FULL LENGTH ARTICLE

Ultra-fast, low dose high-pitch (FLASH) versus prospectively-gated coronary computed tomography angiography: Comparison of image quality and patient radiation exposure

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Background: **Coronary computed tomography angiography (CCTA) is increasingly being used for the evaluation of coronary artery disease; however, radiation exposure remains a major limitation of its use.**

Objective: **To compare image quality and radiation exposure in two groups of patients undergoing CCTA using a 256-slice dual-source helical computed tomography scanner with high-pitch (FLASH) or prospective [step-and-shoot (SAS)] gating protocols.**

Methods: **A prospective, single-center study was performed in our cardiac center. In total, 162 patients underwent CCTA with either FLASH or SAS scanning protocols. Subjective image quality was graded on the basis of a four-point grading system (1, non-diagnostic; 2, adequate; 3, good; 4, excellent). Objective image quality was assessed using image signal, noise, and signal-to-noise ratio (SNR). The effective radiation dose was also estimated.**

Results: **The clinical and demographic characteristics of the patients in both groups were similar. The median age of the patients in both groups was 48.43 years, and males accounted for 63% and 68.7% of the FLASH and SAS groups, respectively. We found that the subjective image quality obtained with the FLASH protocol was superior to that obtained with the SAS protocol (3.35 þ 0.6 mSv vs. 2.82 þ 0.61 mSv; $p < 0.001$). Image noise was higher in the FLASH group but was not statistically significant (25.0 þ 6.13 vs. 24.0 þ 6.8; $p = 0.10$), whereas the signal and SNR was significantly higher with the FLASH protocol than with the SAS protocol [(469 þ 116 vs. 397 þ 106; $p > 0.001$) and (21.6 þ 8.7 mSv vs. 16.6 þ 7.7 mSv; $p < 0.001$), respectively]. Radiation exposure was 62% lower in the FLASH protocol than in the SAS protocol, (1.9 þ 0.4 mSv vs. 5.12 þ 1.8 mSv; $p < 0.001$).**

Conclusion: **The use of 256-slice CCTA performed with the FLASH protocol has a better objective and subjective image quality as well as lower radiation exposure when compared with the use of prospective electrocardiography gating.**

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Keywords: Computed tomography angiography, ECG gating, Cardiac CT protocol, Radiation exposure

Abbreviations

CCTA	Coronary computed tomography angiography
CTA	Computed Tomography Angiography
CAD	coronary artery disease
ECG	Electrocardiography
MPR	curved multi planar reformates
VR	volume rendering
LAD	left anterior descending artery
SAS	step and shoot
ICA	invasive coronary angiography
DSCT	dual source CT scanner
MIP	maximum intensity projection
SNR	signal to noise ratio
DLP	Dose-Length-Product
BMI	Body Mass Index

Introduction

Computed tomography angiography (CTA) is an accepted diagnostic tool for the assessment of coronary artery disease and a widely-used alternative to invasive coronary angiography (ICA) [1]. However, coronary CTA (CCTA) has a disadvantage of the high radiation dose, which remains a matter of concern [2] mainly due to the subsequent lifetime potential risk of cancer [3,4]. On the other hand, it is important to develop methods that reduce the radiation dose without compromising the image quality. Various strategies have been developed to reduce the radiation exposure of patients, the most important one being prospectively electrocardiography (ECG)-gated CCTA [step-and-shoot (SAS) mode]; the scan in this protocol is triggered by the ECG signal at a predefined time interval that is averaged using multiple cardiac cycles, and the actual acquisition is usually performed at the diastolic phase in which the motion artifact is minimal. The scan is stopped at the rest of the cardiac cycle, with a scan pitch of 1 and no overlap between slices (Fig. 1A). Thus, this scan mode is more susceptible to heart rate variability but is considered as the best radiation saving technique compared with the retrospective ECG-gating and ICA [5,6]. A new generation of dual-source computed tomography (CT) scanners has introduced a new scan mode, a prospectively ECG-triggered data acquisition with very high pitch values (Siemens Definition FLASH, Siemens Healthcare, Forchheim, Germany). This technique enables acquisition of the entire heart within a single cardiac cycle using a time window of approximately 250 milliseconds (Fig. 1B). From the data acquired, cross-sectional images are reconstructed with a temporal resolution of 75 milliseconds; the high-pitch scan is associated with a very low radiation exposure in patients with low, regular heart rates [7]. The pitch in this technique can be increased while still allowing image reconstruction due to

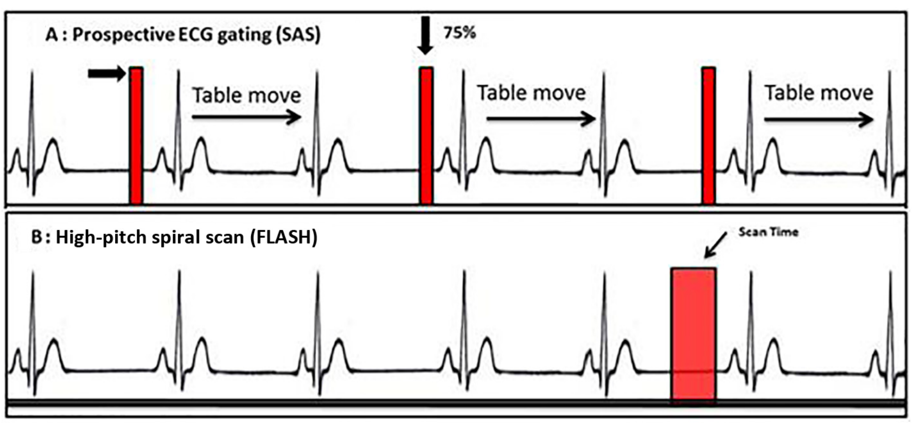

Figure 1. (A) In prospective gating, the X-ray beam is turned on only at a predefined time of the cardiac cycle, usually at 75% of the R–R interval (black arrow), and turned off during the rest of the cardiac cycle; (B) in the high-pitch spiral scan (FLASH), a very high pitch value is used, which allows the scanning of entire heart in about 250 milliseconds with a temporal resolution of 75 milliseconds.

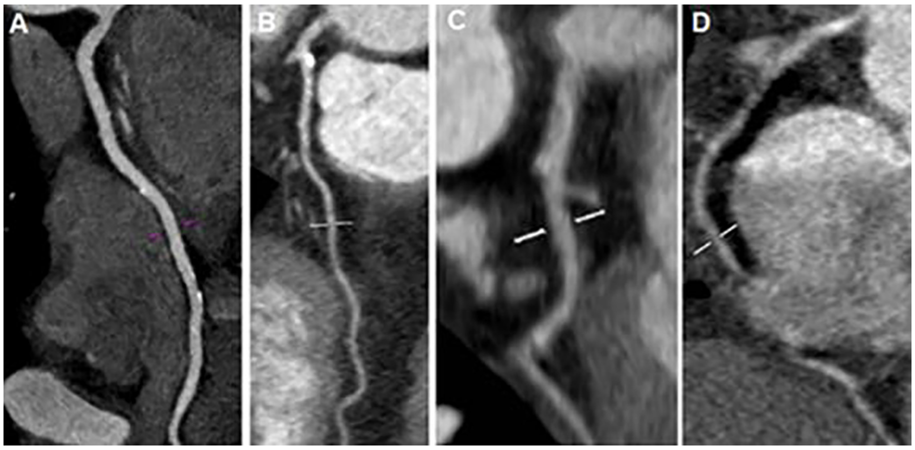

Figure 2. Subjective image quality. (A) Excellent picture quality (score of 4); (B) good image quality (score of 3); (C) fair image quality (score of 2); (D) poor image quality (score of 1).

dual-source geometry. In previous studies, a very high pitch value (up to 3.4) was used to cover the volume of the heart in a single cardiac cycle with excellent image quality (''misalignment'' or ''stair-step'' artifacts were not observed) and a radiation dose of <1.0 mSv [8,9]. Overlapping is avoided, thus substantially reducing the effective radiation dose to the patient. In our research, we hypothesized that cardiac imaging with the FLASH protocol can lower the radiation exposure without affecting the image quality; in case of positive findings, the FLASH protocol can be recommended as a solution for the increased radiation exposure due to CCTA while maintaining a good image quality. The purpose of our work was to compare the image quality and radiation exposure using the FLASH protocol versus the SAS protocol with 256-slice CTA.

Materials and methods

Study design

A prospective analysis was conducted of the data gathered from 82 FLASH CTA scans and 80 SAS CTA scans performed in our cardiac center between March and August 2015 for patients who presented with chest pain and intermediate risk for coronary artery disease, palpitation, shortness of breath, atrial fibrillation, and other indications. The results of subjective and objective image quality as well as radiation doses were compared between the two groups. Patients with uncontrollable arrhythmia or heart rate >65 beats per minute, previous allergic reaction to the iodinated contrast material, pregnancy, renal impairment (serum creatinine >130 μmol/L), and inability to hold breath were excluded. A signed informed consent was obtained from all the patients. The study was approved by the ethics committee of Prince Sultan Cardiac Center, Qassim.

Data acquisition and reconstruction protocol

Imaging in both protocols was performed using a dual-source scanner (256 slices, Siemens Definition Flash, Siemens Healthcare, Forchheim, Germany), rotation time of 280 milliseconds, temporal resolution of 75 milliseconds, 0.6-mm collimation, and tube current of 320 mAs which has adjustment with body habitus as needed. A 100-kV tube voltage was used for patients with a body weight of <80 kg, whereas a 120-kV tube voltage was used for patients with a body weight of >80 kg. In the SAS protocol, imaging started with a scout image, followed by a calcium score scan with 3-mm slice thickness and prospective gating at 75% of the cardiac cycle. We used a 0.6-mm slice thickness and ECG gating at 75% of the cardiac cycle during the breathing hold in inspiration for enhanced CTA scan. In the FLASH protocol, we used the same parameters for slice thickness as in the SAS protocol, but the scan was performed at 65% of the cardiac cycle (helical scan). The ''test bolus'' technique was used with 4-second delay time after the peak contrast enhancement of a region of interest in the ascending aorta using 15 mL of contrast agent (370 mg iodine/mL) and then 20 mL normal saline. The CCTA scan was performed by injecting approximately 75 mL and 65 mL of contrast agent in the SAS and the FLASH scans, respectively, followed by injecting 45 mL of saline solution at a rate of 6 mL/second. Prior to CTA, all patients with a baseline heart rate of >65 beats per minute

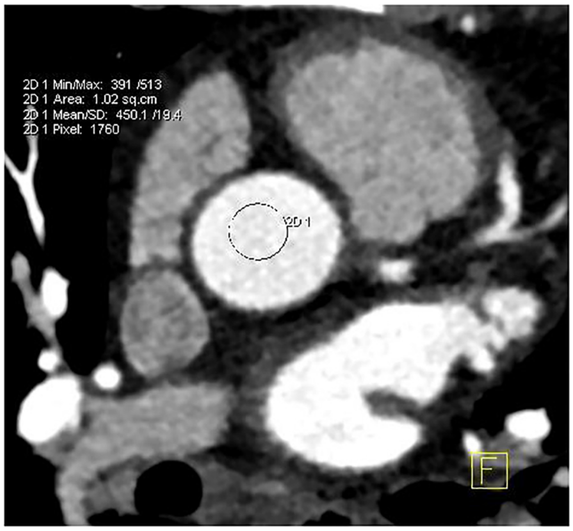

Figure 3. Objective image quality assessment. Axial image at the level of the ascending aorta above the coronary level. The objective image quality was assessed using a slice thickness of 1 mm and a region of interest of 1 cm^2 to determine the Hounsfield unit mean value (signal) and standard deviation (noise) and subsequently calculating the signal-to-noise ratio.

received 5–20 mg of metoprolol intravenously. Sublingual nitroglycerin (0.5 mg) was administered to all the patients during the scan unless contraindicated. Medium smooth kernels (B26f) were reconstructed for post-processing using a multimodality work place (MMWP; Siemens Medical Solutions, Erlangen, Germany). Axial, coronal, sagittal, and oblique multiplanar reconstruction, thin-slab maximum intensity projection, and volume-rendered images were reformatted. Furthermore, reconstruction was performed at 75% window in the SAS scans and at 65% prespecified window of the cardiac cycle in the FLASH scans.

Image quality assessment

Subjective image quality: All coronary segments were evaluated by two blinded and independent cardiologists with at least 6 years of experience in CCTA imaging. Image quality was graded on the basis of a four-point grading system [10,11] as follows: score 1, non-diagnostic; impaired image quality that precluded appropriate evaluation of the coronary arteries due to severe motion artifacts, severe image noise, or insufficient contrast; score 2, adequate; reduced image quality but sufficient to rule out significant stenosis; score 3, good; presence of artifacts but fully preserved ability to assess the presence of luminal stenosis; score 4, excellent; complete absence of motion artifacts, strong attenuation of vessel lumen, and

Table 1. Clinical and demographic characteristics of the patients in the FLASH and SAS protocols.

Patient characteristics	FLASH CTA (n = 82)	SAS CTA (n = 80)	p
Age (yr)	48.43 ± 11.6	48.43 ± 11.9	0.9
Sex			0.1
Male	52 (63%)	55 (68.7%)	
Risk factors			
Diabetes	29 (35.3%)	18 (22.5%)	0.09
Hypertension	36 (43.9%)	22 (27.5%)	0.08
Dyslipidemia	20 (24.3%)	15 (18.7%)	0.29
Smoking	11 (13.4%)	18 (22.5%)	0.12
Family history of CAD	7 (8%)	10 (12.5%)	0.23
Weight (kg)	82.6 ± 12	84.5 ± 14.39	0.43
Body mass index	30.7 ± 4.6	30.8 ± 5.4	0.87
Heart rate (bpm)	58 ± 5	58 ± 4.7	0.7
Calcium scores	15.67 ± 31	34.5 ± 165	0.38

Data are presented as n (%) or mean ± SD.
bpm = beats per minutes; CAD = coronary artery disease; CTA = computed tomography angiography; SAS = step-and-shoot; SD = standard deviation.

clear delineation of vessel walls, with the ability to assess luminal stenosis as well as plaque characteristics (Fig. 2). We interpreted axial, coronal, and sagittal views and different post-processing reconstruction models including maximum intensity projection, multiplanar reconstruction, and volume-rendered images to determine the factors that degrade the image quality.

Objective image quality: The objective image quality was evaluated by two independent readers on PACS system workstation or MMWP. The measurements were performed in the ascending aorta just above the level of coronary arteries using a slice thickness of 1 mm and region of interest of 1 cm^2 to determine the mean Hounsfield unit value (signal) and the standard deviation (noise) and subsequently calculating the signal-to-noise ratio (SNR) for all the patients [12] in both groups (Fig. 3).

Radiation dose estimation

We collected the required parameters to estimate the radiation dose, which included the volume CT dose index and dose length product (DLP), for both protocols. The calculation of the effective dose was based on a method proposed by the European Working Group for Guidelines on Quality Criteria in CT: effective radiation dose (mSv) is the product of DLP and an organ weighting factor for the chest [effective dose = 0.014 × DLP (mGy cm^{-1})] [13,14].

Statistical methods

Statistical analyses were performed using SPSS version 21 (SPSS Inc, Chicago, IL, USA). Data

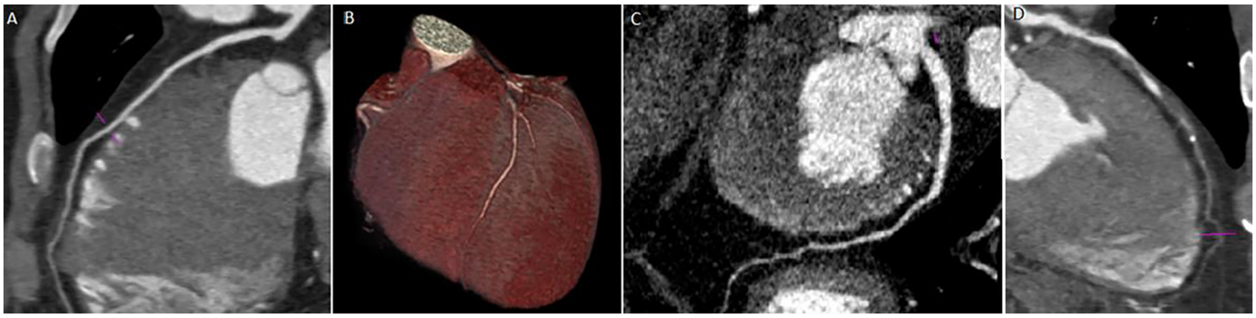

Figure 4. Examples of FLASH coronary computed tomography angiography scans. (A) Multiplanar reformation image showing a normal left anterior descending artery with excellent image quality; (B) volume rendering image showing absence of step stair artifacts. (C) multiplanar reformation showing a noisy image, but the image is still diagnostic; (D) multiplanar reformation image showing severe stenosis at the proximal part of the left anterior descending artery (LAD), followed by total occlusion of the artery at the middle part.

were expressed as mean ± standard deviation. A p value <0.05 was considered statistically significant. Chi-square test was used to compare categorical variables, and t test was used to compare numerical variables between the two groups.

Results

Baseline clinical characteristics

We performed a comprehensive analysis of the FLASH and SAS CTA scan results. Baseline clinical characteristics of the patients in both groups were similar (Table 1); the mean age of the patients in both groups was 48.43 years, and males accounted for 63% and 68.7% ($p = 0.1$) of the FLASH and SAS groups, respectively. Body mass index was 30.7 ± 4.6 versus 30.8 ± 5.4 ($p = 0.87$) in the FLASH and SAS groups, respectively. A total of 137 patients had chest pain as a presenting complaint, 11 were referred for pulmonary vein study prior to radiofrequency ablation, 9 had congenital heart disease, and 5 were referred to detect the left anterior descending artery graftability before cardiac surgery. Furthermore, 59 patients had coronary findings, and the remaining had normal coronary anatomy.

Image quality

Subjective image quality was better in the FLASH protocol than in the SAS protocol (3.35 ± 0.6 mSv vs. 2.82 ± 0.61 mSv; $p < 0.001$). Motion artifacts were the most common reason for degrading image quality scores, especially affecting the right coronary artery in the SAS group (three scans were non-diagnostic because of the motion artifacts in the SAS group vs. none in the FLASH group). Step stair artifacts were seen in 21 patients in the SAS group and none in the FLASH group. Fig. 4 represents examples of FLASH CTA scanning. Respiratory artifacts and coronary calcification were the second reason for degrading image quality scores in both the scan protocols; respiratory artifacts had the worst effect, but they were infrequent. Higher heart rate during the scan was observed more in the scans with poorer scores. We observed that SNR was better in the FLASH protocol than in the SAS protocol (21.6 ± 8.7 mSv vs. 16.65 ± 7.7 mSv; $p < 0.001$) despite the slightly increased image noise, which was explained by an increased signal in this group. Subjective and objective image quality in both scan groups is shown in Table 2.

Radiation dose

The effective radiation dose was significantly lower (62%) in the FLASH group than in the SAS group (1.92 ± 0.44 mSv vs. 5.13 ± 1.68 mSv; $p <$ 0.001; Table 3). On the other hand, the use of 100-kV tube voltages was associated with an extra 22% and 28% reduction in radiation exposure in

Table 2. Image quality results in both groups.

	FLASH CTA	Standard prospective CTA	p
Objective image quality			
Signal	469 ± 116	397 ± 106	<0.001
Noise	25.0 ± 6.13	24.0 ± 6.8	0.10
Signal-to-noise ratio	21.6 ± 8.7	16.65 ± 7.7	>0.001
Subjective image quality score	3.35 ± 0.6	2.82 ± 0.61	>0.001

Data are presented as mean ± SD.
CTA = computed tomography angiography; SD = standard deviation.

Table 3. Radiation exposure: Comparing the effective radiation dose and the dose length product in the FLASH and the SAS scan protocols. Radiation exposure is significantly reduced using the FLASH protocol compared with using the SAS scan protocol.

	FLASH	SAS	*p*
Effective radiation dose (mSv)	1.92 ± 0.44	5.13 ± 1.68	>0.001
Dose length product (mGy)	137.3 ± 32	366.42 ± 120	>0.001

SAS = step-and-shoot.

Table 4. Gating scan method and tube current voltage of the FLASH and SAS groups.

	FLASH No. of patients (%)	SAS No. of patients (%)	*p*
ECG gating	82	80	
kV			
100	31	30	0.9
120	51	50	0.95

ECG = electrocardiography; SAS = step-and-shoot.

the FLASH and the SAS protocol, respectively, compared to 120 kV. Tables 3 and 4 represent the radiation doses and the used kV in both protocols.

Discussion

CT technology continues to rapidly evolve, especially in the area of reducing radiation dose while preserving image quality. The aim of our work was to compare image quality and radiation exposure in two groups of patients undergoing CCTA using a 256-slice dual-source helical CT scanner with high-pitch (FLASH) or prospective SAS gating protocols. This prospective study shows that the high-pitch spiral CCTA scan protocol (FLASH) offers a significant reduction in radiation exposure compared with the SAS protocol, with maintaining the diagnostic yield of CTA. The major challenge when selecting the CCTA scan protocol is to obtain optimal image quality with the lowest possible radiation exposure. Motion artifacts are the main determinants of image quality and it is related to the selected scan protocol, heart rate, part of the cardiac cycle for acquisition, and scan time. Other artifacts are thought to be patient-specific (e.g., the presence of coronary calcifications with the blooming and beam hardening artifacts related to it). In our study, we focused on the presence of coronary motion artifacts as a subjective image quality and objectively on the noise, signal, and SNR as both are related to the selected scan protocol. The SAS protocol is well validated and is currently considered as the standard scan protocol for cardiac imaging [15]; high-pitch scan protocol is known to reduce the radiation exposure with good diagnostic accuracy [16,17]. We scanned our patients using either a FLASH or an SAS scan protocol in patients with heart rate ≤65 beats per minute. We found that the FLASH scan protocol provided high image quality in patients with heart rates <55 beats per minute with almost no motion artifacts. Similar observations were noted in previous studies [18]. We observed that the image quality is maintained even with heart rate up to 65 beats per minute, which is in agreement with the findings of previously published studies [15,8]. The radiation exposure in our study was significantly lower in the FLASH protocol than in the prospective protocol. In general, the radiation exposure can be lowered using different techniques, such as ECG-triggered high-pitch spiral scan and prospective ECG-triggered axial scan [19–21], minimizing the field of scanning guided by calcium score images and reducing the tube voltage when possible. SAS is an acquisition technique associated with low radiation exposure, and several studies have shown that it allows a significant reduction of the radiation exposure without the loss of image quality and diagnostic accuracy [22,5,21]. The prospectively high-pitch spiral acquisition (FLASH) allows further and significantly lower effective radiation dose, as shown by previously published studies [15,7]. Achenbach et al. [7] showed that the average effective dose was <1 mSv with high-pitch scan, and the radiation exposure was further reduced without compromising the image quality with increasing the pitch to 3.4. Kröpil et al. [23] reported an estimated effective dose of 1.4 ± 0.7 mSv (range, 0.4–3.1) with high-pitch scan. A comparative study of different dose-saving techniques reports effective dose values of 4.2–9.8 mSv for retrospective protocols with different ECG-pulsing techniques and 2.8–4.3 mSv for prospective ECG-triggered CTA [23]. In our study, the radiation doses were significantly lower in the FLASH protocol than in the SAS protocol (1.92 ± 0.44 mSv vs. 5.13 ± 1.68 mSv; $p < 0.001$); these findings were in agreement with those of the previous studies.

Study limitations

Our study included several limitations. First, the number of patients included in the study was small compared with some previous studies. Second, the tube voltage was set according to the patient's body weight regardless of the patient's body mass index, which may have an effect on the resultant image quality. Finally, ICA which is considered the reference standard for grading the coronary stenosis was used in a limited number of patients in whom we found a significant stenosis on CTA; thus, the diagnostic accuracy was not fully evaluated.

Conclusions

Our findings suggest that the high-pitch helical scan (FLASH) using a 256-slice dual-source CT scanner offered a significant reduction in radiation exposure without affecting the diagnostic yield of CTA compared with prospective gating scanning.

Remarks

This paper was awarded first place in the Professor Mohamed Alfagih prize during the Saudi Heart Association 27 meeting in February 12–15, 2016 and got published as an abstract in the Journal of the Saudi Heart Association.

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