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FULL PAPER

Contrast dose reduction with shortened injection durations in coronary CT angiography on 16-cm Wide-detector CT scanner

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Objectives: To investigate the use of shortened contrast injection with late triggering in coronary CT angiography (CCTA) for decreasing contrast dose and maintaining image quality.

Methods: 106 patients for CCTA on a 16-cm wide-detector CT were prospectively enrolled into groups A ($n = 50$) and B ($n = 56$) randomly. Patient weight-dependent contrast medium (Iopamiro, 370 mgI ml⁻¹) at dose rate of 25 mgI/kg/s was used with 8 s and the standard 10 s injection time in groups A and B, respectively. CT values of the aortic sinus (AS), right coronary artery, left anterior descending and left circumflex at the proximal, middle and distal segments were measured and compared. Subjective image quality was evaluated and analyzed with Fisher exact test. Contrast dose, injection rate and enhancement duration (between the start of enhancement in AS and scan finish) were also compared.

Results: There was no difference in the injection rate and enhancement duration between the two groups (p

> 0.05), while the total contrast dose in group A (36.2 ± 5.7 ml) was significantly lower than in group B (46.4 ± 6.3 ml) ($p < 0.001$). There was no difference for CT values in all major coronary vessels between the two groups and no difference in subjective image quality scores (all $p > 0.05$).

Conclusion: It is feasible to shorten contrast injection to 8 s in CCTA on wide-detector CT systems to significantly reduce contrast dosage, maintain adequate enhancement and reduce contrast-related artifacts.

Advances in knowledge: (1) Coronary CT angiography (CCTA) scans with shortened contrast medium injection duration and late triggering are feasible with a 16-cm wide-detector CT system (2) Compared with the conventional CCTA with 10 s contrast injection duration, the new contrast injection protocol of using shortened injection duration (to 8 s) and late triggering reduces contrast dose to 36.2 ml, while maintaining adequate enhancement in vessels and reducing contrast-related artifacts.

INTRODUCTION

With the rapid development of CT equipment and technology, the image quality and success rate of coronary CT angiography (CCTA) is improving, providing more accurate information for clinical evaluation of coronary artery disease. Adequate enhancement in coronary vessels is the basic requirement for the diagnosis of vascular stenosis and plaques, and is dependent on the concentration of the contrast agents, injection volume and injection rate.¹ On the other hand, since the iodine contrast-medium used in the CCTA examination is excreted by the kidney, it may have potential renal nephrotoxic effect.² In addition, excessive injection of contrast-medium may result in retention of contrast in the right

atrium and superior vena cava during the scan, appearing artifacts that affect the diagnosis. Therefore, it is crucial to balance image quality and contrast dose and optimize contrast dose injection protocols in CCTA.

The injection duration is a key factor affecting the enhancement in vessels and the amount of contrast media used after we have selected a certain injection rate in the CCTA examination. Traditionally, it takes about 5 s or more scanning time to cover the entire heart on a 64-slice CT scanner and 5 to 6 s scan delay after triggering for patient to follow the breath-holding command. Studies have shown that to ensure adequate enhancement in coronary vessels at the end of scanning, the injection duration should not be less than 10 s on a 64-slice CT scanner.^{3,4} The recently

published CCTA multicenter randomized trial results indicate the use of contrast injection time of 15 s for CT scanners with 64-detector rows or more.⁵ However, with the introduction of a 16-cm wide-detector CT system, CCTA acquisition time has been greatly reduced to less than 1 s and CCTA may be performed with free-breathing that shortens the required delay time after triggering the scan. The current contrast injection duration may not be appropriate for CCTA of such short scan duration and scan delay. The purpose of this study was to investigate the feasibility of using shortened contrast injection duration in CCTA on a 16-cm wide-detector CT to reduce contrast dose and maintain image quality, comparing with the 10 s contrast injection duration protocol in conventional CCTA.

METHODS AND MATERIALS

This study was approved by local institutional review board. Informed written consent was obtained by all the patients.

Patient population

This study was designed as a prospective study, and was approved by the institutional review board of our hospital. All participants gave written informed consents. One author (JL) is an employee of GE Healthcare, the manufacturer of the CT system used in this study. The other authors, who are not GE Healthcare employees, had control of the data and information that might have represented a conflict of interest for (JL). 106 subjects (58 males and 48 females; age: 30–81 years, mean age: 57.5 ± 10.6 years) with clinically suspected coronary heart disease or having high risk factors of coronary heart disease were randomly enrolled into one of the two groups (Group A: experimental group, and Group B: control group) between March and October of 2017. The basic information of patients, including age, sex, heart rate at the time of scanning, height and weight, was recorded. Patients with the following condition were excluded: 1. known to be allergic to iodine; 2. renal insufficiency (estimated glomerular filtration rate $<30 \text{ ml min}^{-1} \text{ s}^{-1}$);⁴ 3. with hyperthyroidism; 4. after coronary stent implantation, coronary artery bypass grafting or with cardiac pacemaker implantation; 5. with severe coronary calcification and severe stenosis or occlusion of coronary arteries that affecting the CT value measurement in coronary arteries.

Contrast-medium injection protocols

The contrast injection was performed by a double-syringe power injector. The contrast medium Iopamiro (370 mgI ml^{-1}) at a patient weight-dependent dose rate of 25 mgI/kg/s was used in both groups, while the injection duration was different. Group A used an injection duration of 8 s, and Group B the routine 10 s. The injection rate and total contrast medium dosage were determined using formula (1) and (2), respectively.

$$\text{Injection rate (ml/s)} = \frac{25 (\text{mgI/kg/s}) * \text{weight (kg)}}{370 (\text{mgI/ml})} \quad (1)$$

$$\text{Dosage of contrast medium (ml)} = \text{injection rate (ml/s)} * \text{injection time (s)} \quad (2)$$

In this study, we limited the injection rate to be less than 6.0 ml s^{-1} for safety consideration. In both groups, 30 ml physiological saline each was injected at the same speed before and after the contrast medium injection to prepare vessels and to ensure a high utilization rate of contrast medium.⁶ The injection rate, contrast medium dosage and enhancement duration (defined as the time between the start of positive enhancement in the aortic sinus and the finish of CCTA scan) were recorded for all subjects.

Scanning parameters

All CCTA procedures were performed on a 256 row multislice CT scanner with 16-cm wide-detector collimation (Revolution CT, GE Healthcare, Waukesha, WI) using the prospective ECG triggered cardiac scan mode. All subjects were scanned in the free-breathing condition. Patients were asked to be steady and to have a shallow breath during the scanning.

After connected to a ECG monitor, a non-contrast scan was first performed to evaluate the calcification scores followed by contrast-enhanced CCTA. The contrast enhanced scan range was from 1 cm beneath the bifurcation of the trachea to 1 cm beneath the diaphragm. CCTA was performed using a prospective ECG triggering within one heartbeat. The bolus tracking technique was used to control the start of CCTA in both groups: Contrast medium was injected following the saline flush and the monitoring scans started immediately after the start of the contrast injection with the region of interest (ROI) for monitoring the contrast enhancement placed in the descending aorta one centimeter below the bifurcation of the trachea, covering one third of the cross section of the blood vessel; CCTA was triggered when the preset threshold was reached in the monitoring ROI but the real scan started after a pre-defined delay time after the triggering. In our study, both groups used the preset threshold of 220HU and delay time of 1.6 s. These values were higher than the 80–100 HU threshold and shorter than the 5–6 s delay time in conventional CCTA. The other scanning parameters were as follows: tube voltage: 120kV; tube current: smart mA (100–700 mA); gantry rotation time: 0.28 s r^{-1} ; detector width: 120–160 mm dependent on the patient heart size. The CCTA images were reconstructed using the CCTA scan data with the thickness of 0.625 mm using the new generation adaptive statistical iterative reconstruction (ASIR-V) algorithm (at 50% strength) at the best cardiac phase. The best cardiac phase for image reconstruction was automatically selected by the Smartphase technique on the scanner.

To ensure the consistency, all subjects were examined by the same technician and assisting nurse. The volume CT dose index (CTDI_{vol} , in mGy) and dose-length-product (DLP, in $\text{mGy} \times \text{cm}$) were recorded by the system and the effective dose in millisieverts (mSv) was estimated as the product of DLP and a conversion coefficient k . The k value of $0.014 \text{ mSv/(mGy-cm)}$ for the chest was used.

Image quality analysis

The reconstructed axial images were transmitted to a GE Advantage Workstation (ADW4.6, GE Healthcare, Waukesha, WI). The CT values in the target blood vessels were measured by a

deputy chief physician for CT vascular imaging diagnosis who was blinded to patient clinical data and the contrast medium injection protocols. The CT values of the right coronary artery (RCA), left anterior descending (LAD) and left circumflex (LCX) at the proximal (1 cm from the point of origin), middle and distal segments, and aortic sinus (AS) (at the level of origin of left coronary artery) were measured with image display Window Width of 800 HU and Window Level of 100 HU.⁷⁻⁹ Coronary segments were subdivided according to the 18-segment model of the Society of Cardiovascular Computed Tomography guidelines.¹⁰ The round ROI for AS was larger than 150 mm², and placed in the center of the vessel to avoid calcification and plaque during measurement. Segments with a diameter of at least 1.5 mm were included. CT values of the three main coronary arteries (RCA, LAD and LCX) at the proximal, middle and distal segments were averaged to produce the average values for these segments.

The subjective image quality was evaluated by another deputy chief physician for CT vascular imaging diagnosis who was also blinded to patient clinical data and the contrast medium injection protocols using a four-point scale as follows: 4 (excellent) = excellent image quality, great vascular enhancement, smooth and clear vessel contour; 3 (good) = good image quality, good vascular enhancement, minor contrast-induced image degradation, clear contours, sufficient diagnostic information; 2 (adequate) = adequate image quality and vascular enhancement, moderate contrast-induced image degradation that affecting vessel lumen evaluation; 1 (poor) = non-diagnostic, not enough or no vascular enhancement, severe contrast-induced artifacts. Scores greater or equal to 2 were considered diagnostic.

Statistical analysis

Microsoft excel file was used to record the data, and commercially available software SPSS20 (IBM, New York, NY) was used for statistical analyses. Continuous variables were expressed as mean $\pm$ standard deviation (SD). The independent-samples *t* test was used to compare the general patient data, radiation dose, total contrast dose, injection rate, enhancement duration and the mean CT value of each ROI. The χ^2 test was used to compare patient gender. Fisher exact test was applied to analyze the subjective scoring and contrast-related artifacts in the right atrium and superior vena cava. A *p* value of less than 0.05 was regarded as statistically significant.

RESULTS

Patient demographic

All subjects were successfully examined without any adverse reactions. There was no significant difference between the two groups in sex, age, patient heart rate, weight and body mass index (BMI). The summary is displayed in Table 1.

Objective image quality analysis

The mean CT value in the aortic sinus, proximal, middle and distal segments of the three main coronary arteries were tested to show no significant difference between the two groups (*p* = 0.143, *p* = 0.152, *p* = 0.066, *p* = 0.209, respectively). The two groups achieved the similar enhancement in the main vessels, and all images were acceptable for diagnosis. The enhancement results are summarized in Figure 1.

Subjective image quality analysis

There was no significant difference in the subjective image quality score between the two groups (*p* = 0.751). 38 (76%)

Table 1. Patient basic information, scan and contrast medium injection-related parameters

	Group A (<i>n</i> = 50) 8 s injection duration	Group B (<i>n</i> = 56) 10 s injection duration	<i>p</i> value
Basic information			
Male (%)	24 (48%)	34 (60.7%)	0.189
Age (year)	57.9 $\pm$ 10.6	57.1 $\pm$ 10.7	0.703
BMI (kg·m ⁻²)	24.4 $\pm$ 3.3	24.3 $\pm$ 2.6	0.776
Heart rate (bpm)	70.4 $\pm$ 15.0	70.3 $\pm$ 14.3	0.965
Injection-related parameters			
Injection rate (ml s ⁻¹)	4.5 $\pm$ 0.71	4.6 $\pm$ 0.63	0.401
Dosage (ml)	36.2 $\pm$ 5.7	46.4 $\pm$ 6.3	<0.001
Zero-to-trigger (s) ^a	5.43 $\pm$ 1.12	5.67 $\pm$ 0.95	0.237
Delay time (s) ^b	1.56 $\pm$ 0.07	1.56 $\pm$ 0.08	0.738
Scan duration (s)	0.52 $\pm$ 0.13	0.54 $\pm$ 0.14	0.605
Enhancement duration (s) ^c	7.52 $\pm$ 1.14	7.77 $\pm$ 0.99	0.234

BMI, body mass index; ED, effective dose;

^aZero-to-trigger: time between the start of the positive enhancement and reaching 220 HU in the aortic sinus;

^bDelay time: time between the trigger and the start of scan;

^cEnhancement duration: time between the start of positive enhancement in the aortic sinus and the finish of CCTA scan, sum of zero-to-trigger, delay time and scan duration.

Figure 1. Comparison of CT values between two groups (AS): CT value for aortic sinus; proximal: average CT value for the proximal segments of right coronary artery (RCA), left anterior descending (LAD) and left circumflex (LCX); middle: average CT value for the middle segments of RCA, LAD and LCX; distal: average CT value for the distal segments of RCA, LAD and LCX.

and 12 (24%) had scores of 4 and 3, respectively in Group A, while 39 (66.7%), 16 (30%) and 1 (3.3%) had scores of 4, 3 and 2, respectively in Group B. Neither groups had images scored at 1. However, the contrast-related artifacts in the right atrium and superior vena cava appeared in 9 patients in Group B reducing the image quality scoring and diagnostic confidence, 0 in Group A ($p = 0.003$). These results are showed in Table 2 and image examples are shown in Figure 2a,b,d and e.

Radiation and contrast medium dosage

The scan time for CCTA was less than 0.9 s for all patients in both groups (0.52 ± 0.13 s in Group A vs 0.54 ± 0.14 s in Group B, $p = 0.605$). There was no difference in radiation dose between the two groups (1.93 ± 1.02 mSv in Group A vs 1.66 ± 1.08 mSv in Group B, $p = 0.189$), and no difference between the two groups

with respect to the contrast injection rate (4.5 ± 0.7 ml s⁻¹ in Group A vs 4.6 ± 0.6 ml s⁻¹ in Group B, $p = 0.401$). On the other hand, the contrast medium dosage between the two groups had significant difference (36.2 ± 5.7 ml in Group A vs 46.4 ± 6.3 ml in Group B, $p < 0.001$), the contrast medium dosage of Group A decreased by 22% compared with that in Group B. These results are summarized in Table 1.

Enhancement duration

There was no significant difference between the two groups in the enhancement duration: 7.52 ± 1.14 s in Group A vs 7.77 ± 0.99 s in Group B, ($p = 0.234$) (Table 1). Figure 2c,f shows an example of the enhancement duration measurement for the two groups.

DISCUSSION

In our study, we investigated the feasibility of using shortened contrast injection duration in CCTA on a 16-cm wide-detector CT for reducing contrast dose and maintaining image quality. We compared two patient weight-dependent contrast medium injection protocols with the proposed 8 s injection duration and the conventional 10 s injection duration. Our results showed that the two different injection protocols can achieve the similar enhancement of between 300 and 420 HU in all main coronary arteries. However, the use of 8 s contrast injection protocol reduced contrast dose by 22% compared with the conventional 10 s protocol (36.2 ± 5.7 ml vs 46.4 ± 6.3 ml). The 36 ml contrast dosage for CCTA patients in our study was about 50% less than the 60–90 ml recently reported in a CCTA multicenter trial paper.^{5,9,11,12} Furthermore, contrast-related artifacts caused by the right atrium and superior vena cava because of the retention of excess contrast medium occurred in 9 (16%) patients in the conventional 10 s contrast injection group (Group B). The use of the shortened contrast injection further reduced this type of artifacts to 0 in the 8 s group (Group A). In our study, we further analyzed the enhancement duration (the time between the start of positive enhancement in the aortic sinus and the finish of CCTA scan) to validate the selection of 8 s injection protocol. Our results indicated that the average enhancement duration in CCTA for our patient population was about 7.6 s, suggesting the 8 s contrast injection duration was adequate and appropriate for ensuring enhancement of coronary vessels at the end of scanning.

Optimizing contrast medium delivery to obtain proper contrast enhancement is very important in the diagnosis of coronary artery disease. Low enhancement level in the vessels reduces the contrast between coronary artery and the surrounding tissue, affecting the identification of vessel and stenosis, and the separation of vessels from plaque and thrombus. On the other hand, over enhancement may also affect the correct measure of calcifications and plaques, causing underestimate of the area of non-calcified plaques, thus underestimating the extent of the stenosis. In addition, the increased use of iodinated contrast-medium may increase the risk of contrast-induced nephropathy (CIN). Many studies have shown that CIN is closely related to an existing renal insufficiency and the large amount of contrast medium.^{13–16} Therefore, reducing the amount of contrast medium in CCTA examination is one of the key factors to prevent its adverse

Table 2. Subjective score and contrast-related artifacts

	Group A (<i>n</i> = 50)	Group B (<i>n</i> = 56)	<i>p</i> value ^{<i>b</i>}
Subjective score			0.738
Score 4	38	39	
Score 3	12	16	
Score 2	0	1	
Score 1 ^{<i>a</i>}	0	0	
Contrast-related artifacts			
(Yes)	0	9	0.003

^aScore 1 was considered non-diagnostic.

^bFisher exact test.

Figure 2. Comparison of image quality and enhancement duration between the two groups. (a–c) male, weight = 80 kg with the proposed 8 s injection duration protocol. contrast dosage = 43 ml, injection rate = 5.4 ml s^{-1} , and enhancement duration* = 7.4 s. CT value of AS = 337 HU, no contrast-related artifacts in the right atrium and superior vena cava, subjective score was 4. (d–f) female, weight = 68 kg with the conventional 10 s injection duration protocol., contrast dosage = 46 ml, injection rate = 4.6 ml s^{-1} , and enhancement duration** = 7.5 s CT value of AS = 449 HU, have contrast-related artifacts in the right atrium and superior vena cava (where red arrows point in (d) and (e), subjective score was 3. *The time between the start of positive enhancement in the tracked ROI and the end of the scan: sum of the time-to-trigger time (5.3 s, 2c, between the two arrows), system scan delay time (1.6 s) and scan time (0.5 s). **The enhancement duration of 7.5 s was the sum of time-to-trigger time (5.5 s, 2f, between the two arrows), delay time of 1.6 s and scan time of 0.4 s.

effects. There has been a lot of effort to reduce the use of contrast medium, and the most effective way is to use the lower tube voltages when possible to achieve similar enhancement at lower contrast dose.^{7,17–19} In our study, we did not investigate the use of lower tube voltages such as 100 or 80 kV, and instead focusing on the investigation for additional dose reduction methods. However, the use of lower tube voltages in CCTA is certainly not mutually exclusive to the method we investigated in this paper and can be easily combined.

The use of 10 s or longer contrast injection duration in conventional CCTA was established based on older generations of CT scanners with 4 cm or less detector collimation that require 5 s or more scan time to cover the entire heart and 5 to 6 s scan delay after triggering for patient to follow the breath-holding command. The relatively long scan time requires a longer enhancement plateau to ensure adequate enhancement for distal cardiac vessels, as suggested by the guideline of Asian Cardiovascular Imaging.⁴ And the recently published CCTA multicenter randomized trial results indicate the use of contrast injection time of 15 s for CT scanners with 64-detector rows or more.⁵ The introduction of a 16-cm wide-detector collimation has changed the scan mode from the slow helical mode (for high heart rate patients) or multisequential axial mode (for low or medium heart rate patients) to a single prospective axial scan mode that

covers the entire heart in less than 1 s for patients of all heart rates. Furthermore, with the 16-cm wide-detector collimation, CCTA in free-breathing is feasible and demonstrates excellent image quality.^{12,20} This scan mode change not only requires more precise timing for the peak enhancement, but also enables shorter enhancement plateau thus shorter injection duration. There have been several previous studies that investigated the feasibility of contrast medium volume reduction in CCTA using the 320-row wide-detector system,^{11,21,22} and demonstrated the ability of achieving similar image quality at reduced contrast dosage. However, none of the works focused on investigating the impact of different contrast injection protocols. Hein et al¹¹ randomly assigned 40, 50, 60 and 70 ml contrast medium to 4 different groups and compared their image quality; Oda et al²¹ focused on the use of 80 kV tube voltage to reduce 25% contrast volume with same contrast injection protocol; and Kim et al²² compared the image quality and diagnostic accuracy between the group with 40 ml and group with 60 ml contrast volume and concluded that image quality and diagnostic accuracy were similar between the two groups. In our study, we used a 256-slice, 16-cm wide-detector CT system with 0.28 s gantry rotation speed. All CCTA scans were performed in less than 0.9 s with free-breathing which enable the minimum scan delay of 1–2 s after the scan triggering. We adapted the patient weight-dependent contrast injection protocol and applied higher-than-normal

threshold for triggering CCTA scan to ensure adequate and more consistent enhancement among patients of different weights and different cardiac functions. We analyzed the zero-to-trigger time and the enhancement duration of all subjects and found that the mean zero-to-trigger time (between the start of enhancement to reaching 220 HU attenuation) in aortic sinus was 5.43 ± 1.12 s in group A, and 5.67 ± 0.95 s in group B with the scan protocol in our study (120 kVp and 370 mgI ml^{-1} iodine concentration), and the enhancement duration (the time between the start of enhancement in aortic sinus and the finish of CCTA scan) was 7.52 ± 1.14 s and 7.77 ± 0.99 s for groups A and B, respectively with no statistically significant difference. This finding suggested that scans finished about 8 s after the contrast entered the aortic sinus and the continuous injection of contrast medium beyond that point was redundant and may even contribute to the excessive contrast medium buildup in the right atrium and superior vena cava. We speculate that the zero-to-trigger time will be shorter if lower tube voltage is used with the same dose rate of $25 \text{ mgI kg}^{-1} \text{ s}^{-1}$, requiring even shorter injection duration and further contrast dose reduction.

It has been demonstrated in previous studies that patient weight is one of the main factors affecting the coronary artery enhancement.^{9,23–25} In routine CCTA, constant contrast dosage with constant injection rate is often used. This will result in nonuniform enhancement of coronary arteries for different patients. To ensure the consistent and uniform enhancement in vessels, we have done two things in our study. One thing was to use an individualized contrast medium injection protocol with patient weight-dependent contrast dose calculation. The contrast injection time was fixed and the injection flow rate was adjusted. The other measure was to adjust the triggering threshold from the common 80 HU to a higher 220 HU and perform CCTA with the minimum scanner delay time of about 1.6 s instead of the 8 s in the conventional CCTA with breath-holding. This change was enabled by the fact that breath-holding is not required on our CT scanner with 16-cm wide-detector that covers the entire heart with less than 1 s.²⁰ In conventional CCTA with breath-holding, longer delay time is needed for generating the breath-holding instruction and for patients to follow the instruction. By using a threshold much closer to the target enhancement value in vessels and shorter scan delay we could consistently achieve CT enhancement of 300–420HU in the main coronary arteries and across patient population.

It is worth pointing out that the 22% contrast dose reduction was an expected mathematic outcome considering that both groups had similar body weight distributions and the contrast volume injected was based on the patient weight. Furthermore, since contrast medium was not shared between patients and the currently contrast medium is stored in a 50 ml bottle, even though the average total contrast volume in the study group was only 36 ml, the contrast dose saving was not converted into the economic saving for patients. Perhaps smaller contrast medium bottles are needed to be more economic.

There were several limitations in this study. First, this was a single center study with limited number of patients, it is necessary to further expand the sample size and conduct a multicenter study to verify the conclusion. Second, in this study, the injection rate was calculated based on the body mass of the subjects, and for patients with excessive body mass, the injection rate would be too high to be safely performed. To avoid the potential risks of contrast medium extravasation, we limited the injection rate to be less than 6.0 ml s^{-1} , which corresponded to a maximum patient weight of 89.4 kg, which meant that patients with weight greater than 90 kg (6 subjects in our study) may not receive desired contrast dosage. Third, in our study, we used a single tube voltage of 120 kV for all patients. Since tube voltages have effect on the enhancement, further studies are needed to investigate the use of patient-dependent tube voltages to further decrease the injection duration and/or contrast concentration. Fourth, our study only evaluated the vessel CT enhancement and image quality, further validation against invasive angiography is required if diagnostic accuracy is desired. Fifth, our study did not include patients with poor cardiac function. Further studies are needed on whether our protocol is suitable for patients with cardiac impairment. On the other hand, even though reduced cardiac output may still result in dense contrast in the SVC in such patients despite shortened infusion times, we believe shortened infusion times may reduce the strength and occurrence of dense contrast.

In conclusion, it is feasible to shorten contrast injection duration to 8 s in CCTA on a 16-cm wide-detector CT system to significantly reduce contrast dosage, maintain adequate enhancement in vessels and at the same time reduce contrast-related artifacts.

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