Curr Cardiovasc Imaging Rep (2014) 7:9274
DOI 10.1007/s12410-014-9274-0

Coronary CT Angiography in Patients with Atrial Fibrillation

Tendoh Timoh · Samad Zaheeruddin · Pranay Krishnan · Monvadi B. Srichai

Published online: 23 May 2014

Abstract Coronary computed tomography angiography (CTA) has become a very useful non-invasive test in the evaluation of coronary artery disease (CAD). Patients with arrhythmias, particularly atrial fibrillation (AF), are often difficult to study with coronary CTA due to difficulties in image acquisition and temporal resolution. About a quarter of patients with AF have concomitant CAD, and knowledge of underlying CAD is important in the management of these patients. Although the presence of AF has been considered a relative contraindication for coronary CTA, technological developments in CT scanner design, acquisition and post processing techniques have improved the ability to consistently obtain diagnostic image quality with similar diagnostic performance characteristics as in patients with sinus rhythm. This article reviews the current data on use of coronary CTA in the evaluation of CAD in patients with AF.

This article is part of the Topical Collection on *Cardiac Computed Tomography*

T. Timoh
Medstar Washington Hospital Center, Department of Cardiology, Medstar Georgetown University Hospital, 110 Irving St. NW, Washington, DC 20010, USA
e-mail: Tendoh.F.Timoh@medstar.net

S. Zaheeruddin
Department of Internal Medicine, Medstar Georgetown University Hospital, 3800 Reservoir Rd NW, 5 PHC, Washington, DC 20007, USA
e-mail: Samad.Zaheeruddin@gunet.georgetown.edu

P. Krishnan
Department of Radiology, Medstar Georgetown University Hospital, 3800 Reservoir Road NW, Washington, DC 20007, USA
e-mail: pranay.krishnan@gunet.georgetown.edu

M. B. Srichai (✉)
Medstar Heart Institute, Medstar Georgetown University Hospital, 3800 Reservoir Road NW, 5 PHC, Washington, DC 20007, USA
e-mail: srichai@alum.mit.edu

Keywords Coronary computed tomography angiography · Atrial fibrillation · Coronary artery disease · Computed tomography

Introduction

Coronary computed tomography angiography (CTA) has become a very useful non-invasive test in the evaluation of coronary artery disease (CAD), including detection of calcified and non-calcified atheroma and in quantifying the degree of luminal coronary stenosis. CCTA has a high diagnostic accuracy for identification of significant (>50 % luminal stenosis) CAD, with high sensitivity and specificity, and excellent negative predictive values [1–5]. Although useful, this technique is not without its pitfalls. One of the most often encountered difficulties is the evaluation of CAD in patients with arrhythmias, stemming from difficulties in image acquisition and temporal resolution.

Atrial fibrillation represents the most common arrhythmia in the world, affecting approximately 2.2 million people in the United States and 4.5 million in the European Union [6, 7]. The prevalence of AF increases with age, from 2 % at age 60-69 years to almost 9 % at age 80-89 years [8]. AF is frequently associated with other cardiac conditions including CAD, with prevalence of approximately 25 % [9]. In fact, CAD may be one of the potential etiologic factors for AF [10]. The presence of CAD has been related to recurrent AF episodes, symptoms, and increased risk of death [11, 12]. Patients diagnosed with first episode of AF but without established CAD represent a high risk cohort at increased risk for coronary ischemic events and mortality [13]. Finally, it has been observed that obstructive CAD occurs more frequently in patients with a history of AF compared to those without a history of AF [14]. Thus, knowledge of underlying CAD is important in the management of patients with AF, prompting diagnostic testing for evaluation of underlying CAD.

In the past, AF was considered a relative contraindication to coronary CTA [15] primarily due to degradation in image quality related to marked variability of the cardiac cycle leading to significant phase mismatch and coronary motion artifact. Advances in CT acquisition techniques have improved the ability to obtain diagnostic quality images even with cardiac arrhythmias. In this review, we will examine the current data on use of coronary CTA in patients with atrial fibrillation, including current guidelines, available acquisition protocols, and recommended approaches. We will also highlight areas for future research and technological advancement.

Challenges of Coronary CTA in Atrial Fibrillation

Patients with AF are often referred for non-invasive stress testing for assessment of underlying CAD. There are notable limitations with non-invasive stress tests in the setting of arrhythmias [16–18], and patients are often referred to invasive coronary angiography for definitive evaluation of CAD. Similarly, arrhythmias pose problems in the evaluation of CAD with coronary CTA, and patients with arrhythmias were often excluded from large studies evaluating the diagnostic accuracy of coronary CTA for CAD.

A main challenge with coronary artery imaging in general is the small diameter of the arteries ranging from 2-5 mm at the origin, tortuous course, and complex physiologic motion due to cardiac and respiratory motion. Even with breath holding, the coronary arteries have a rapid movement ranging from 16 to 117 mm/s during the cardiac cycle [19]. Thus, optimal image quality, particularly when imaging small coronary arteries, relies on the ability to "freeze" cardiac motion. Current generation CT scanners have an absolute temporal resolution of about 75-200 ms depending on the scanner and acquisition protocol, which is significantly decreased compared to conventional coronary angiography which has a temporal resolution of approximately 6 ms [20]. Thus, in order to generate motion-free images for coronary CTA, the heart structures need to remain still for this period of time. In addition, depending on how wide the CT scanner detectors are and how the heart lies in the chest, multiple gantry rotations are often needed to acquire a volumetric dataset through the whole heart.

Coronary CTA imaging is often performed in conjunction with electrocardiographic (ECG) gating with data reconstruction set to occur during the mid diastolic phase, or rest period when there is minimal cardiac motion. However, depending on the heart rate and coronary artery of interest, there may be significant variability in the duration of the rest period [21], which has been shown to have significant implications on coronary CTA image quality [22, 23]. With most CT scanners, data acquisition occurs over multiple cardiac cycles that are then pieced together to form the volumetric dataset. Thus, optimal imaging of the coronary arteries requires a slow and regular heart rate (HR) [24, 25], ideally less than 65 beats per minute [26]. Patients with AF provide a challenge with coronary CTA imaging due to difficulty achieving these goals of slow and regular HR needed to optimize coronary artery image quality. The current guidelines for cardiac CT have no specific recommendations concerning coronary CTA imaging in AF [27, 28], although the appropriate use criteria for cardiac CT from 2010 do not recommend the use of coronary CTA for evaluation of CAD when AF is the underlying rhythm during imaging [15]. However, there has been significant research in the past few years regarding this topic, which deserves further attention.

Current Methods for Optimizing Image Quality in the Presence of Arrhythmias

Modulation of HR

Image quality with coronary CTA is dependent on heart rate and heart rate variability, and is best optimized in the setting of a slow and regular heart rate [22–25]. The use of oral and intravenous beta-blockers and non-dihydropyridine calcium channel blockers, which have been shown to reduce heart rate, minimize ectopy, and decrease heart rate variability [24, 29, 30], leading to improved image quality [24, 29], are highly encouraged to modulate HR, particularly in patients with AF [31, 32]. In extreme cases, temporary pacing has been used as a method to modulate HR prior to imaging [33].

Data Acquisition Mode

Coronary CTA imaging is commonly performed with retrospective ECG-gated helical techniques or prospective ECG-triggered axial techniques. The latter technique with minimized duration of the data acquisition window is the preferred mode in patients who have stable sinus rhythm and low heart rates in order to minimize radiation exposure to patients [34]. Newer acquisition techniques such as prospective ECG-triggered high pitch helical scan are also available on dual source CT scanners with the ability to lower radiation exposure even further for patients with slow and regular heart rates [35]. However, for patients with irregular heart rhythms, high heart rates or both, retrospective ECG-gated helical scanning is often preferred to allow for flexible data reconstruction during any phase of the cardiac cycle [36••].

Optimal Phase Selection

The coronary arteries demonstrate consistent patterns of rapid motion during the cardiac cycle, with maximal motion occurring during ventricular contraction in early to mid systole, during rapid ventricular filling in early diastole, and during atrial contraction in late diastole [19, 37]. This is accompanied by two periods of relatively quiescent phases occurring during mid to late systole and mid diastole. As previously mentioned, coronary CTA data sets are often acquired and reconstructed in the mid diastolic phase to optimize image quality. This reconstruction phase may be expressed as a percentage of the R-R interval (e.g., 70 %) or an absolute delay from the prior (+650 ms) or preceding (-350 ms) R wave. The relatively fast HR and variable R-R interval in patients with AF makes it problematic to select the classical mid diastolic phase for image reconstruction [32, 36••, 38]. Despite the shorter duration of systole when compared to diastole, the systolic duration is relatively constant and less affected by changes in HR [23, 38–41]. With higher heart rates, the duration of the mid diastolic rest period shortens significantly more than that of the mid to late systolic period [42]. Because of the beat to beat variability in the diastolic time period in patients with AF, acquisition and reconstruction algorithms have focused on the shorter but less variable systolic phase.

Multiple studies have shown that image acquisition and reconstruction in the late systolic phases in patients with AF provide the best diagnostic image quality [32, 37, 39, 43•]. The optimal timing of systolic phase reconstructions that yield the best diagnostic images falls around 250-300 ms after the peak of the R-wave [38, 41, 43•, 44]. This correlates to intervals located at 30-35 % of the R-R interval in patients with low heart rates or 40-45 % in patients with high heart rates [41], although the use of absolute delay times rather than percentages has been associated with improved image quality in patients with AF [45]. Evaluation of multiple reconstruction phases within late systole and very early diastole is often needed to improve diagnostic evaluation of coronary arteries in patients with AF [32, 39, 43•].

Advanced Post Processing

Advanced post processing techniques such as ECG editing capability allow users to modify the position of the temporal windows. This technique can enable correction of or compensation for artifacts that may occur due to heart rhythm irregularities, thereby improving overall image quality [31, 44, 46, 47] (Fig. 1). This technique is best applied in the setting of retrospective ECG-gated helical acquisitions, which allow for flexible reconstructions throughout the cardiac cycle.

Advanced Acquisition Algorithms

Improvements in image acquisition using advanced arrhythmia rejection/compensation algorithms are offered by nearly all vendors as a means to limit radiation exposure. In most cases, the CT scanner will monitor the R-R interval for an appropriate heart beat for imaging, and will maintain the same scan location and suspend acquisition until the next heart beat in the event of early ectopic beats (e.g., premature atrial contractions) [31, 43•]. The effectiveness of these advanced algorithms in reducing overall radiation dose compared to traditional acquisition algorithms has not yet been proven [36••].

Temporal Resolution

Current generation CT scanners have a minimum gantry rotation time (time required to complete a 360° rotation) between 280 and 400 ms depending on manufacturer and model. The routine use of half-scan reconstruction results in an effective temporal resolution of approximately one half the time

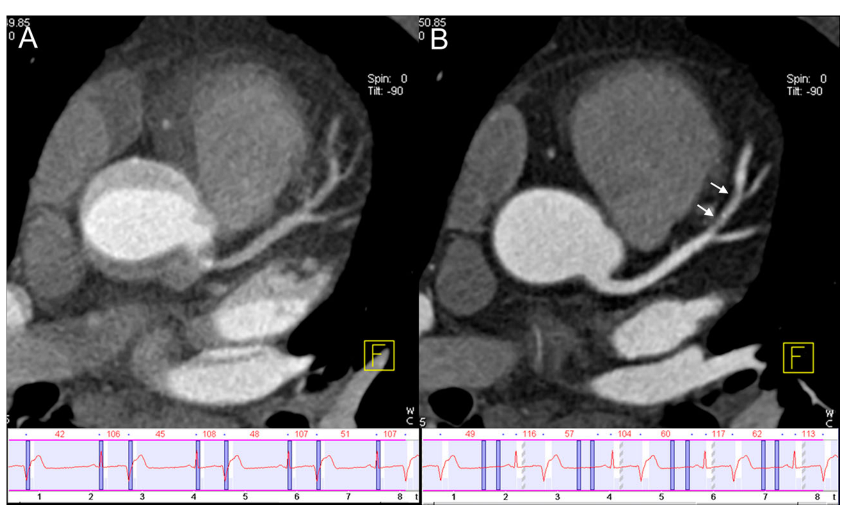

Fig. 1 Example of ECG-editing technique to improve image quality in arrhythmia. There is improvement in visualization of the LAD which demonstrates no significant disease in the proximal segment, but significant stenoses in its mid segment (arrows)

required for the CT scanner to complete a full 360° rotation or 140 to 200 ms [48]. Additional methods to improve effective temporal resolution include the use of partial scan reconstructions from multiple adjacent cardiac cycles or multisegment reconstruction algorithms, but this technique is particularly susceptible to misregistration artifacts related to beat to beat variability and ectopic beats, as occurs in AF [49]. In 2006, dual source CT (DSCT) scanners with two sets of x-ray sources and two sets of detectors offset 90° from each other in the CT gantry allowed for additional improvement in temporal resolution to approximately 83 ms by combining data from the two sets of detectors with only a 90° gantry rotation and without the need to combine multiple cardiac cycles [44], which is ideal for imaging patients with AF compared to multisegment reconstructions. The improvement in temporal resolution offered by dual source scanners has been one of the driving forces of research into the utility of coronary CTA imaging in AF.

Single Heart Beat Imaging

Wide detector coverage scanners such as the 320-slice CT scanner has the ability to provide whole heart imaging with up to 16 cm through plane coverage in a single gantry rotation [50]. Advanced acquisition protocols including acquisition over multiple heart beats (up to 4 at maximum) with arrhythmia rejection can be performed to allow for selection of data reconstruction from a single heart beat with the longest R-R interval in patients with significant variability in the R-R interval and to allow for multisegment reconstruction to improve effective temporal resolution as needed. This greatly minimizes misregistration artifacts that may occur from the piecing together of data from multiple cardiac cycles with varying R-R intervals that often occurs in AF.

Radiation Exposure

There exists a lifetime attributable risk of cancer with the use of coronary CTA [34, 51], although that risk is very small in comparison to other life risks including risk of cardiovascular disease [52]. Radiation dose reduction techniques should be routinely employed whenever possible to reduce overall radiation exposure to the patient. As mentioned previously, the method of data acquisition can largely affect overall radiation exposure. In the absence of arrhythmias, low dose scan protocols including prospective ECG-triggered axial scan or retrospective ECG-gated helical scan with dose modulation should be utilized whenever possible [34]. In the presence of arrhythmias such as AF, however, retrospective ECG-gated helical scanning without dose modulation has been advocated to allow for flexibility in data reconstruction throughout the cardiac cycle at the expense of increased radiation exposure to the patients [36••]. Advances in CT technology found in newer generation scanners offer dose reduction options such as automated exposure control, automated kVp selection, and iterative reconstruction that offer the ability to reduce radiation dose and improve image quality for all coronary CTA patients [53]. These new CT systems in conjunction with advanced acquisition protocols and settings designed specifically for patients with arrhythmias have the potential to improve dose optimizing techniques for patients with AF without compromising image quality.

Studies of CCTA in Atrial Fibrillation

There have been several suggested techniques in coronary CTA imaging for addressing the high heart rate and increased heart rate variability that commonly occurs with atrial fibrillation. Early studies with single source CT scanners (SSCT) evaluated the effect of different reconstruction phases [45], multisegment techniques to improve effective temporal resolution [32], and ECG editing to improve temporal registration of data from different cardiac cycles [32, 47, 54] as methods to improve image quality in the setting of AF. Although these techniques were shown to improve overall image quality, there was still a considerable number of coronary segments with limited image quality affecting overall diagnostic performance with negative correlation between image quality and increasing mean heart rate and heart rate variability [32].

The introduction of dual source CT (DSCT) scanners with significant improvement in temporal resolution without the use of multisegment reconstruction represented a leap forward for coronary CTA evaluation of patients with AF. Building on techniques used in earlier studies, including optimal phase reconstruction and ECG editing, several studies demonstrated significant improvement in image quality and diagnostic performance of coronary CTA with DSCT (Fig. 2) compared to older SSCT systems [55]. Also the influence of heart rate and heart rate variability on overall image quality is less with DSCT compared with SSCT [24, 25], likely because the temporal resolution remains constant at 83 ms at all heart rates for DSCT whereas the multisegment reconstruction algorithms used in SSCT reach a comparable temporal resolution only at specific heart rates [41].

Wide detector scanners offer other significant advantages in the setting of AF with the ability to scan the whole heart in a single heart beat, minimizing misregistration artifacts due to varying cardiac cycles [31, 50]. Studies using 320-detector scanners for the evaluation of CAD in patients with AF have demonstrated high diagnostic image quality [31, 50, 56, 57] and diagnostic accuracy [56, 57] (Table 2). However, the limited temporal resolution offered by these scanners at present often requires data acquisition from multiple cardiac cycles in patients with AF in order to utilize multisegment reconstruction techniques to improve effective temporal

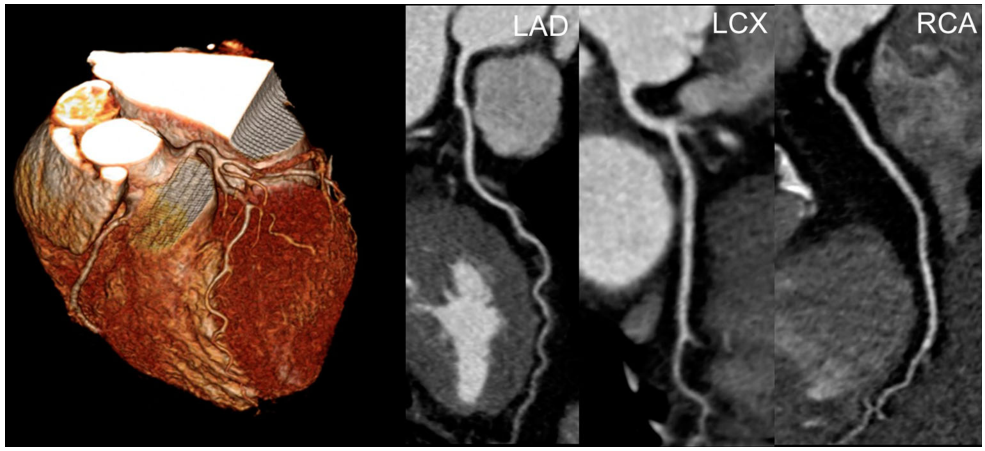

Fig. 2 82 year old man with persistent atrial fibrillation who underwent coronary CTA for evaluation of chest pain symptoms and pre-procedural evaluation prior to radiofrequency ablation. Patient had a mean heart rate 115 bpm with significant variability between 63-171 bpm. Patient was scanned on 64-slice DSCT using prospective ECG-triggered axial scanning with data window set at 250-400 ms

resolution [31, 50, 56] or to ensure a long enough cycle length for optimal image reconstruction [50], which increases overall radiation dose compared to single heart beat scanning [58].

Currently, much attention has been focused on reducing radiation exposure in cardiac CT imaging. There have been a number of acquisition techniques developed that focus on providing robust, high quality diagnostic coronary CTA imaging with low radiation exposure for difficult to image patients including those with arrhythmias such as AF. The use of prospective ECG-triggered protocols, often with arrhythmia rejection schemes and narrow data acquisition windows, has been shown to reduce overall radiation exposure with similar rates of non-diagnostic coronary segments compared to retrospective ECG-gated protocols [43•, 57]. High pitch helical scanning using a double cycle acquisition method is another novel technique that has been shown to provide high diagnostic image quality with very low radiation exposure (<2 mSv) [59•]. Table 1 provides a summary of the imaging parameter data from studies of coronary CTA in patients with AF.

Studies that focused on evaluating the diagnostic accuracy of coronary CTA compared to conventional coronary angiography for patients with AF are summarized in Table 2. A recent systematic review and meta-analysis on the diagnostic accuracy of coronary CTA in patients with AF was performed by Vorre and colleagues and included seven studies performed on various CT scanners including 64-slice SSCT, DSCT, and 320 MDCT [36••]. At per-patient analysis compared to conventional coronary angiography, the sensitivity, specificity, positive predictive value, and negative predictive values were 94 % (85-98 %), 91 % (85-94 %), 79 % (66-85 %), and 97.5 % (94-99 %) respectively [36••]. The high sensitivity and negative predictive value is similar to results of prior studies in patients with sinus rhythm [60]. With the improved temporal resolution offered by DSCT, Sun and colleagues performed a systematic review on the diagnostic accuracy of coronary CTA in AF using DSCT scanners [61••]. Compared to conventional coronary angiography, patient level analysis demonstrated sensitivity, specificity, positive likelihood ratio, and negative likelihood ratio of 97.7 % (85.6-99.7 %), 83.8 % (73.6-90.6 %), 6.0 (3.6-10.1), and 0.03 (0.004-0.2), respectively [61••]. The similar diagnostic performances in AF compared to sinus rhythm noted in both of these meta-analyses were at the expense of comparatively higher radiation doses [36••, 44, 61••].

Current Experience, Controversies and Beyond

Despite the available data on the comparable image quality and diagnostic accuracy of coronary CTA for evaluating CAD in patients with AF when compared to that of patients with sinus rhythm, many centers are hesitant to adopt routine coronary CTA imaging for patients with AF. A major limiting factor is that most institutions do not have DSCT or 320-slice CT scanners that were utilized in most of the studies with demonstrated efficacy in AF patients. An additional limitation is that several studies documenting the usefulness of coronary CTA in AF utilized ECG-editing to improve image quality or required review of multiple datasets in a single exam in order to adequately review each coronary segment. As these post processing techniques in data analysis can be fairly time consuming, often requiring advanced skills and expertise, as in the case of ECG-editing, these services are often not readily available on a routine basis in a busy clinical practice.

There has been much criticism in the reported success rates of the aforementioned studies in coronary CTA imaging of patients with AF. The small number of individual studies and total number of patients included and the methodology applied with respect to non-diagnostic segments were considered significant limitations of the meta-analysis reported by Vorre and colleagues [36••, 62, 63]. Another criticism was the inclusion of SSCT scanners in a meta-analysis mostly powered with data from DSCT, limiting the ability to generalize the results across all types of CT scanners [36••, 62, 63]. Classically, there is a negative correlation between heart rate variability and image quality with SSCT scanners [24] that is

Table 1 Imaging parameters for different CCTA techniques in atrial fibrillation

Author	No of patients	Type of scanner	Imaging technique	Mean HR (bpm)	Min-max HR (bpm)	Mean HR variability (bpm)	Mean age (years)	% non-diagnostic segments	Mean effective radiation dose (mSv); dose length product (mGy-cm)
Kondo et al. 2013 [57]	*75*	320-MDCT (Aquilon, Toshiba)	PG-axial (single); number of cycles and data window varied based on HR	*54.7*	*NA*	*NA*	*71*±10	*1.3 (patient level)*	*9.5*±6.6; 680
Srichai et al. 2013 [43•]	30	128-slice DSCT (Definition, Siemens)	PG-axial; data window 250-400 ms	82±20	48-131	71±22 (29-108)	64±13	2.1	6.5±2.4; 464
Wang et al. 2013 [59•]	47	128-slice DSCT (Definition, Siemens)	PG-double high pitch helical	1st scan: 70.6±14.8 2nd scan: 71.6±18.3	1st scan: 38-114 2nd scan: 37-124	1st scan: 56.9±21.7 (9-90) 2nd scan: 37.4±24.8 (7-100)	64.5±12.1	1st scan: 1.3 2nd scan 2.5	1.3±0.4; 93
Xu et al. 2013 [69•]	50	128-slice DSCT (Definition, Siemens)	PG-axial; data window 30-50 % and 200-400 ms	90.2±20.7	62-157	69.6±20.9 (30-119)	58.7±10.9	0.6	4.3±1.9; 306
Xu et al. 2013 [69•]	50	128-slice DSCT (Definition, Siemens)	RG- helical	90.5±22.8	53-156	65.7±19.3 (25-101)	55.8±14.0	3.5	12.0±5.3; 855
Uehara et al. 2011 [58]	46	320-MDCT (Aquilon, Toshiba)	RG-axial (single); number of cycles varied based on HR	69±23	NA	NA	69.7±9.9	2.1	NA
Xu et al. 2011 [56]	37	320-MDCT (Aquilon, Toshiba)	PG-axial (single); number of cycles and data window varied based on HR	88±23.4	38-151	24.5±17 (0-60)	60.5±6	3.2	10.7±3.9; 765
Zhang et al. 2011 [39]	22	64-slice DSCT (Definition, Siemens)	RG-helical	89±8	80-118	NA	72.1±8.3	3	8.7±3.2; 619
Marwan et al. 2010 [44]	60	64-slice DSCT (Definition, Siemens)	RG-helical	70±15	32-107	NA	71±7	NA	16±5; 1186
Bettencourt et al. 2009 [70]	32	64-slice DSCT (Definition, Siemens)	RG-helical	NA	NA	NA	NA	NA	9.1±2.5; 653
Pasricha et al. 2009 [31]	12	320-MDCT (Aquilon, Toshiba)	RG/PG-axial (single); number of cycles varied base on HR, data window 65-99 % for PG	66.5±10	NA	NA	67	4	15.9; 1134
Rist et al. 2009 [38]	68	64-slice DSCT (Definition, Siemens)	PG-axial; data window 30-80 %	77±25	26-181	NA	64±11	8	13.3±6; 943
Yang et al. 2009 [32]	60	64-slice SSCT (Aquilon, Toshiba)	RG-helical	90±13.1	47-153	19.4±7 (8-39)	58.7±12.9	3	11.9±3.5; 853
Matsumoto et al. 2008 [47]	19	64-MDCT (Sensation-64, Siemens)	RG-helical	56.6±5.8	NA	12.1±3.7	69±9	0	NA
Wang et al. 2008 [55]	30	64-slice DSCT (Definition, Siemens)	RG-helical	81.7±16.0	54-110	65.7±25.5 (27-111)	69.0±9.2	1.4	NA
Wolak et al. 2008 [71]	24	64-slice DSCT (Definition, Siemens)	RG-helical	74±14	36-173	47.8±27.4	68.5 +/- 14	10	21.6±6.5; 1541
Oncel et al. 2007 [40]	15	64-slice DSCT (Definition, Siemens)	RG-helical	83±9	69-131	NA	58.5 +/- 9	6	11.4±1.1; 812

Effective radiation doses were calculated for each study in accordance with Society of Cardiac Computed Tomography guidelines based on a conversion factor of 0.014 mSv/mGy*cm [34]. *MDCT* multidetector computed tomography, *DSCT* dual source computed tomography, *PG* prospective gating, *RG* retrospective gating, *HR* heart rate, *NA* not available [31, 32, 38–40, 43•, 44, 47, 55–58, 59•, 69•, 70, 71]

Table 2 Diagnostic accuracy of CCTA (vs. invasive coronary angiography) in atrial fibrillation

Author	No of patients	Type of scanner	Imaging technique	Mean HR (bpm)	% non-diagnostic segments	Sensitivity (per patient /segment/ artery)	Specificity (per patient /segment/ artery)	PPV (per patient /segment/ artery)	NPV (per patient / segment/ artery)
Kondo et al. 2013 [57]	17	*320-MDCT (Aquilon, Toshiba)*	*PG-axial (single); number of cycles and data window varied based on HR*	NA	1.3 (patient level)	100/66.7/NA	80 / 94.2/ NA	92.3/62.5/NA	100/95.1/ NA
Xu et al. 2011 [56]	37	320-MDCT (Aquilon, Toshiba)	PG-axial (single); *number of cycles and data window varied based on HR*	88±23	3.2	90/90/93.8	92.6/99.3/ 96.8	81.8/85.7/ 83.3	96.2/99.5/ 98.9
Zhang et al. 2011 [39]	22	64-slice DSCT (Definition, Siemens)	RG-helical	89±8	3	100/74/85	89/97/96	93/81/85	100/96/96
Marwan et al. 2010 [44]	60	64-slice DSCT (Definition, Siemens)	RG-helical	70±15	NA	100/NA/95	85/NA/94	67/NA/60	100/NA/99
Tsiflikas et al. 2010 [72]	25	64-slice DSCT (Definition, Siemens)	RG-helical	NA	NA	NA/72/NA	NA/89/NA	NA/61/NA	NA/92/NA
Bettencourt et al. 2009 [70]	32	64-slice DSCT (Definition, Siemens)	RG-helical	NA	NA	80/NA/NA	93/NA/NA	67/NA/NA	96/NA/NA
Rist et al. 2009 [38]	21	64-slice DSCT (Definition, Siemens)	PG-axial , data window 30-80 %	77±25	0	90/89/NA	82/98/NA	82/76/NA	90/99/NA
Yang et al. 2009 [32]	60	64-slice SSCT (Aquilon, Toshiba)	RG-helical	90±13	3	100/86.4/NA	96/99.3/NA	80/79/NA	100/99.6/NA
Oncel et al. 2007 [40]	15	64-slice DSCT (Definition, Siemens)	RG-helical	84±9	6	89/87/87	83/98/96	89/77/87	83/99/96

DSCT dual-source CT, *MDCT* multi-detector CT, *RG* retrospective gated, *PG* prospective-gated, *HR* Heart Rate, *bpm* beats per minute, *NA* not applicable, *PPV* positive predictive value, *NPV* negative predictive value [32, 38–40, 44, 56, 70, 72] not apparent with DSCT and 320-MDCT studies [64, 65•]. Further limitations are the historically small number of relevant studies that exist in this patient group [36••, 61••], and that although analysis of CAD at the per patient level is good, there may be decreased diagnostic performance at the artery and segment levels [61••] (Table 2).

As our population ages, we can only expect a growth in the incidence of AF and a resultant increase in the number of patients with AF referred for non-invasive evaluation to exclude significant CAD. The recent growth in catheter based therapies for AF has led to significantly increase use of cardiac CT for anatomic evaluation of the left atrium, interatrial septum and pulmonary veins, exclusion of left atrial appendage thrombus, and 3-dimensional integration into electroanatomical mapping systems to facilitate performance of catheter ablation therapies [66–68]. Cardiac CT scans in this setting are often performed with substantially lower spatial and temporal resolution compared to coronary CTA scans, often without the use of ECG gating or triggering, in order to minimize radiation exposure [34]. With the need to contain burgeoning medical costs, sometimes brought about by frequent diagnostic testing, as well as respect for limiting the amount of extraneous medical radiation to our patients, the ability to provide information on the coronary arteries in addition to anatomic information needed for catheter ablation therapies as a combination study is extremely attractive. To reach this goal, further development of CT scanners and acquisition protocols that provide consistent diagnostic image quality with low radiation exposure in patients with arrhythmias are needed. This will likely necessitate the use of multi detector scanners with high temporal resolution and whole heart single heart beat scanning. Finally, post processing techniques that are easily implemented with the goal of improving overall image quality of a single volumetric dataset will aid in improving the workflow associated with diagnostic analysis of these studies.

Conclusions

In conclusion, coronary CTA can be performed for evaluation of CAD in patients with AF, but remains difficult for routine implementation given the limited available data as compared to coronary CTA with sinus rhythm, considerable expertise needed to optimize image acquisition and post processing of datasets, and necessary scanner technology.

Compliance with Ethics Guidelines

Conflict of Interest Tendoh Timoh, Samad Zaheeruddin, Pranay Krishnan, and Monvadi B. Srichai declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Vanhoenacker PK, Heijenbrok-Kal MH, Van Heste R, Decramer I, Van Hoe LR, Wijns W, et al. Diagnostic performance of multidetector CT angiography for assessment of coronary artery disease: meta-analysis. Radiology. 2007;244(2):419–28.
2. Mowatt G, Cummins E, Waugh N, Walker S, Cook J, Jia X, et al. Systematic review of the clinical effectiveness and cost-effectiveness of 64-slice or higher computed tomography angiography as an alternative to invasive coronary angiography in the investigation of coronary artery disease. Health Technol Assess. 2008;12:iii–iv. ix-143.
3. Paech DC, Weston AR. A systematic review of the clinical effectiveness of 64-slice or higher computed tomography angiography as an alternative to invasive coronary angiography in the investigation of suspected coronary artery disease. BMC Cardiovasc Disord. 2011;11:32.
4. Li S, Ni Q, Wu H, Peng L, Dong R, Chen L, et al. Diagnostic accuracy of 320-slice computed tomography angiography for detection of coronary artery stenosis: meta-analysis. Int J Cardiol. 2013;168(3):2699–705.
5. Menke J, Unterberg-Buchwald C, Staab W, Sohns JM, Seif Amir Hosseini A, Schwarz A. Head-to-head comparison of prospectively triggered vs retrospectively gated coronary computed tomography angiography: meta-analysis of diagnostic accuracy, image quality, and radiation dose. Am Heart J. 2013;165(2):154–63 e3.
6. Fuster V, Ryden LE, Cannom DS, Crijns HJ, Curtis AB, Ellenbogen KA, et al. 2011 ACCF/AHA/HRS focused updates incorporated into the ACC/AHA/ESC 2006 guidelines for the management of patients with atrial fibrillation: a report of the American College of Cardiology Foundation/American Heart Association Task Force on practice guidelines. Circulation. 2011;123(10):e269–367.
7. Haissaguerre M, Jais P, Shah DC, Takahashi A, Hocini M, Quiniou G, et al. Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins. N Engl J Med. 1998;339(10):659–66.
8. Wolf PA, Abbott RD, Kannel WB. Atrial fibrillation as an independent risk factor for stroke: the Framingham Study. Stroke. 1991;22(8):983–8.
9. Lok NS, Lau CP. Presentation and management of patients admitted with atrial fibrillation: a review of 291 cases in a regional hospital. Int J Cardiol. 1995;48(3):271–8.
10. Lip GY, Beevers DG. ABC of atrial fibrillation. History, epidemiology, and importance of atrial fibrillation. BMJ. 1995;311(7016):1361–3.
11. Corley SD, Epstein AE, DiMarco JP, Domanski MJ, Geller N, Greene HL, et al. Relationships between sinus rhythm, treatment, and survival in the Atrial Fibrillation Follow-Up Investigation of Rhythm Management (AFFIRM) study. Circulation. 2004;109(12):1509–13.
12. Curtis AB, Gersh BJ, Corley SD, DiMarco JP, Domanski MJ, Geller N, et al. Clinical factors that influence response to treatment strategies in atrial fibrillation: the Atrial Fibrillation Follow-up Investigation of Rhythm Management (AFFIRM) study. Am Heart J. 2005;149(4):645–9.
13. Miyasaka Y, Barnes ME, Gersh BJ, Cha SS, Bailey KR, Seward JB, et al. Coronary ischemic events after first atrial fibrillation: risk and survival. Am J Med. 2007;120(4):357–63.
14. Nucifora G, Schuijf JD, Tops LF, van Werkhoven JM, Kajander S, Jukema JW, et al. Prevalence of coronary artery disease assessed by

multislice computed tomography coronary angiography in patients with paroxysmal or persistent atrial fibrillation. Circ Cardiovasc Imaging. 2009;2(2):100–6.
15. Taylor AJ, Cerqueira M, Hodgson JM, Mark D, Min J, O'Gara P, et al. ACCF/SCCT/ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR 2010 Appropriate Use Criteria for Cardiac Computed Tomography. A report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, the Society of Cardiovascular Computed Tomography, the American College of Radiology, the American Heart Association, the American Society of Echocardiography, the American Society of Nuclear Cardiology, the North American Society for Cardiovascular Imaging, the Society for Cardiovascular Angiography and Interventions, and the Society for Cardiovascular Magnetic Resonance. J Cardiovasc Comput Tomogr. 2010;4(6):407 e1–33.
16. Hobday TJ, Pellikka PA, Attenhofer Jost CH, Oh JK, Miller Jr FA, Seward JB. Chronotropic response, safety, and accuracy of dobutamine stress echocardiography in patients with atrial fibrillation and known or suspected coronary artery disease. Am J Cardiol. 1998;82(11):1425–7. *A9*.
17. Sciagra R, Sotgia B, Boni N, Pupi A. Assessment of the influence of atrial fibrillation on gated SPECT perfusion data by comparison with simultaneously acquired nongated SPECT data. J Nucl Med. 2008;49(8):1283–7.
18. Harrison A, Adluru G, Damal K, Shaaban AM, Wilson B, Kim D, et al. Rapid ungated myocardial perfusion cardiovascular magnetic resonance: preliminary diagnostic accuracy. J Cardiovasc Magn Reson. 2013;15(1):26.
19. Achenbach S, Ropers D, Holle J, Muschiol G, Daniel WG, Moshage W. In-plane coronary arterial motion velocity: measurement with electron-beam CT. Radiology. 2000;216(2):457–63.
20. Achenbach S, Daniel WG. Computed tomography of the coronary arteries: more than meets the (angiographic) eye. J Am Coll Cardiol. 2005;46(1):155–7.
21. Wang Y, Vidan E, Bergman GW. Cardiac motion of coronary arteries: variability in the rest period and implications for coronary MR angiography. Radiology. 1999;213(3):751–8.
22. Wintersperger BJ, Nikolaou K, von Ziegler F, Johnson T, Rist C, Leber A, et al. Image quality, motion artifacts, and reconstruction timing of 64-slice coronary computed tomography angiography with 0.33-second rotation speed. Investig Radiol. 2006;41(5): 436–42.
23. Srichai MB, Hecht EM, Kim D, Babb J, Bod J, Jacobs JE. Dual-source computed tomography angiography image quality in patients with fast heart rates. J Cardiovasc Comput Tomogr. 2009;3(5):300–9.
24. Leschka S, Wildermuth S, Boehm T, Desbiolles L, Husmann L, Plass A, et al. Noninvasive coronary angiography with 64-section CT: effect of average heart rate and heart rate variability on image quality. Radiology. 2006;241(2):378–85.
25. Matt D, Scheffel H, Leschka S, Flohr TG, Marincek B, Kaufmann PA, et al. Dual-source CT coronary angiography: image quality, mean heart rate, and heart rate variability. AJR Am J Roentgenol. 2007;189(3):567–73.
26. Poon M. Technology insight: Cardiac CT angiography. Nat Clin Pract Cardiovasc Med. 2006;3(5):265–75.
27. Schroeder S, Achenbach S, Bengel F, Burgstahler C, Cademartiri F, de Feyter P, et al. Cardiac computed tomography: indications, applications, limitations, and training requirements: report of a Writing Group deployed by the Working Group Nuclear Cardiology and Cardiac CT of the European Society of Cardiology and the European Council of Nuclear Cardiology. Eur Heart J. 2008;29(4):531–56.
28. Mark DB, Berman DS, Budoff MJ, Carr JJ, Gerber TC, Hecht HS, et al. ACCF/ACR/AHA/NASCI/SAIP/SCAI/SCCT 2010 expert consensus document on coronary computed tomographic angiography: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. Circulation. 2010;121(22):2509–43.
29. Shim SS, Kim Y, Lim SM. Improvement of image quality with beta-blocker premedication on ECG-gated 16-MDCT coronary angiography. AJR Am J Roentgenol. 2005;184(2):649–54.
30. Rochitte CE, Azevedo GS, Shiozaki AA, Azevedo CF, Kalil Filho R. Diltiazem as an alternative to beta-blocker in coronary artery computed tomography angiography. Arq Bras Cardiol. 2012;99(2):706–13.
31. Pasricha SS, Nandurkar D, Seneviratne SK, Cameron JD, Crossett M, Schneider-Kolsky ME, et al. Image quality of coronary 320-MDCT in patients with atrial fibrillation: initial experience. AJR Am J Roentgenol. 2009;193(6):1514–21.
32. Yang L, Zhang Z, Fan Z, Xu C, Zhao L, Yu W, et al. 64-MDCT coronary angiography of patients with atrial fibrillation: influence of heart rate on image quality and efficacy in evaluation of coronary artery disease. AJR Am J Roentgenol. 2009;193(3):795–801.
33. Al Fagih A, Al Ghamdi SA, Dagriri K, Al Zahrani G. Controlling rate and rhythm increases feasibility of CT angiography in atrial fibrillation. Clin Med Res. 2010;8(2):96–8.
34. Halliburton SS, Abbara S, Chen MY, Gentry R, Mahesh M, Raff GL, et al. SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT. J Cardiovasc Comput Tomogr. 2011;5(4):198–224.
35. Achenbach S, Marwan M, Schepis T, Pflederer T, Bruder H, Allmendinger T, et al. High-pitch spiral acquisition: a new scan mode for coronary CT angiography. J Cardiovasc Comput Tomogr. 2009;3(2):117–21.
36.•• Vorre MM, Abdulla J. Diagnostic accuracy and radiation dose of CT coronary angiography in atrial fibrillation: systematic review and meta-analysis. Radiology. 2013;267(2):376–86. *This recent meta-analysis provides information on overall diagnostic accuracy for coronary CT angiography in patients with atrial fibrillation*.
37. Lu B, Mao SS, Zhuang N, Bakhsheshi H, Yamamoto H, Takasu J, et al. Coronary artery motion during the cardiac cycle and optimal ECG triggering for coronary artery imaging. Investig Radiol. 2001;36(5):250–6.
38. Rist C, Johnson TR, Muller-Starck J, Arnoldi E, Saam T, Becker A, et al. Noninvasive coronary angiography using dual-source computed tomography in patients with atrial fibrillation. Investig Radiol. 2009;44(3):159–67.
39. Zhang JJ, Liu T, Feng Y, Wu WF, Mou CY, Zhai LH. Diagnostic value of 64-slice dual-source CT coronary angiography in patients with atrial fibrillation: comparison with invasive coronary angiography. Korean J Radiol. 2011;12(4):416–23.
40. Oncel D, Oncel G, Tastan A. Effectiveness of dual-source CT coronary angiography for the evaluation of coronary artery disease in patients with atrial fibrillation: initial experience. Radiology. 2007;245(3):703–11.
41. Seifarth H, Wienbeck S, Pusken M, Juergens KU, Maintz D, Vahlhaus C, et al. Optimal systolic and diastolic reconstruction windows for coronary CT angiography using dual-source CT. AJR Am J Roentgenol. 2007;189(6):1317–23.
42. Herzog C, Abolmaali N, Balzer JO, Baunach S, Ackermann H, Dogan S, et al. Heart-rate-adapted image reconstruction in multidetector-row cardiac CT: influence of physiological and technical prerequisite on image quality. Eur Radiol. 2002;12(11):2670–8.
43.• Srichai MB, Barreto M, Lim RP, Donnino R, Babb JS, Jacobs JE. Prospective-triggered sequential dual-source end-systolic coronary CT angiography for patients with atrial fibrillation: a feasibility study. J Cardiovasc Comput Tomogr. 2013;7(2):102–9. *This study provides information on the feasibility of prospectively ECG-triggered sequential CCTA with a DSCT in AF patients. It showed that end-systolic acquisition provided diagnostic image quality with potentially lower radiation exposure*.

44. Marwan M, Pflederer T, Schepis T, Lang A, Muschiol G, Ropers D, et al. Accuracy of dual-source computed tomography to identify significant coronary artery disease in patients with atrial fibrillation: comparison with coronary angiography. Eur Heart J. 2010;31(18): 2230–7.
45. Sato T, Anno H, Kondo T, Harigaya H, Inoue K, Kakizawa S, et al. Applicability of ECG-gated multislice helical ct to patients with atrial fibrillation. Circ J. 2005;69(9):1068–73.
46. Cademartiri F, Mollet NR, Runza G, Baks T, Midiri M, McFadden EP, et al. Improving diagnostic accuracy of MDCT coronary angiography in patients with mild heart rhythm irregularities using ECG editing. AJR Am J Roentgenol. 2006;186(3):634–8.
47. Matsumoto H, Kondo T, Watanabe S, Kikumoto R, Shimada T, Hiraoka Y, et al. ECG-edited middiastolic phase reconstruction improves image quality at 64-MDCT coronary angiography of patients with atrial fibrillation. AJR Am J Roentgenol. 2008;191(6):1659–66.
48. Kalender WA. Computed tomography: fundamentals, system technology, image quality, applications. 2nd ed. Weinheim: Wiley-VCH; 2005.
49. Collins J. Image quality and radiation dose at coronary CT angiography. Suppl Appl Radiol. 2007:42–55.
50. Uehara M, Takaoka H, Kobayashi Y, Funabashi N. Diagnostic accuracy of 320-slice computed-tomography for detection of significant coronary artery stenosis in patients with various heart rates and heart rhythms compared with conventional coronary-angiography. Int J Cardiol. 2012;167(3):809–15.
51. Einstein AJ, Henzlova MJ, Rajagopalan S. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. JAMA. 2007;298(3):317–23.
52. Gerber TC, Carr JJ, Arai AE, Dixon RL, Ferrari VA, Gomes AS, et al. Ionizing radiation in cardiac imaging: a science advisory from the American Heart Association Committee on Cardiac Imaging of the Council on Clinical Cardiology and Committee on Cardiovascular Imaging and Intervention of the Council on Cardiovascular Radiology and Intervention. Circulation. 2009;119(7):1056–65.
53. Suh YJ, Kim YJ, Hong SR, Hong YJ, Lee HJ, Hur J, et al. Combined use of automatic tube potential selection with tube current modulation and iterative reconstruction technique in coronary CT angiography. Radiology. 2013;269(3):722–9.
54. Catalan P, Leta R, Hidalgo A, Montiel J, Alomar X, Vilades D, et al. Ruling out coronary artery disease with noninvasive coronary multidetector CT angiography before noncoronary cardiovascular surgery. Radiology. 2011;258(2):426–34.
55. Wang Y, Zhang Z, Kong L, Song L, Merges RD, Chen J, et al. Dual-source CT coronary angiography in patients with atrial fibrillation: comparison with single-source CT. Eur J Radiol. 2008;68(3):434–41.
56. Xu L, Yang L, Fan Z, Yu W, Lv B, Zhang Z. Diagnostic performance of 320-detector CT coronary angiography in patients with atrial fibrillation: preliminary results. Eur Radiol. 2011;21(5):936–43.
57. Kondo T, Kumamaru KK, Fujimoto S, Matsutani H, Sano T, Takase S, et al. Prospective ECG-gated coronary 320-MDCT angiography with absolute acquisition delay strategy for patients with persistent atrial fibrillation. AJR Am J Roentgenol. 2013;201(6):1197–203.
58. Uehara M, Funabashi N, Ueda M, Murayama T, Takaoka H, Sawada K, et al. Quality of coronary arterial 320-slice computed tomography images in subjects with chronic atrial fibrillation compared with normal sinus rhythm. Int J Cardiol. 2011;150(1):65–70.
59.• Wang Q, Qin J, He B, Zhou Y, Yang JJ, Hou XL, et al. Computed tomography coronary angiography with a consistent dose below 2 mSv using double prospectively ECG-triggered high-pitch spiral acquisition in patients with atrial fibrillation: initial experience. Int J Cardiovasc Imaging. 2013;29(6):1341–9. *This study evaluates a promising new technique, high-pitch spiral CT acquisition, in its ability to provide consistent diagnostic image quality in patients with atrial fibrillation. An advantage of this technique is the consistent low radiation exposure offered by this technique.*
60. Abdulla J, Abildstrom SZ, Gotzsche O, Christensen E, Kober L, Torp-Pedersen C. 64-multislice detector computed tomography coronary angiography as potential alternative to conventional coronary angiography: a systematic review and meta-analysis. Eur Heart J. 2007;28(24):3042–50.
61.•• Sun G, Li M, Jiang ZW, Xu L, Peng ZH, Ding J, et al. Diagnostic accuracy of dual-source CT coronary angiography in patients with atrial fibrillation: meta analysis. Eur J Radiol. 2013;82(10):1749–54. *This recent meta-analysis provides information on diagnostic accuracy of coronary CT angiography in patients with atrial fibrillation focused on use of dual source CT scanning.*
62. Schuetz GM, Schlattmann P, Dewey M. Coronary CT angiography cannot be recommended in patients with atrial fibrillation. Radiology. 2013;269(3):947–8.
63. Yu BB, Zhai JL, Sun G. Diagnostic performance of CT angiography in patients with atrial fibrillation. Radiology. 2013;268(2):610–1.
64. Weustink AC, Neefjes LA, Kyrzopoulos S, van Straten M, Neoh Eu R, Meijboom WB, et al. Impact of heart rate frequency and variability on radiation exposure, image quality, and diagnostic performance in dual-source spiral CT coronary angiography. Radiology. 2009;253(3):672–80.
65.• Sun G, Li M, Jiang XS, Li L, Peng ZH, Li GY, et al. 320-detector row CT coronary angiography: effects of heart rate and heart rate variability on image quality, diagnostic accuracy and radiation exposure. Br J Radiol. 2012;85(1016):e388–94. *This study provides information on the improved resolution of the 320-detector row CT and its ability to resolve step artefact and decrease radiation dose caused by irregular heart rate.*
66. Kim YY, Klein AL, Halliburton SS, Popovic ZB, Kuzmiak SA, Sola S, et al. Left atrial appendage filling defects identified by multidetector computed tomography in patients undergoing radiofrequency pulmonary vein antral isolation: a comparison with transesophageal echocardiography. Am Heart J. 2007;154(6): 1199–205.
67. Niinuma H, George RT, Arbab-Zadeh A, Lima JA, Henrikson CA. Imaging of pulmonary veins during catheter ablation for atrial fibrillation: the role of multi-slice computed tomography. Europace. 2008;10 Suppl 3:iii14–21.
68. Kistler PM, Rajappan K, Jahngir M, Earley MJ, Harris S, Abrams D, et al. The impact of CT image integration into an electroanatomic mapping system on clinical outcomes of catheter ablation of atrial fibrillation. J Cardiovasc Electrophysiol. 2006;17(10):1093–101.
69.• Yang L, Zhang Z, Wang Y, Jin Z, Zhang L, et al. Prospectively ECG-triggered sequential dual-source coronary CT angiography in patients with atrial fibrillation: comparison with retrospectively ECG-gated helical CT. Eur Radiol. 2013;23(7):1822–8. *This study provides information on the feasibility of prospectively ECG-triggered sequential CCTA with a DSCT in AF patients. It showed that image quality is improved and with significant decrease in radiation exposure.*
70. Bettencourt N, Rocha J, Carvalho M, Leite D, Toschke AM, Melica B, et al. Multislice computed tomography in the exclusion of coronary artery disease in patients with presurgical valve disease. Circ Cardiovasc Imaging. 2009;2(4):306–13.
71. Wolak A, Gutstein A, Cheng VY, Suzuki Y, Thomson LE, Friedman J, et al. Dual-source coronary computed tomography angiography in patients with atrial fibrillation: initial experience. J Cardiovasc Comput Tomogr. 2008;2(3):172–80.
72. Tsiflikas I, Drosch T, Brodoefel H, Thomas C, Reimann A, Till A, et al. Diagnostic accuracy and image quality of cardiac dual-source computed tomography in patients with arrhythmia. Int J Cardiol. 2010;143(1):79–85.