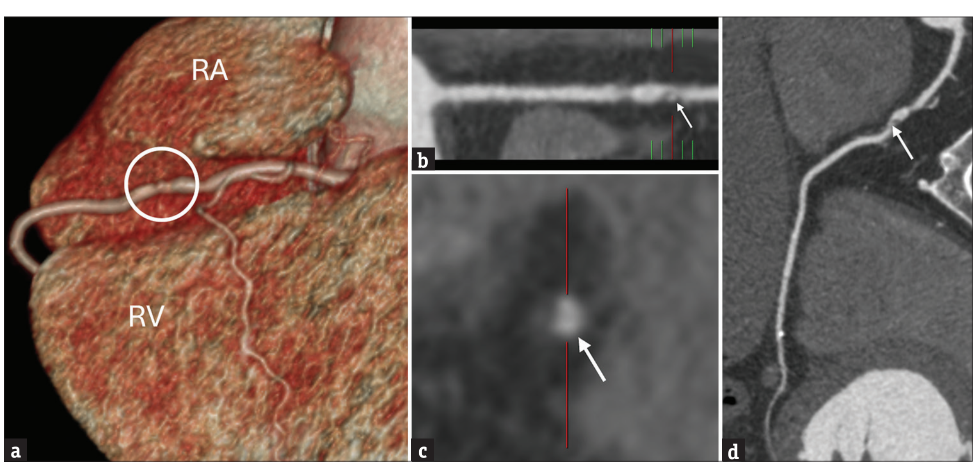

Figure 1: Coronary computed tomography angiography of a 56-year-old man. It showed severe (70%–95%, white circle) stenosis in the right coronary artery (RCA), confirmed by volume-rendering (a) as well as multiplanar reconstruction (b-d). Note spotty calcifications (arrow) in the plaque of RCA, implies vulnerable plaque. RA: Right atrium, RV: Right ventricle

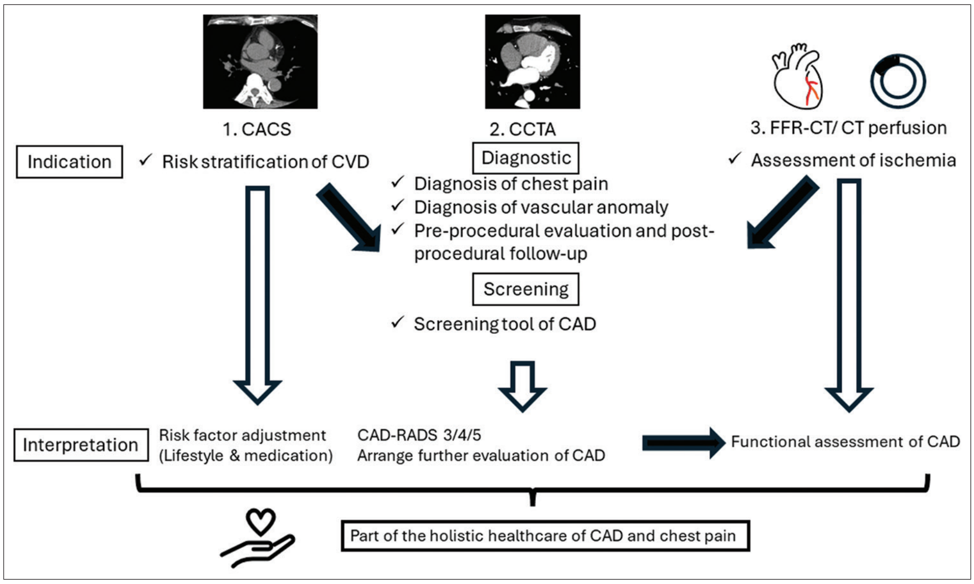

Figure 2: Overview of the state-of-the-art application of coronary computed tomography angiography (CCTA). This figure summarizes the indication of CCTA in the clinical practice, including (1) the utility of coronary artery calcium score to make the risk stratification, (2) the utility of CCTA for diagnosis and screening, (3) fraction flow reserve-CT and CT perfusion to assess functional assessment of coronary arterial territory. CACS: coronary artery calcium score, CCTA: coronary computed tomography angiography, CAD: coronary artery disease, CVD: cardiovascular disease, FFR: fraction flow reserve

Coronary computed tomography angiography in the evaluation of vulnerable plaque

Vulnerable plaque evaluation via CCTA offers insights into the biochemical composition of plaques that are at risk of causing acute coronary events. These plaques typically have a low CT attenuation value, ranging from −30 to 60 HU, which indicates a lipid-rich core, compared to fibrous plaques that register between 61 and 149 HU and calcified plaques which appear from 150 to 1300 HU [42]. A key feature in identifying high-risk plaques is the positive remodeling index, where a value >1.1 suggests significant vessel enlargement at the plaque site [43]. Another critical sign is the "napkin-ring sign," which depicts a plaque with a dense peripheral rim and a low-attenuation core, indicative of a necrotic core surrounded by a fibrous cap. Longitudinal studies have demonstrated that features such as low attenuation plaque, positive remodeling, and the napkin-ring sign are associated with increased risk for ACS events [44].

Coronary computed tomography angiography in planning coronary revascularization

In the 2013 Synergy Between Percutaneous Coronary Intervention With TAXUS and Cardiac Surgery (SYNTAX) revolution trial [45], CCTA was utilized for decision-making in percutaneous coronary intervention (PCI) and coronary artery bypass grafting (CABG) procedures. Currently, the SYNTAX I and II scores are accessible online (https://syntaxscore.org/calculator/start.htm) to evaluate the complexity of CAD and assist in selecting the appropriate revascularization method, either PCI or CABG.

Furthermore, CCTA is valuable for preprocedural planning of interventional procedures. Its uses include evaluating plaque in coronary arteries, predicting procedural success for chronic total occlusion PCI through CCTA-derived scores, and identifying coronary lesions that might benefit from additional techniques to enhance stent implantation success by evaluating calcium scores and calcific plaque distribution [46].

In addition, the ongoing FASTTRACK CABG trial (ClinicalTrials.gov: NCT04142021) explores the feasibility and safety of planning and executing CABG based on preprocedural CCTA, FFR-CT, and a postoperative 30-day CCTA study to assess the potential of CCTA in evaluating coronary anatomy without invasive coronary angiography [47].

Emerging technologies in cardiac computed tomography: Machine learning, dose reduction, and photon counting

Machine learning in coronary computed tomography angiography

The application of machine learning and deep learning in CCTA has markedly advanced the field, enhancing both the evaluation and interpretation of imaging data. Deep learning techniques have been applied to automate the quantification of calcified plaque volumes and severity of stenosis, achieving accuracy levels comparable to expert radiologists [48]. Furthermore, machine learning algorithms have facilitated the calculation of calcium scores from single-session contrast-enhanced CCT scans by utilizing virtual noncontrast scans derived from spectral CT imaging [49]. Advances in super-resolution reconstruction techniques have significantly reduced image noise and minimized artifacts associated with calcified plaques [50]. In addition, deep learning has been utilized to generate four-dimensional noise-reduction images, enhancing the visualization of coronary arteries and aiding in the planning of interventional procedures [51]. Predictive models based on deep learning have also been developed to estimate the success rates of PCIs in patients with chronic total occlusions, providing valuable preprocedural information that can guide clinical decisions [52].

Dose reduction in coronary computed tomography angiography

Dose-reduction strategies in CCTA have become a critical focus to minimize patient exposure to ionizing radiation while maintaining diagnostic accuracy. High-pitch spiral acquisition techniques cover the entire cardiac volume in a single gantry rotation, significantly reducing radiation exposure to as low as 1.7 mSv [53]. Prospective ECG triggering, which synchronizes image acquisition with the mid-diastolic phase of the cardiac cycle when the heart motion is minimal, has also been shown to reduce radiation doses by up to 90% compared to traditional retrospective ECG-gating methods [54,55]. The implementation of iterative reconstruction algorithms in image processing further reduces radiation dose by allowing for less noisy image reconstructions from fewer data points, potentially reducing doses by up to 40% [56,57]. Recent advancements in deep-learning image reconstruction have achieved additional dose reductions of up to 43% without compromising image quality [58]. Photon-counting CT technology, which enhances signal detection efficiency and improves contrast resolution, offers promising reductions in radiation dose while enhancing diagnostic capabilities [59].

Photon-counting computed tomography

Photon-counting computed tomography (PCCT), equipped with a revolutionary detector that counts the energy level of each received photon, enables the precise measurement of transmitted spectra [60]. The PCCT detector's smaller pixel size allows for higher resolution, up to 0.11 mm–25 mm, compared to traditional CT where the resolution is only 0.625 mm [61,62]. It effectively reduces the blooming artifact from calcified plaques or metallic coronary stents [63]. Ongoing prospective studies are expected to further highlight the benefits of PCCT [61,63,64].

Conclusion

Over the last two decades, advancements in CT technology have solidified the role of CCT as a pivotal noninvasive diagnostic tool in cardiology. With its high sensitivity for detecting coronary artery stenosis and a robust framework for functional cardiac assessment, CCT stands as a cornerstone in the noninvasive diagnosis and management of cardiac diseases. Innovations such as photon-counting CT and deep learning algorithms have pushed the boundaries further, offering higher-resolution images and significant reductions in radiation exposure. Looking forward, the integration of advanced computational methods and continued technological refinement is expected to expand the utility of CCT, enhancing its diagnostic accuracy and reducing procedural risks. The future of CCT is poised to deliver greater clinical value, influencing both the early detection of cardiovascular diseases and the precision of therapeutic interventions.

Declaration of ethics patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given his consent for his images and other clinical information to be reported in the journal. The patient understands that his name and initials will not be published and due efforts will be made to conceal identity, but anonymity cannot be guaranteed.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of interest

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