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ORIGINAL ARTICLE

Influence of virtual monochromatic spectral image at different energy levels on motion artifact correction in dual-energy spectral coronary CT angiography

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Abstract

Purpose To investigate the influence of virtual monochromatic spectral (VMS) CT images at different energy levels on the effectiveness of a motion correction technique (SSF) in dual-energy Spectral coronary CT angiography (CCTA).

Materials and methods 29 cases suspected of or diagnosed with coronary artery disease underwent Spectral CCTA using a prospective ECG triggering with 250 ms padding time. SSF was applied to the determined least-motion phase to generate 6 additional sets of VMS images with energy levels from 40 to 100 keV. CT value and standard deviation (SD) in the aortic root and epicardial adipose tissue were measured. Image quality of the RCA, LAD and LCX was evaluated on a per-vessel basis in each patient. Two reviewers evaluated the artery using the score of the segment.

Results The low energy VMS images increased CT value and image noise compared with higher-energy VMS images, except 90 keV and 100 keV. The CNR of 40–70 keV were higher than those of 80–100 keV ($P < 0.05$). The image quality scores for images at 50–80 keV were higher than those of 40, 90, and 100 keV ($P < 0.05$), and the VMS image quality at 50 keV and 60 keV with SSF was the highest.

Conclusion SSF can effectively reduce the motion artifacts when coronary vessels have suitable contrast enhancement which can be achieved by adjusting energy levels of VMS images.

Keywords Coronary artery · Tomography · X-ray computed · Spectral CT imaging

Introduction

Coronary atherosclerotic heart disease is a leading cause of human death in the common cause. Coronary CT angiography (CCTA) is now widely used clinically for diagnostic purpose with a good diagnostic accuracy and very high negative predictive value [1]. However, the heart is the fastest moving organ in the body, and in a heartbeat, coronary arteries undergo 3D irregular movements with shapes changing correspondingly [2]. So even with the continuous improvement in the scanning speed, including the use of dual-source CT, coronary motion artifacts still exist and adversely affect the diagnosis [3], especially in patients for whom the collected scan information is not from the best cardiac cycle. Motion detection and correction algorithms such as the SnapShot Freeze (SSF) algorithm are often used in CCTA to further improve the temporal resolution. The low intracoronary contrast enhancement itself is another source for the poor quality of CCTA images. In addition, since SSF is largely based on tracking the vessels to correct their vasomotor movement to reduce pulsating artifacts [4, 5], the lack of appropriate enhancements in the vessel may affect the tracking ability and thus, the effectiveness of motion correction. However, the contrast enhancement in coronary vessels depends on many factors such as cardiac function, scan trigger time, contrast agent concentration, flow rate and total dose, and by simply increasing the concentration of contrast agent and dose to ensure adequate contrast enhancement may increase the risk of artifacts and contrast-induced kidney disease. On the other hand, the dual-energy Spectral CT provides sets of virtual monochromatic spectral (VMS)

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images that change the CT attenuation values of contrast agent in the vessel by changing the photon energy level [6]. The purpose of this retrospective study was thus to investigate the influence of VMS images at different energy levels on the motion correction effectiveness of SSF technique in dual-energy Spectral coronary CT angiography (CCTA).

Materials and methods

The motion-correction algorithm (Snapshot Freeze, SSF) evaluated in this study uses the information acquired from the multi-phase reconstructions within a single heartbeat to characterize the motion (both motion trajectory and velocity) of individual vessels independently and to determine the actual vessel position at the prescribed target phase [7]. The principle is to determine the whereabouts of the three major branches of the coronary artery independently in the target phase and 80 ms before and after this target phase to characterize their motion trajectories along the whole length of the vessels at different stages of a cardiac cycle through a special mathematical model, and then accurately compensate for the motion to reduce motion artifacts. The SSF algorithm effectively shortens the reconstruction temporal window for an improved temporal resolution and improves CCTA images compared with the images without SSF [5, 8].

This study was approved by the institutional review board of our hospital and a written informed consent was obtained from each participant prior to the study. 29 cases suspected of or diagnosed with coronary artery disease in our hospital from August to October 2016 underwent a dual-energy Spectral CCTA. The patient population consisted of 18 males and 11 females with ages ranging from 36 to 72 years (mean 60.5 years). Patients had mean weight of 64.51 kg (ranging from 40 to 82 kg), mean Body Mass Index (BMI) of 23.34 kg/m^2 (ranging from 16.73 to 31.11 kg/m^2), and heart rates of 60.66 ± 6.14 bpm (47–76 bpm). The main clinical symptoms were chest tightness, precordial discomfort or chest pain. Subjects had no serious heart, liver, and kidney dysfunction or severe arrhythmia and no history of allergy to contrast agent and could hold breath for 15 s.

Before the scans, patients underwent breathing training and their heart rates were checked regularly. If necessary, oral metoprolol tablets at 25–50 mg dosage were given about 30 min before the CT scans, so that the heart rates were kept at less than 75 bpm. All patients underwent the prospective ECG-triggered CCTA using the Spectral imaging mode centered at the 75% cardiac phase with 250 ms of padding time on a Discovery 750HD CT scanner (GE Healthcare, Milwaukee, WI) in supine position. The 250 ms of padding time would allow to generate CCTA images covering cardiac phases between 55 and 85% of the R–R interval for the patients in our study. The scan range was from 1 cm under the bifurcation of trachea to the diaphragmatic surface of the heart. Collimator width, reconstruction slice thickness and spacing were 0.625 mm, width of detector was 40 mm, and rotation speed was 0.35 s. The patient body mass index (BMI)-dependent dual-energy Gemstone Spectral Imaging (GSI) scan protocols were used to optimize dose performance: for patients with BMI ≤ 22.5 kg/m^2, 375 mA tube current was selected; and for patients with BMI > 22.5 kg/m^2, 600 mA was selected. The effective radiation dose (ED) of CCTA was calculated according to the European Working Group for Guidelines on Quality Criteria in CT. The dose-length product (DLP) for the contrast-enhanced CCTA acquisition was measured in mGy × cm in each patient [9]. The ED was calculated as the DLP times a conversion coefficient for the chest ($K = 0.014$ mSv/mGy × cm). Before CCTA, test bolus scans were obtained to determine the scan delay for CCTA after the administration of 20 mL of iohexol (350 mgI/mL) via antecubital venous access at the injection rate of 4.5–5.0 mL/s with a dual-tube power injector. The timing for CCTA acquisition was determined by adding 14 s to the time-to-peak contrast enhancement in the center of aortic root at the level of the left main artery. Contrast medium (Iohexol, 350 mgI/mL) with total volume of 0.8 times the patient weight (in kg) was then injected at the rate determined by dividing the total contrast agent dosage (in mL) by the total injection time of 12 s. The contrast injection was followed by 20 mL physiological saline at the same injection rate.

The first reconstruction step was limited to the 70 keV photon energy which is the system default and equivalent to the average energy of the 120 kVp tube voltage. All CCTA images were reconstructed using 40% adaptive statistical iterative reconstruction (ASIR). The CCTA images were reconstructed at cardiac phases from 55 to 85% at a 5% interval with the SSF motion correction algorithm to generate 7 image sets. These axial image sets were transferred to a GE AW4.6 workstation to generate the volume rendering (VR), maximum intensity projection (MIP), and curved planar reformation (CPR) images for analysis with the CardIQX software. The image quality of the axial and reformatted images with different cardiac phases was analyzed by two independent readers with extensive experience in CCTA using the 18-segment model based on the Society of Cardiovascular Computed Tomography Guidelines [10]. The two reviewers noted coronary artery motion artifacts, and graded image quality in consensus for the right coronary artery (RCA), left anterior descending artery (LAD) and left circumflex artery (LCX) on the per-vessel basis in each patient, left main trunk was used as part of the LAD: image quality was evaluated by scoring the artery using the score of the segment (with diameter greater than 1.5 mm) having the most severe motion artifacts along the entire course of the artery. A

semi-quantitative 5-point scoring system was used [11]: (5) Excellent image quality, clear vessel boundary and display, no motion artifact; (4) good image quality, mostly clear boundary, only a small amount of motion artifacts, not affecting the diagnosis; (3) suboptimal image quality but interpretable, can be used for diagnosis, may affect the diagnostic accuracy; (2) poor image quality and difficult-to-perform vessel analysis; (1) non-diagnostic, poor image quality with severe motion-related artifacts. The cardiac phase in which SSF produced the best image quality with the least-motion artifacts was then chosen.

The second reconstruction step was to reconstruct CCTA images applying SSF motion-correction technique with energy levels ranging from 40 to 100 keV (with a 10 keV interval) at the chosen cardiac phase (with the least-motion artifacts using SSF algorithm). Finally, the same two radiologists performed the qualitative evaluation in the same blinded manner on these seven sets of images. The scores for the three major coronary arteries (LAD, LCX, and RCA) were generated using the same worst-case method for the segments in the vessels. These images were evaluated using the observation window fixed at the window width of 800HU and window level of 300HU.

The CT and standard deviation (SD) values in the aortic root and epicardial adipose tissue of these seven image sets were measured to calculate the contrast-to-noise ratio (CNR) for the aortic root. These measurements, together with the image quality and the interpretability of the three main coronary arteries were compared among the different VMS images. Statistical comparison was carried using the SPSS20.0 statistical software, and $P < 0.05$ was deemed significant. The one-way ANOVA was used to compare the image noise, CT value and CNR of the aortic root for VMS images, and Wilcoxon signed-rank test was used to compare the image quality scores of VMS images with SSF at different energy levels.

Results

Radiation dose parameters

The mean value of DLP of CCTA was 524.02 ± 39.58 mGy cm, and the mean of ED was 7.34 ± 0.55 mSv.

CT evaluability and image quality

The CT enhancement value and image noise in the aorta was higher at low keV, and decreased with the increase of keV (Table 1). There were significant differences of CT value and noise between groups ($P < 0.05$), except those between 90 keV group and 100 keV groups ($P > 0.05$). There were no significant differences of CNR between 40, 50, 60, and 70 keV groups ($P > 0.05$), but were higher than those of 80–100 keV images ($P < 0.05$).

The cardiac phases where the use of SSF provided the best image with the least-motion artifacts and highest interpretability in RCA, LAD and LCX were distributed in all the RR cardiac phases we reconstructed: 6 cases in 85% phase, 2 in 80% phase, 2 in 75% phase, 3 in 70% phase, 1 in 65% phase, 3 in 60% phase, and 12 in 55% phase. The 50–80 keV SSF images had average scores in all major vessels greater than 4 and with no statistically significant difference between the groups ($P > 0.05$). The scores in these energy groups were higher than that of 40, 90, and 100 keV SSF images, and 70 keV without SSF was lowest ($P < 0.05$). The use of photon energies other than 70 keV further optimized the performance of SSF in some cases, especially for LCX (Table 2, Figs. 1 and 2).

Discussion

CCTA provides a safe, reliable and noninvasive evaluation for coronary artery disease [12], including the extent of coronary artery stenosis, plaque composition, and post-implantation evaluation. The studies for myocardial perfusion and coronary flow reserve using CT have also made considerable progress. However, CCTA is not perfect, first, it still needs to follow the minimum effective dose principle, reasonable optimization of the scanning parameters to further reduce the X-ray dose [13]. Second, many factors can reduce the image quality for diagnosis, and the stent placement, severe calcification, high body mass, and cardiac motion-induced artifacts are among the main limiting factors [14]. How to improve the temporal resolution to reduce motion artifacts and obtain high-quality images is one of the primary focus in CCTA [15]. Beside the hardware improvement such as the use of multiple X-ray sources and the increase of gantry rotation speed which is closer to its mechanical limit,

Table 1 The image noise, CT values and CNR for the 7 VMS image sets (mean ± standard deviation)

VMS	40 keV	50 keV	60 keV	70 keV	80 keV	90 keV	100 keV	*F* value	*P* value
Noise	62.98 ± 9.35	44.66 ± .38	30.87 ± 5.61	22.99 ± 4.28	19.52 ± 3.71	18.23 ± 3.17	16.80 ± 2.96	284.347	< 0.001
CT value	1367.83 ± 240.79	916.14 ± 154.63	639.77 ± 105.60	466.60 ± 74.37	353.9 ± 55.41	280.45 ± 42.39	229.44 ± 32.46	326.527	< 0.001
CNR	23.77 ± 3.85	24.76 ± 3.56	24.83 ± 4.41	24.87 ± 4.50	22.75 ± 3.93	19.55 ± 3.25	17.53 ± 2.92	17.003	< 0.001

Table 2 Image quality score comparison among VMS images with SSF at various energy levels (mean ± standard deviation)

VMS	Without SSF 70 keV	With SSF							χ^2 value	*P* value
		40 keV	50 keV	60 keV	70 keV	80 keV	90 keV	100 keV		
RCA	2.03 ± 0.57	3.72 ± 1.25	4.45 ± 0.83	4.69 ± 0.47	4.69 ± 0.47	4.31 ± 0.97	3.59 ± 1.45	3.07 ± 1.36	115.259	0.000
LAD	3.97 ± 1.05	4.34 ± 0.94	4.72 ± 0.45	4.72 ± 0.45	4.69 ± 0.47	4.62 ± 0.68	4.52 ± 0.95	4.45 ± 0.99	61.093	0.000
LCX	4.21 ± 1.08	4.72 ± 0.70	4.83 ± 0.47	4.76 ± 0.58	4.46 ± 0.58	4.76 ± 0.58	4.66 ± 0.77	4.52 ± 0.91	43.167	0.000

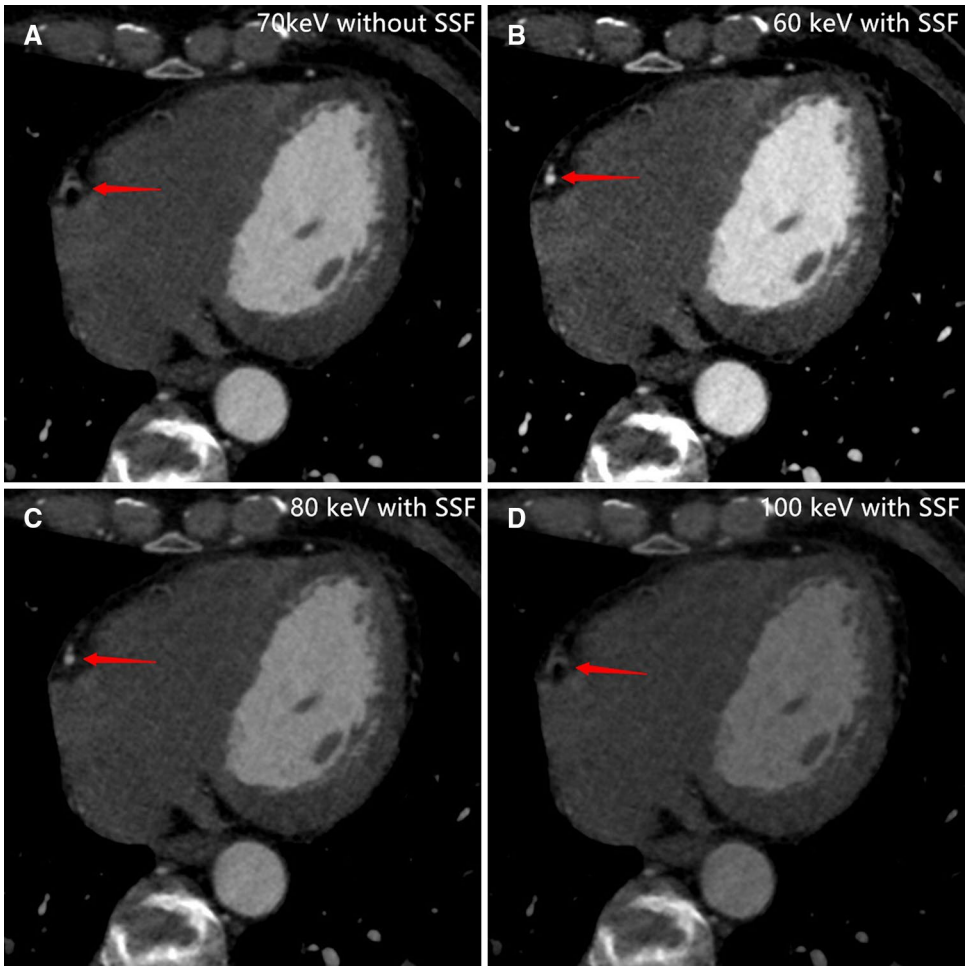

Fig. 1 Male, 55 years old with chest pain and a heart rate of 72 bpm. CCTA examination in the 80% cardiac phase indicated multiple calcified plaques in coronary arteries with no significant narrowing. **a** The image at 70 keV without motion correction, the mid-RCA was unclear, non-diagnostic (1 point). **b–d** Are for VMS images at different energy levels with SSF. The boundaries of the mid-RCA on the 60 keV and 80 keV images were clear, no motion artifacts, fully diagnostic (5 points). The boundaries of the mid-RCA on the 100 keV image were not clear, non-diagnostic (1 point)

software approaches, such as multi-sector reconstruction, motion detection and correction techniques are also often used. The three main branches of the coronary arteries follow complexed and different motion trajectories with different velocities and amplitudes during the cardiac cycle [16]. These motion differences increase as the heart rate increases [5]. In the clinical application, since it is hard to predict the exact cardiac phases where coronary vessels will have the least motion due to the inconsistency of the motions of different vessels, as well as heart rate variation, respiratory movement and other restrictions, CCTA scans often cover extended cardiac phases either using the retrospective ECG gating mode or extended padding time in the prospective ECG trigging mode. Both approaches result in higher radiation dose, with the dose increase from the retrospective ECG gating mode being much higher.

Dual-energy spectral CT provides sets of virtual monochromatic spectral (VMS) images in the energy range between 40 and 140 keV that change the CT attenuation values of contrast agent in the vessels by changing the photon energy level [6]. Monochromatic images generated in dual-energy Spectral CT avoid the average attenuation effect and have better density contrast and less beam hardening artifacts than the conventional polychromatic

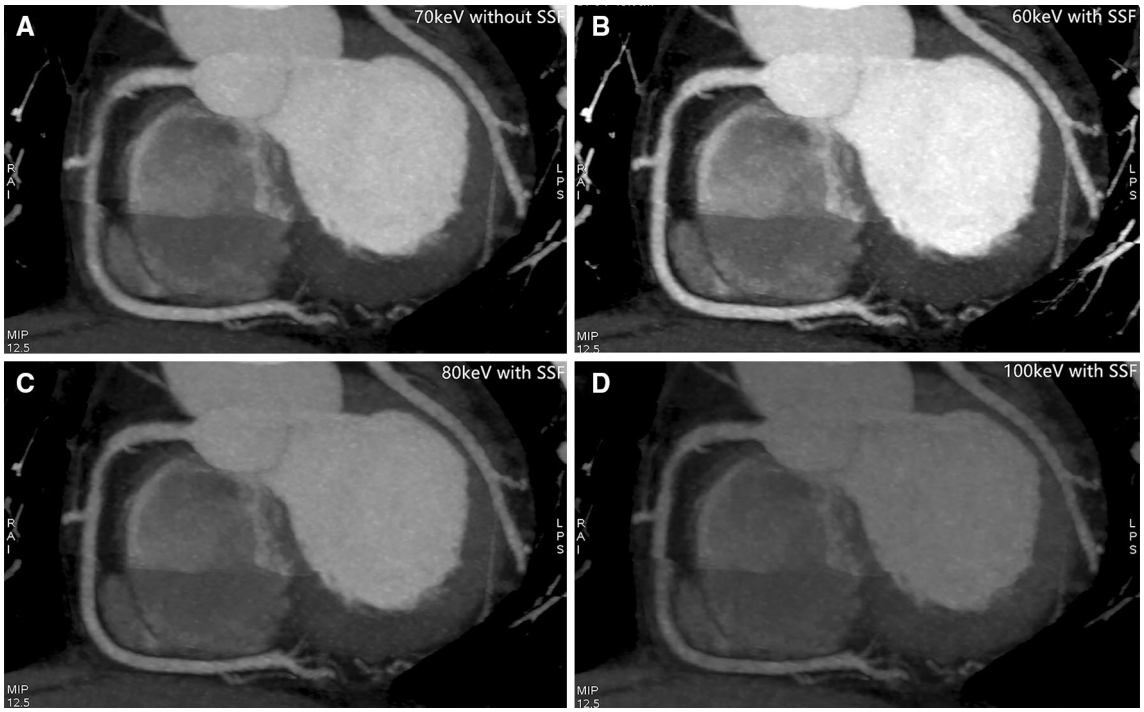

Fig. 2 Male, 54 years old with chest pain and a heart rate of 66 bpm. CCTA examination in the 65% cardiac phase indicated multiple calcified plaques in RCA, the proximal RCA was slightly narrow. **a** The image at 70 keV without motion correction, and the impact of local vascular contour beat artifacts in the proximal and middle RCA was evaluated, poor image quality and difficult-to-perform vessel analysis (2 point). **b–d** was for VMS images at different energy levels with SSF. The boundaries of the mid-RCA on the 60 and 80 keV images were clear, no motion artifacts (5 points). The boundaries of the mid-RCA on the 100 keV images were not clear, resulting in poor image quality and difficult-to-perform vessel analysis (2 point)

kVp images [17]. In addition, lower photon energies increase the photoelectric effect to increase the CT attenuation value of contrast agent, which can be used to overcome the suboptimal contrast enhancement under normal imaging conditions. Our results indicated that in some cases, especially for LCX, VMS images at 50 keV, higher enhancement in the vessels further improved image quality compared with that of the default 70 keV VMS images. However, lower-energy VMS images tend to have higher image noise, which may adversely affect the vessel tracking and image quality. This was reflected by the slightly lower scores with 40 keV VMS images, especially for RCA. On the other hand, higher energy level VMS images produce lower contrast attenuation values [18], and low attenuation value in vessels may affect the effectiveness of vessels tracking. In this study, we found that VMS images at 90 and 100 keV had average attenuation values in the aortic root that were lower than 280HU, in comparison with the value of 466HU at 70 keV. This was used to simulate clinical situations where adequate enhancement was not achieved and how it might affect the effectiveness of vessels tracking and motion correction. Once the intravascular blood density is too low and the SSF is unable to function, it is possible to increase the CT value using lower keV, thereby enabling the SSF to function. And our results indicated that the image quality scores at the energies of 90 and 100 keV were less than those at the 50–80 keV.

There are some limitations in this study: first, study population is still small, more patients are still needed to study the detailed dependency of the motion correction algorithm on patient heart rate. Second, we only compared image-quality dependence of the SSF images on photon energy, and lacked comparison with the gold standard from the invasive angiography, further validation is required if diagnostic accuracy is desired. Third, to ensure the reconstruction of adequate cardiac phases for comparison, the padding time for this study was set to 250 ms rather than the minimum 80 ms, resulting in slightly higher radiation dose.

In conclusion, SSF can effectively reduce the motion artifacts when intra-coronary has an adequate contrast attenuation. By adjusting the CT attenuation in coronary vessels to appropriate values using different energy levels, VMS can compensate for the inadequate enhancement caused by various clinical conditions and maximize the effect of SSF for correcting motion artifacts in CCTA.

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Compliance with ethical standards

Conflict of interest Each author for this manuscript has participated sufficiently to take public responsibility and there were no conflicts of interest related to the work.

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