

Ultra-low dose one-step CT angiography for coronary, carotid and cerebral arteries using 128-slice dual-source CT: A feasibility study

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Abstract. Atherosclerotic diseases are systemic and patient outcomes depend on comprehensive imaging evaluation. Computed tomography angiography (CTA) is a powerful tool used to assess atherosclerosis. However, the scanning protocol is designed for cardiovascular and cerebrovascular imaging, which require considerations into the radiation dose, contrast agent and image quality. The purpose of the present study was to evaluate ultra-low dose one-step CTA for coronary, carotid and cerebral arteries with a low concentration contrast agent. A total of 78 patients were enrolled and randomly divided into two groups: Group A (n=38) and B (n=40). High-pitch CTA for coronary, carotid and cerebral arteries with a tube voltage of 70 or 80 kVp and 40 ml contrast agent (270 mgI/ml) was performed by a 128-slice dual-source CT scanner for group A. Standard high-pitch CTA with a tube voltage of 100 kVp and 60 ml contrast agent (370 mgI/ml) was conducted for group B. The image quality, radiation dose and amount of contrast agent

in group A were evaluated and compared with group B. The dose length product for groups A and B was 62.95 ± 21.54 vs. 160.15 ± 15.13 mGy cm, respectively ($t = -23.157$, $P < 0.001$). The mean total iodine content was 10.8 ± 0 mg for group A and 22.2 ± 0 mg for group B. In total, 99.4% of the arterial segments could be assessed for the two groups ($\chi^2 = 0.267$, $P = 0.606$). The results revealed that ultra-low dose one-step high-pitch CTA can provide assessable image quality, and minimize the radiation dose and contrast agent.

Introduction

Atherosclerotic disease is systemic and, with the same pathogenesis, atherosclerosis of the coronary, carotid and cerebral arteries usually exists at the same time with clinical relevance (1-4). Cardiovascular and cerebrovascular diseases are the primary cause of mortality in China, particularly in the developed area (5). Screening, diagnosis and evaluation are the most important means to reduce the threat of mortality in patients with atherosclerotic disease (5). Compared with gold standard digital subtraction angiography, computed tomography angiography (CTA) is a non-invasive and high-powered tool that can assess atherosclerosis and provide accurate information on arterial anatomy (2,6), via CTA (2), digital subtraction angiography (3), ultrasound (4) and magnetic resonance angiography (7).

However, the CT scan protocol is designed for cardiovascular and cerebrovascular imaging, and therefore considerations must be made in regard to the radiation dose, iodine load and image quality (2). Due to the risks of radiological examination, the radiologists and engineers must consider the physical characteristics of CT scanners. The 128-slice dual-source CT (DSCT) has ~2 vertical tube detector systems, a rotation time of up to 280 msec and a table-moving speed of up to 45.8 cm/sec. These physical characteristics can significantly reduce the radiation dose and the amount of contrast agent required (8,9). High temporal resolution can also maintain or improve image quality for CT coronary angiography (CTCA) (8,9). In previous studies, cardiovascular and cerebrovascular imaging has utilized the

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Abbreviations: ATCM, automated tube current modulation; BMI, body mass index; bpm, beats per minute; BW, body weight; CNR, contrast-to-noise ratio; CPR, curved planar reconstruction; CTA, CT angiography; CTCA, CT coronary angiography; CTDI, volume CT dose index; DLP, dose length product; DSCT, dual-source CT; ED, effective dose; HR, heart rate; HRv, heart rate variability; LAD, left anterior descending; LCX, left circumflex; LM, left main; RCA, right coronary artery; ROI, region of interest; SNR, signal-to-noise ratio; TDC, time density curve; ULD, ultra-low dose

Key words: radiation dose, image quality, computed tomography angiography, high-pitch scan, contrast agent

128-slice DSCT, obtaining a reliable image quality with a low-dose length product (DLP; 224.83–256.30 mGy·cm) and contrast agent (60–80 ml) (10,11). However, these studies were conservative with a high tube voltage (100 or 120 kV) and high concentration contrast agent (370 mg/ml), and did not utilize the advantages of 128-slice DSCT, particularly by combining the iterative algorithm and ultra-low tube voltage to reduce the radiation dose for the patients of standard body type. Cardiovascular and cerebrovascular imaging was also performed with 256-slice CT and first-generation DSCT, with a higher radiation dose and amount of the contrast agent when compared with those of the second-generation DSCT (12,13).

In addition, several studies have shown that CTCA using a high-pitch scanner can maintain the sensitivity and negative predictive value, with a radiation dose <0.2 mSv and the contrast agent (370 mgI/ml) as low as 30 ml (14–17). By combining a low voltage setting and the iterative algorithm, it may be possible that a low volume and low concentration of the contrast agent could be used for cardiovascular and cerebrovascular high-pitch scanning (17,18). As indicated in the present study, this reliable and safe tool for atherosclerosis assessment should be considered for use in clinical practice (14,15,17,18).

The aim of the present study was to combine high-pitch scanning, low tube voltage, iterative algorithm and low-concentration contrast agent to evaluate an ultra-low dose (ULD) one-step CTA for coronary, carotid and cerebral arteries.

Materials and methods

Patients. The present prospective study was approved by the Ethics Committee of Inner Mongolia Medical University Affiliated Hospital (Inner Mongolia, China), and all recruited patients signed informed consent forms. A total of 80 patients who were suspected to have cardiovascular and cerebrovascular diseases were enrolled in the present study between January 2016 and May 2017. The inclusion criteria were as follows: i) Heart rate (HR) ≤ 70 beats per minute (bpm), or HR could be reduced to <70 bpm by using oral metoprolol; ii) HR variability (HRv) ≤ 5 bpm; iii) body weight (BW) ≤ 70 kg; and iv) body mass index (BMI) ≤ 28 kg/m². The exclusion criteria included: i) poor breathing; ii) extravasation of the contrast agent; iii) previous iodine allergy; and iv) underactive renal function (serum creatinine ≥ 120 μ mol/l). All patients received nitroglycerin sublingually 5 min prior to the examination.

According to the treatment plan, all patients were randomly divided into two groups (groups A and B), among which 2 patients (all in Group A) were excluded from the study population, as they had either a HRv of ≥ 5 bpm (n=1) or poor breathing (n=1). Finally, a total of 38 patients in group A and 40 patients in group B were enrolled. The median age was 58 years old (range: 25–80 years old), including 34 males and 44 females. The data of the two groups is presented in Table I, and a flow chart of the present study is presented in Fig. 1.

Scanning and contrast agent injection technology. The elbow vein was catheterized with an 18-gauge catheter (BD Intima II 18G; BD Biosciences; Becton, Dickinson and Company, Franklin Lakes, NJ, USA), and the indwelling

needle was tested with 20 ml physiological saline prior to the contrast agent injection. All CTA examinations were performed using a second-generation 128-slice DSCT system (Somatom Definition Flash; Siemens Healthineers, Erlangen, Bavaria, Germany) with a Stellar Photon Detector. The acquisition parameters were as follows: i) Detector collimation was 2x64x0.6 mm; ii) gantry rotation time of 280 msec; iii) a pitch of 3.4 for high-pitch scan; iv) the tube current for both groups was set to 320 mAs, and the automated tube current modulation (ATCM; CAREdose 4D; Siemens Healthineers) was enabled; v) tube voltage was set to 70 or 80 kVp for group A (experience group) and 100 kVp for group B (control group).

For the bolus-tracking technique, a region of interest (ROI) was placed on the left atrium and image acquisition was initiated at 5 sec until the attenuation of left atrium was >50 HU in group A. In group B, a conventional setting with a ROI on the aortic root (above 100 HU) and a delay time of 5 sec was used. The phase to be triggered was set at 55% of the R-R interval. The low concentration contrast agent (iodixanol injection 270 mgI/ml; GE Healthcare, Chicago, IL, USA) was used for group A. The high-concentration contrast agent (iopromide 370 mgI/ml; Bayer, Shanghai, China) was used for group B. Following this, 40 ml of saline was injected with an injection rate of 5.0 ml/sec for the two groups. All patients were scanned from 2 cm below the diaphragm to the top of the head. All CTA technique parameters are presented in Table I.

Image reconstruction and processing. The section thickness was reconstructed with 0.75 mm. A medium smooth convolution kernel (I26f) and an iterative algorithm with SAFIRE 3 (a medium strength level of 3, strength 1–5) were used for group A. Filter back projection with a medium smooth convolution kernel (B26f) was used for group B. Image processing and storage were performed with an advanced three-dimensional workstation (AW version 4.4; GE Healthcare). The curved planar reconstruction (CPR) technique was applied for the evaluation of the three types of coronary arteries, and image quality was evaluated on CPR as well as axial images of vessels and segments.

Radiation dose and contrast agent. Volume CT dose index (CTDI_{vol}) and DLP were recorded for each patient. The effective dose (ED) was calculated with the following formula: $ED = DLP \times k$. In the present study, the k values for chest and head-neck were 0.014 and 0.0013 mSv/mGy·cm, respectively (19). The injection volume was recorded by the operators. The mean total iodine content was calculated according to the product of the concentration and volume.

Image quality

Subjective evaluation of image quality

Coronary artery. The coronary artery was divided into 15 segments according to the standards of The American Heart Association (20): The right coronary artery (RCA) was divided into segments 1–4, left main (LM) was assigned segment 5, left anterior descending (LAD) was divided into segments 6–10, and the left circumflex (LCX) was divided into segments 11–15.

Table I. Baseline data.

Parameters	Group A (n=38)	Group B (n=40)	Statistics	P-values
Age (years)	60.47±10.69	55.60±9.47	2.134 ^a	0.036
Female (%)	71.05	42.50	6.461 ^b	0.013
Body height (cm)	162.13±5.45	163.80±6.06	-1.275 ^a	0.206
BW (kg)	61.55±7.46	64.20±5.45	-1.796 ^a	0.076
Body mass index (kg/m ²)	23.41±2.58	23.97±2.12	-1.039 ^a	0.302
Heart rate (beats per second)	57.61±7.11	60.20±8.49	-1.459 ^a	0.149
Scan length (cm)	55.30±4.43	56.64±3.39	-1.507 ^a	0.136
Scan mode	High-pitch scan	High-pitch scan	-	-
Tube voltage	70 kVp for BW≤60 kg 80 kVp for 60 kg<BW≤70 kg	100 kVp	-	-
Tube current	320 mAs	320 mAs	-	-
Bolus tracking	Left atrium trigger	Aortic root trigger	-	-
Contrast agent	5.0 ml/sec for 40 ml (270 mgI/ml)	5.0 ml/sec for 60 ml (370 mgI/ml)	-	-
Algorithm of image reconstruction	Iterative algorithm (SAFIRE 3)	Filter back projection	-	-

^at value and ^bχ² value. BW, body weight.

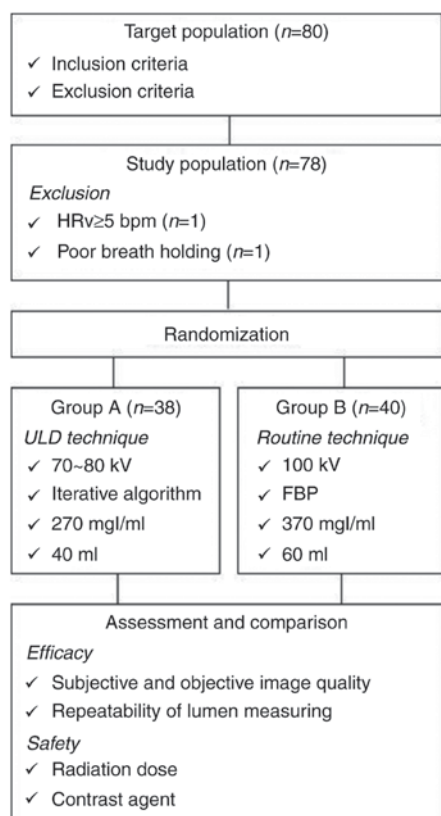


Figure 1. Flow chart of the study design. HRv, heart rate variability; ULD, ultra-low dose; FBP, filter back projection.

Carotid and cerebral arteries. The carotid artery was divided into the following segments: The common carotid, extracranial internal carotid, extracranial vertebral and subclavian arteries. The cerebral artery segments analyzed included the

intracranial internal carotid, intracranial vertebral, anterior cerebral, middle cerebral, posterior cerebral and basilar arteries.

Rule of image quality scale. Arterial diameters of <1.5 mm were not evaluated. The image quality of the arteries was assessed by 4 scores: 4=excellent, with no artifacts; 3=good, with mild artifacts and unrestricted evaluation; 2=assessable, with moderate artifacts, but still evaluable; and 1=unacceptable (21). All images were evaluated by two independent readers (A and B, with 5 and 4 years' experience in cardiovascular diagnosis, respectively) on the AW4.4 workstation.

Objective evaluation of image quality

Coronary artery. The mean attenuation and standard deviation of the aortic root, LM, proximal of the LAD, proximal of the LCX, and proximal of the RCA were measured in all patients by placing ROIs. The standard deviation was measured as the image noise, and the mean attenuation of the background was measured in the adipose tissue around the aortic root.

Carotid and cerebral arteries. Measuring targets on a display length of 1/2 place were used for various vessels, including the common carotid, extracranial internal carotid and extracranial vertebral arteries, as well as the subclavian artery for the carotid artery; the cerebral arteries included the intracranial internal carotid, intracranial vertebral, middle cerebral and basilar arteries. The attenuation of the background for the carotid and cerebral arteries was measured on the adipose tissue from the right lower jaw space and temporal fossa.

Rule of density measuring. The artifacts, vessel wall and plaques were avoided when setting ROIs. The signal-to-noise

ratio (SNR) and contrast-to-noise ratio (CNR) were calculated with the following formulae: $SNR = \text{mean attenuation} / \text{noise}$, and $CNR = (\text{mean attenuation of artery} - \text{mean attenuation of adipose tissue}) / \text{noise}$.

Repeatability of lumen measuring for the experimental group.

There were various measuring targets labeled on the coronary, carotid and cerebral arteries for group A, including the 1/2 display length of the following vessels: LM, LAD, LCX, RCA, and the common carotid, extracranial internal carotid, extracranial vertebral, subclavian, intracranial internal carotid, intracranial vertebral, middle cerebral and basilar arteries. Firstly, according to the targets, the axial image of the lumen was reconstructed and then stored by an operator (C). Secondly, the lumen diameter was measured and recorded by two readers (A and B). Thirdly, the second measurement was completed by assessor A after 30 days. The vessel wall and plaques were not measured. Lumen diameter was obtained using the average value of the maximal and minimal diameters recorded by the assessors.

Statistical analysis. SPSS version 13 software (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Quantitative variables were expressed as the mean \pm standard deviation, and the categorical variables were expressed as frequencies or percentages. The independent samples t-test and Mann-Whitney U-test were employed to compare quantitative variables. The paired t-test was used for paired data comparisons. Categorical variables were compared with the χ^2 test. Inter-reader variability between the two readers in regard to image quality scoring was evaluated with κ statistics. A κ value of <0.20 indicated a poor agreement; a κ value of $0.21-0.40$ indicated a fair agreement; a κ value of $0.41-0.60$ indicated a moderate agreement; a κ value of $0.61-0.80$ indicated a good agreement; and a κ value of $0.81-1.00$ indicated a very good agreement. In the experimental group, measurement correlations between the intra-reader and inter-reader were demonstrated by a scatter plot, and measurement consistency between the intra-reader and inter-reader were indicated using the Bland-Altman plot. The Bland-Altman plot revealed the average difference, and ± 1.96 standard deviation as the consistency of the limits. $P < 0.05$ was considered to indicate a statistically significant difference.

Results

Patient data. CTA for all patients ($n=78$) in the two groups was successfully completed. None of the patients had serious adverse events. The patient data are presented in Table I.

Radiation dose and contrast agent. The $CTDI_{vol}$ was 1.23 ± 0.41 mGy for Group A and 3.19 ± 1.05 mGy for Group B. Notably, the difference was statistically significant ($t=-10.811$, $P < 0.001$). The DLP was 62.95 ± 21.54 mGy·cm for Group A, and 160.15 ± 15.13 mGy·cm for Group B, which was decreased by 61% ($t=-23.157$, $P < 0.001$). The ED was 0.32 ± 0.11 mSv for Group A and 0.79 ± 0.08 mSv for Group B, which indicated a decrease by 59% in Group A ($t=-22.173$, $P < 0.001$). The contrast agent volume was 40 ± 0 and 60 ± 0 ml for Groups

A and B, respectively. The mean total iodine content was 10.8 ± 0 mg for Group A and 22.2 ± 0 mg for Group B, which indicated a decrease by 51% in Group A. The comparisons of radiation dose and contrast agent in each group were presented in Table II.

Image quality

Subjective evaluation of image quality. There were 2,468 segments evaluated by the two readers, the frequency of which is presented in Table III. Following the Kappa test, $\kappa=0.702$, $P < 0.001$, in consideration of good agreement between two readers, any observation was deemed valid. In the present study, the outcomes recorded by reader A were used.

There were 1,979 segments with a score of 4, 395 with a score of 3, 80 with a score of 2 and 14 with a score of 1. On a per-segment and -patient basis, differences in assessable rates between group A and B were not statistically significant (99.42% vs. 99.45% for per-segment; 84.21% vs. 87.50% for per-patient; data not shown). Notably, patients who had any segment of the arteries that was not assessable would be judged as failure. The mean scores were slightly lower in group A compared with group B (3.74 ± 0.55 vs. 3.78 ± 0.51 , $Z=-1.589$, $P=0.112$); however, the difference was not statistically significant.

In total, 99.19% (489/493) and 99.40% (501/504) of the coronary arterial segments had assessable image quality for groups A and B, respectively; the difference was not statistically significant ($\chi^2=0.167$, $P=0.683$). The mean image scores for the two groups was similar (3.70 ± 0.58 vs. 3.75 ± 0.53 , $t=-1.485$, $P=0.138$). On a per-patient basis, the difference of the proportion of the two groups was not statistically significant [92.11% (35/38) vs. 95.00% (38/40), $\chi^2=0.272$, $P=0.602$].

In total, 99.58% (719/722) of the carotid and cerebral arteries could be assessed for group A and 99.47% (755/759) for group B; the difference was not statistically significant ($\chi^2=0.098$, $P=0.755$). Per-patient the proportion of assessable image quality was 92.11% (35/38) for group A, and 92.50% (37/40) for group B; the difference was not statistically significant ($\chi^2=0.004$, $P=0.948$). Fig. 2 presents high quality images of a normal patient who received an ultra-low radiation dose and iodine load. Fig. 3 presents images obtained by ultra-low dose CTA where coronary artery lesions were clearly displayed. The images included in Figs. 2 and 3 were all obtained from patients in group A.

Objective evaluation of image quality. The mean attenuation and noise of all arteries in group A was significantly increased compared with that observed in group B (567.15 ± 145.47 vs. 490.37 ± 107.35 HU; and 30.00 ± 11.93 vs. 20.92 ± 7.68 HU, respectively; $P < 0.001$ for both). The SNR and CNR were slightly lower in group A compared with in group B (21.58 ± 9.86 vs. 25.54 ± 13.80 ; and 26.32 ± 11.97 vs. 31.87 ± 17.05 , respectively; $P < 0.001$ for both). The mean attenuation and CNR for each artery were presented in Fig. 4.

Sub-group analysis. With a median BW of 63.00 kg as the dividing point, group A was divided into two groups: <63 and ≥ 63 kg. The mean attenuation and SNR for the patients <63 kg was higher when compared with the patients who were ≥ 63 kg (635.96 ± 118.62 vs. 516.24 ± 104.94 ; $t=3.287$, $P=0.002$ for mean

Table II. Comparisons of both groups for radiation dose and contrast agent.

Parameters	Group A (n=38)	Group B (n=40)	t-values	P-values
CTDI _{vol} (mGy)	1.23±0.41	3.19±1.05	-10.811	<0.001
DLP (mGy·cm)	62.95±21.54	160.15±15.13	-23.157	<0.001
ED (mSv)	0.32±0.11	0.79±0.08	-22.173	<0.001
Contrast agent volume (ml)	40±0	60±0	-	<0.001
Total iodine content (mg)	10.8±0	22.2±0	-	<0.001

CTDI_{vol}, volume CT dose index; DLP, dose length product; ED, effective dose.

Table III. Frequency table for Readers to evaluate agreement

Readers/Scores		Reader A				Total
		Score 4	Score 3	Score 2	Score 1	
Reader B	Score 4	1,889	67	0	0	1,956
	Score 3	90	263	27	0	380
	Score 2	0	65	53	0	118
	Score 1	0	0	0	14	14
	Total	1,979	395	80	14	2,468

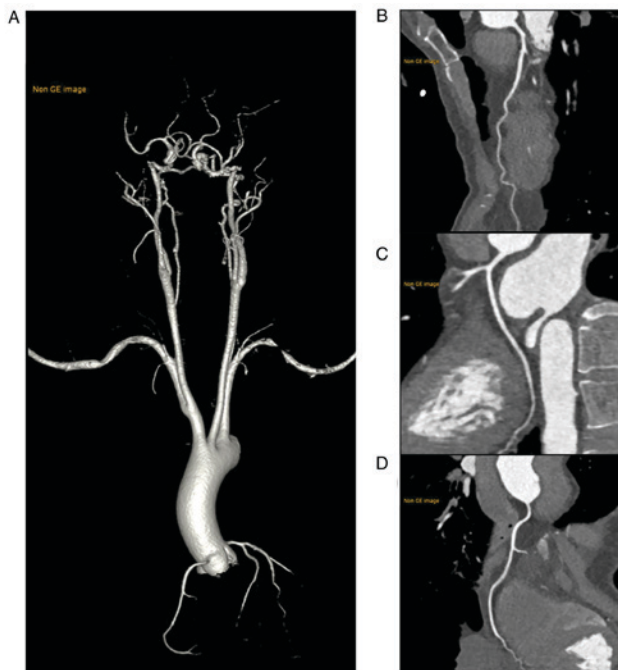


Figure 2. A 58 year old female (body mass index=16.61 kg/m²) with excellent image quality in the (A) carotid, cerebral and coronary arteries, including (B) left anterior descending artery, (C) left circumflex and (D) right coronary artery. Computed tomography coronary angiography was performed by high-pitch scanning (dose length product=33 mGy·cm, injection volume=40 ml).

attenuation; 22.51±2.87 vs.19.98±3.07; t=2.579, P=0.014 for SNR). There was no significant difference between the two sub-groups in regard to noise and CNR (P=0.293 and P=0.050,

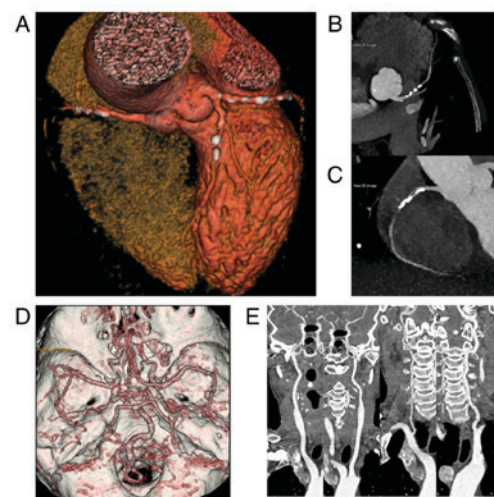


Figure 3. A 69 year old male (body mass index=23.53 kg/m²) with shortness of breath for four years who also presented with dizziness and nausea for 1 week. One-step computed tomography angiography was performed on the coronary, carotid and cerebral arteries for the patient (dose length product=90 mGy·cm, injection volume=40 ml). (A-D) Mixed plaque formation in the proximal segment of (A and B) left anterior descending artery and (A and C) the proximal segment of the right coronary artery; (A) a calcified plaque in the proximal segment of the left circumflex. No abnormalities were observed in the (D) main cerebral arteries and (E) carotid arteries.

respectively). The comparisons of sub-groups for objective image quality were presented in Table IV.

There were negative correlations between BW, and attenuation, SNR and CNR, and the *r* values were -0.535, -0.404 and -0.322, respectively (all P<0.05). There was no correlation between BW and noise (*r*=-0.241, P=0.145).

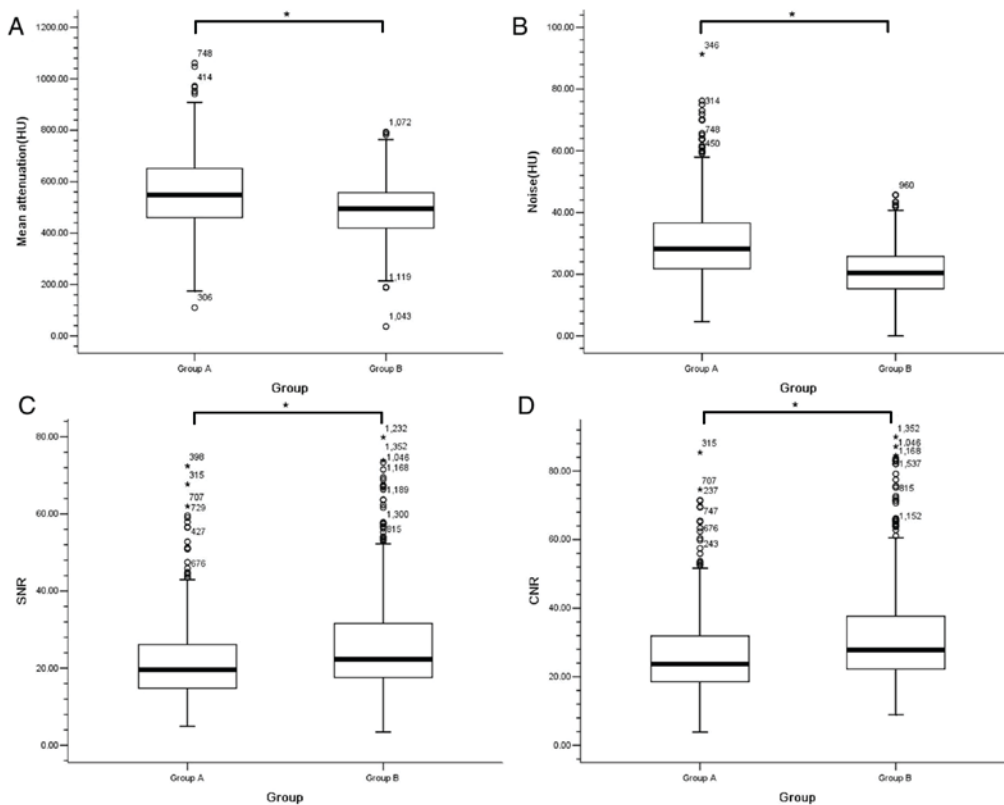


Figure 4. Box plots of objective image quality for arterial segments. (A) Mean attenuation and (B) noise in group A were higher when compared with group B for each arterial segment (all $P<0.001$); The (C) SNR and (D) CNR in group A were slightly lower compared with those observed in group B. * $P<0.001$. SNR, signal-to-noise ratio; CNR, contrast-to-noise ratio.

Per-patient, the mean scores of the coronary artery, and of the carotid and cerebral arteries in group A were 3.70 ± 0.17 and 3.77 ± 0.11 , respectively. The difference was statistically significant (paired t-test: $t=-3.149$, $P=0.003$); however, there was no significant difference in the assessable rate (489/493 vs. 719/722, $\chi^2=0.002$, $P=0.962$).

Repeatability of lumen measuring for the experimental group. The difference of the intra-reader was -0.16 ± 0.47 mm [95% confidence interval (CI): $-1.07, 0.77$]. There were 96% (693/722) of the measuring targets inside the 95% limits of agreement [intraclass correlation coefficient (ICC)=0.954; Fig. 5]. The difference of the inter-reader was -0.16 ± 0.61 mm (95% CI: $-1.35, 1.03$). In total, 95% (686/722) of the measuring targets were inside the 95% limits of agreement (ICC=0.961; Fig. 6).

Discussion

The aim of the present study was to reduce the radiation dose and contrast agent to a very low level for cardiovascular and cerebrovascular CTA. Under the premise of maintaining image assessment, the present results proved that the ED and volume of the contrast agent could be limited to <0.5 mSv and 40 ml, respectively, via a novel scanning protocol in patients with a BW ≤ 70 kg and a BMI ≤ 28 kg/m². Compared with the control group, the ED was decreased by 59% and the amount of contrast agent (total iodine content) was decreased by 51%. The image assessment and attenuation were not affected by the

novel scanning protocol. The reliability for lumen measuring was also verified by quantitative evaluation.

Atherosclerosis-associated correlations between coronary, carotid and cerebral arteries have been reported in various studies (1-4), and it was necessary to use cardiovascular and cerebrovascular CTA for preoperative assessment of the coronary artery via pass-grafting (22). Due to the more accurate anatomical information and non-invasive operation (2,7), cardiovascular and cerebrovascular CTA has the potential to replace other morphological imaging techniques. However, with the potential risks of medical examinations, the use of CTA has been limited in clinical practices, particularly in regard to multiple targets of CT data acquisition, which significantly increase the radiation exposure and the iodine load (2). The present study provided a suitable and repeatable strategy to adapt for clinical requirements. High-pitch scanning has a very fast table-moving speed, which is due to the double tube-detector systems with gaps (8,9). In the present study, only ~ 700 msec was required for scanning (10,11), which is the primary reason to reduce the injection time of the contrast agent. However, a low concentration and volume of the contrast agent were used for CTA, resulting in a decreasing trend in the time density curve (TDC), which affected the arterial enhancement. Therefore, based on previous studies on CTCA (14-18), the present study used 40 ml low concentration contrast agent for the designed protocol. Firstly, the ultra-short scanning time was utilized to provide a sufficient window to identify the peak time. Secondly, increasing the amount of contrast agent could shift the TDC to the right and

Table IV. Comparisons of sub-groups for objective image quality.

Parameters	<63 kg	≥63 kg	t-values	P-values
Attenuation (HU)	635.96±118.62	516.24±104.94	3.287	0.002
Noise (HU)	31.18±5.37	29.14±6.08	1.069	0.292
SNR	22.51±2.87	19.98±3.07	2.579	0.014
CNR	27.60±3.07	23.39±3.48	2.028	0.050

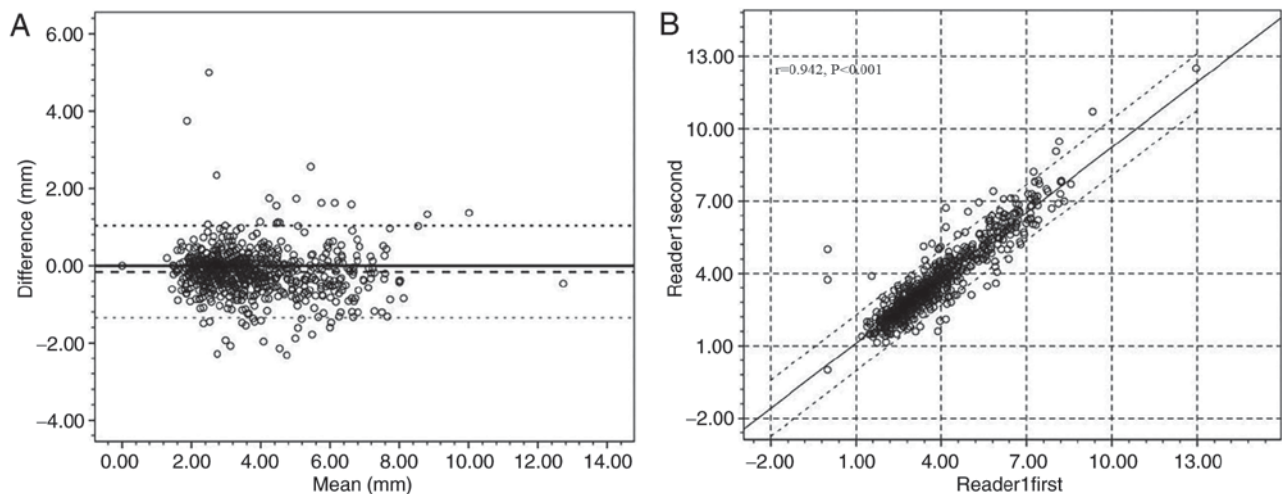


Figure 5. Bland-Altman plot of the measurements (intra-reader) for the (A) low dose setting. In total, 96% of the measuring targets were inside the 95% agreement limits. (B) A scatter plot of the correlations for intra-reader measurements, which revealed a strong correlation, $r=0.942$, $P<0.001$ (Pearson correlation).

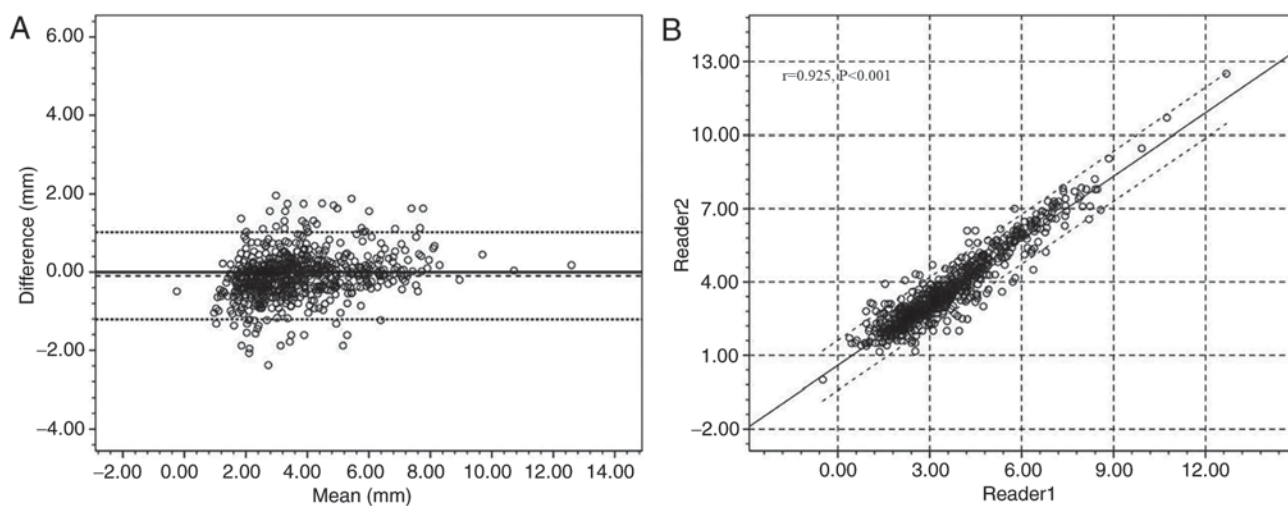


Figure 6. Bland-Altman plot of the measurements (inter-reader) for the (A) low dose setting. In total, 95% of the measuring targets were inside the 95% agreement limits. (B) A scatter plot of the correlations for intra-reader measurements, which revealed a strong correlation, $r=0.925$, $P<0.001$ (Pearson correlation).

up (23). In addition, a fast injection rate of contrast agent was used to make up for the inadequate enhancement. Increasing the injection rate could also shift the TDC to the left and up. According to the above adjustments, the present study improved the arterial attenuation when compared with those observed in previous studies (10-13); the contrast agent volume was reduced significantly in the present study.

Coronary arterial motion is intense and complicated (24); following the high temporal resolution, DSCT can offer

assessable image quality without motion artifacts within a single cardiac cycle (25). Based on the width of several cardiac cycles prior to acquisition, high-pitch scanning requires a suitable acquisition time in order to prospectively predict the correct trigger exposure (10). Calculations revealed that the CTA requires two cardiac cycles for imaging. The scan direction of the conventional CTCA was from head to foot, including a combination of aortic and coronary artery CTA (26). Considering the position of the coronary artery, the present

study changed the scanning direction from foot to head in order to allow part of the coronary artery to be triggered in the first cardiac cycle. This could reduce the transient disturbance of electrocardiograms caused by the fast table-movement, in order to avoid error triggering.

The present study did not include patients with a high HR (>70 bpm), and Goetti *et al* (8) demonstrated that high-pitch scanning had a high failure rate of up to 30% (per patient) in those with a high HR. The first cases using ULD CTCA were reported in several recent studies (14,15,17,18), particularly that of Zhang *et al* (14,15), where excellent image quality was obtained. The contrast agent in the present study was consistent with that used in these studies; however, a CTA with wide coverage was performed in the present study. The primary difference was that the present study used manual bolus tracking by monitoring the left atrium for scanning. According to our previous study (17) and similar literature (27), it is more accurate in regard to timing to monitor the left atrium with such a low volume of contrast agent.

Low-energy X-ray photons can produce a photoelectric effect and increase the arterial signal (11-18,21,27). Tube voltage with low kVp settings could produce an attenuation of >400 HU in the arterial system (14-18). However, this tube voltage reduction could also significantly reduce the radiation dose (8-11,14-18,28), particularly in the improved 128-slice DSCT with a Stellar Photon Detector, which allows for the lowest tube voltage to be set to 70 kVp. Compared with 80 and 100 kVp, 70 kVp could reduce the radiation dose to 75 and 56%, respectively (15). Due to the improved equipment, the radiation dose of the one-step CTA in the present study was significantly lower than that used in previous studies by Sun *et al* (10) and Wang *et al* (11). One-step CTA has been pioneered and demonstrated in previous studies (10-11), but the present study has improved the low dose technique with the help of advantageous equipment. A Stellar Photon Detector can improve the efficiency of photoelectric conversion, and when combined with an iterative algorithm, the low dose technique can reduce the radiation dose and contrast agent while still maintaining the image quality (8,9,29,30).

In the sub-group analysis, the objective image quality was revealed to be affected by BW, including attenuation, SNR and CNR, but had no significant effect on noise. In the equivalent mass injection, there was a negative correlation between BW and attenuation (23), which was also the primary reason for the influence of BW on objective image quality. It was suggested that the injection volume should be linearly adjusted according to BW. Sub-group analysis also demonstrated that BW had no effect on noise, which may provide the stability of ATCM based on patient body type (31). In addition, the image quality of the carotid and cerebral arteries was improved when compared with that of the coronary artery. The may be due to the intense movement of the coronary artery (24). The single phase acquisition of high-pitch scanning also limits further improvements in the image quality (8,9).

There were some limitations in the present study. Firstly, the low sample size. The present study was a feasibility study that analyzed a small sample size, which may have reduced the statistical effectiveness. Secondly, the effectiveness of ULD CTA requires the verification of invasive

angiography; however, the present study validated the reproducibility of the quantitative evaluation and identified that the measurements of lumen diameter using ULD technique could maintain acceptable reliability. It has been indicated that the lumen information obtained by this new technique records reliable measurements. Thirdly, SNR and CNR in the experimental group decreased by ~ 15 and 17% when compared with the control group, and the subjective score also decreased significantly; however, the image assessment and subjective scores between the two groups was not significantly different. In addition, the present study was limited to a cohort of ≤ 70 kg patients and excluded other types of CT scanners, which may diminish the transferability of the present results in obese patients and in studies using other types CT scanners. However, it can be practiced and improved using third-generation DSCT, which can offer higher image quality and lower radiation dose compared with second-generation DSCT (32).

In conclusion, the coronary, carotid and cerebral arteries visualized through one-step high-pitch CTA using second-generation DSCT can provide images of evaluable quality, and minimize the radiation dose and contrast agent.

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Availability of data and materials

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

Authors' contributions

LZ, JB and AL conceived and designed the study. XY, TL, FH, ZW and ZY performed the experiments. LZ, JB and AL wrote the paper. YG and JL analyzed and interpreted the data, and revised the paper critically for important intellectual content. All authors read and approved the manuscript.

Ethics approval and consent to participate

The present prospective study was approved by the Ethics Committee of Inner Mongolia Medical University Affiliated Hospital, and all patients had signed the informed consent form.

Patient consent for publication

All patients provided consent for publication of data.

Competing interests

The authors declare that they have no competing interests.

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