Submillisievert Imaging Protocol Using Full Reconstruction and Advanced Patient Motion Correction in 320-row Area Detector Coronary CT Angiography

Yuko Kawaguchi, MD[1], Shinichiro Fujimoto, MD, PhD[1], Kazuhisa Takamura, MD, PhD[1], Etsuro Kato, MD[1], Shoko Suda, MD[1], Rie Matsumori, MD[1], PhD[1], Makoto Hiki, MD, PhD[1], Kanako K. Kumamaru, MD, PhD[2], Hiroyuki Daida, MD, PhD[1]

1. Department of Cardiovascular Medicine, Juntendo University Graduate School of Medicine, Tokyo, Japan
2. Department of Radiology, Juntendo University Graduate School of Medicine, Tokyo, Japan

Correspondence to:
Shinichiro Fujimoto, MD, PhD
Department of Cardiovascular Medicine, Juntendo University Graduate School of Medicine
2-1-1 Hongo Bunkyo-ku, Tokyo 113-8421, Japan
Telephone number: +81-3-5802-1056
FAX number: +81-3-5869-0627
E-mail: s-fujimo@tj8.so-net.ne.jp

Abstract

Purpose: Radiation exposure remains a concern in the use of coronary CT angiography (CCTA). Full reconstruction (Full) and reconstruction using advanced patient motion correction (APMC) could obtain a lower radiation dose using low tube current scanning in a 320-row Area Detector CT (320-ADCT). The radiation dose for an imaging protocol using Full and APMC in daily practice was estimated.

Methods: A total of 209 patients who underwent CCTA in 1 rotation scanning with 100 kv and adaptive iterative dose reduction 3D in 320-ADCT were enrolled. Imaging protocols were classified into 3 groups based on estimated slow filling time: 1. slow filling time ≥275 msec, Full with 30% of usual tube current (N=43); 2. 206.3 msec ≤slow filling time <275 msec, APMC with 50% of usual tube current (N=48); and 3. 137.5 msec ≤slow filling time <206.3 msec, Half reconstruction (Half) with usual tube current (N=118). Radiation dose was estimated by the effective dose. The diagnostic accuracy of CCTA was compared with that of invasive coronary angiography in 28 patients.

Results: The effective doses of Full, APMC, and Half were 0.77±0.31 mSv, 1.30±0.85 mSv, and 1.98±0.68 mSv, respectively. Of 28 patients, the sensitivity, specificity, accuracy, positive predictive value, and negative predictive value in vessel-based analyses were: Full, 66.7%, 82.4%, 80.0%, 40.0%, and 93.3%; APMC, 100.0%, 80.0%, 83.3%, 50.05, and 100.0%; and Half, 90.9%, 83.0%, 86.3%, 78.95, and 92.9%, respectively.

Conclusions: An imaging protocol using Full and APMC reduced radiation dose and maintained diagnostic accuracy compared to imaging using conventional Half.

Key words: 320-row area detector coronary computed tomography angiography; Full reconstruction; advanced patient motion correction; radiation dosing; submillisievert

Introduction

Coronary computed tomography angiography (CCTA), a noninvasive procedure with high diagnostic precision for coronary artery disease, has recently become widely used clinically (1-3). This imaging technique, however, may increase long-term cancer risk (4, 5), which makes accurate, lower dose coronary artery CT imaging protocols desirable.

The wide gantry used in 320-row area detector CT (320-ADCT) scanners requires X-ray exposure over 360° for angle correction, even when scanning with half reconstruction. The automatic patient motion correction (APMC) function available for 320-ADCT adjusts weighting near 0° and 360° on the sonogram to reduce motion artifacts and is, therefore, useful even for CCTA. The quantity of data and motion artifact reduction achieved with APMC reconstruction rank between half and full reconstruction.

Half reconstruction with 1 rotation scanning, in which a majority of the rotation takes place during the slow-filling phase, is generally used for CCTA performed with a 320-ADCT, but full or APMC reconstruction is possible when the slow-filling phase is longer due to a slower heart rate. Theoretically, full and APMC reconstruction produce scans with image noise comparable to normal half reconstruction, but with a lower tube current and, consequently, a significantly lower radiation dose.

Recently developed adaptive iterative reconstruction and low-voltage scanning protocols have been shown to be useful, low-dose alternatives (6-13).

In a population of patients for whom half reconstruction with 1 rotation scanning in a 320-ADCT operating under low-voltage scanning and adaptive iterative dose reduction using three-dimensional processing (AIDR3D) was indicated, whether selecting the reconstruction protocol according to heart rate and PQ interval resulted in lower dose scans than conventional protocols that were acceptable for diagnostic purposes was evaluated.

Methods

Study population

This was a single-center study. The institutional human research committees of our institution approved the corresponding study components. Anonymous use of the test data for the study was orally explained to all subjects, and written consent was obtained. A total of 360 consecutive patients underwent CCTA performed with a 320-ADCT from October 1, 2014 to April 30, 2015. Seventy-seven of the 360 patients did not undergo volume scanning because of concurrent imaging of a bypass graft after coronary artery bypass surgery or the aorta for aortic evaluation before open-heart surgery. Of the remaining 283 patients, 209 patients underwent 1 rotation scanning were enrolled in this study.

Imaging Protocol Classification

Previous research found the slow filling phase in the mid-diastolic phase to be most closely correlated to the interval from RR to PQ and arrived at a regression formula of slow filling phase = -360 + 0.742 (RR-PQ), r=0.915 (14). The -95% prediction of slow filling phase over an RR-PQ range of 600 to 1500 ms approximates the line represented by the formula -443 + 0.742 (RR-PQ) (14) This approximation was used to calculate the -95% prediction of the slow filling phase based on RR-PQ values in pre-scan breath-hold electrocardiograms. It was decided that half reconstruction would be used if the time was at least 137.5 ms (the time required for half reconstruction at the maximum rate of rotation of 275 ms), APMC reconstruction would be used if the time was at least 206.25 ms, and full reconstruction would be used if the time was at least 275 ms.

CT Acquisition

Patients with a pre-scan heart rate ≥60 beats per minute were given 20 to 40 mg of metoprolol orally and, if the heart rate remained ≥61 beats per minute after 1 hour, they were given an intravenous injection of landiolol (0.125 mg/kg). Patients in whom beta-blockers were contraindicated (due to severe aortic stenosis, systolic blood pressure < 90 mg Hg, bronchial asthma, symptomatic heart failure, or advanced atrioventricular block) did not receive these treatments.

The following devices were used: Aquilion ONE ViSION Edition™ (320-ADCT, Toshiba Medical Systems Corporation, Otawara, Japan), Dual Shot GX 7 (contrast injector, Nemoto Kyorindo Co., Ltd., Tokyo, Japan), Model 7800 ECG monitor (Chronos Medical Devices Inc., Tokyo, Japan), and Ziostation image analyzer (Zio M900, Ziosoft Inc., Tokyo, Japan).

Scanning was performed at a tube voltage of 100 kV except for patients whose body mass index exceeded 30 kg/m^2, who were scanned at 120 kV. Mean tube current was calculated with automatic exposure control for a standard deviation (SD) of 20, with 50% of the value (in mA) used for APMC reconstruction and 30% of the value used for full reconstruction.

With a slice width of 0.5 mm and reconstruction interval of 0.25 mm, the minimum number of rows necessary to include all coronary arteries was selected from 200 rows (100 mm), 240 rows (120 mm), 256 rows (128 mm), 280 rows (140 mm), and 320 rows (160 mm) in reference to unenhanced CT performed when determining the calcium score.

Prospective CTA mode was used for all patients, with a range of X-ray exposure of 75% of the RR interval. The contrast agent iohexol (Omnipaque 350 mg/ml I; Daiichi Sankyo Company, Tokyo, Japan) was injected for 12 sec at 180 mg I/kg/s, followed by injection of 30 mL of saline at the same rate as contrast agent injection.

Intermittent prep scanning with bolus tracking at the four-chamber-view level was performed once every

0.5 sec beginning 10 sec after the start of contrast agent injection. Scanning was started when the contrast agent was visually apparent in the left ventricle. AIDR3D was used for all patients, with intensity at the standard setting.

CCTA interpretation

For plaque detection, both cross-sectional and longitudinal curved multiplanar reformation images were analyzed. Coronary artery segments with a diameter of ≥2 mm were evaluated for the degree of stenosis. The percent ratio of the stenotic lumen to the normal vessel diameter proximal or distal to the stenosis was obtained, and the percent degree of stenosis was determined. From still images taken from multiple projections, measurements were made in the angle showing the narrowest degree of stenosis. The degree of stenosis was evaluated by consensus of two experienced cardiologists who were unaware of the clinical data. Lesions with >50% stenosis were defined as significant.

Radiation dose

Radiation doses were estimated and compared using the extended DLP (DLPe) from 320-detector row CT (15-17). The effective dose was calculated by multiplying the DLPe by 0.014, based on ICRP 102 (18).

Evaluation of Image quality

Image quality (19) was rated by the consensus of three experienced cardiovascular imagers; all were unaware of the clinical data. Excellent images (3 points) had clearly depicted coronary walls on curved multiplanar reformatted views, and images orthogonal to the center line were free of motion artifacts. Acceptable images (2 points) had small motion artifacts considered acceptable for confident diagnoses. Unacceptable images (1 point) had at least one segment with a 3-mm coronary diameter that was not useful for clinical interpretation. Images considered unacceptable because of incomplete breath-hold, lack of temporal resolution, poor contrast, and incorrect imaging scan range were included in this category (1 point). Images that could not be clinically interpreted because of severe calcification and/or the presence of artifact from a stent were excluded from this category.

Evaluation of image noise

SD values were used to compare image noise. CT numbers and SD values were determined in circular 16 mm × 16 mm regions of interest in the ascending aorta, left atrium, or left ventricle at the height of the origin of the left coronary artery in a short-axis image.

Invasive coronary angiography (ICA) measurement

ICA was performed according to standard clinical practice via a femoral or radial approach. In each vessel, percent stenosis was calculated for the most significant lesion as the ratio of the minimum lumen diameter within the lesion divided by the expected normal coronary diameter by assessing a “presumed-to-be-healthy” coronary segment distal and proximal to the stenosis. After reviewing images obtained from multiple projections, measurements were performed in the angle showing the narrowest degree of stenosis to classify the lesion into 6 categories: 0%-25%, 26%-50%, 51%-75%, 75%-90%, 91-99%, and 100% diameter stenosis**.** Lesions with >50% stenosis were defined as significant.

Statistical Analysis

Statistical analyses were performed using Statview J-5.0 for Windows (HULINKS, Inc., Tokyo, Japan). Numerical data are expressed as means ± standard deviation. One factor ANOVA (for age, body height, body weight, body mass index (BMI), tube current, DLP, HR, imaging range and CT value and standard deviation of the CT value of the aorta, left atrium and left ventricle) or chi-squared tests (for sex, hypertension, dyslipidemia, diabetes, current smoking, and family history for coronary artery disease) were used for comparisons between groups to determine the significance of differences. Groups were compared independently using Scheffe analysis. Values at $p<0.05$ were considered significant in all instances.

Sensitivity, specificity, positive predictive value, negative predictive value, and accuracy were calculated on a per-vessel and per-patient basis, whereby ICA served as the standard of reference. A positive finding was defined as the presence of a significant stenosis in ≥1 segment. If ≥1 unassessable segment due to severe calcification, stent, and so on existed on CCTA, the segment was defined as significant stenosis.

Results

Comparison of patient characteristics, image acquisition protocols, and image quality

Patient characteristics are shown in Table 1. Of the 209 patients, 118 (56.5%) underwent half reconstruction, 48 (23.0%) underwent APMC reconstruction, and 43 (20.6%) underwent full reconstruction. The male patients in these groups included 79 patients (66.9%), 33 patients (68.8%), and 29 patients (67.4%), respectively. Patient ages were 64.4±10.0 years, 65.1±11.2 years, and 66.3±9.3 years, height was 163.2±9.5 cm, 163.6±10.6 cm, and 162.9±9.5 cm, body weight was 66.3±14.2 kg, 64.1±12.0 kg, and 62.9±9.8 kg, and BMI was 24.7±3.7 kg/m^2, 23.8±3.0 kg/m^2, and 23.7±3.2 kg/m^2, respectively. No significant differences were noted among the groups. Again, no significant intra-group differences were observed in the prevalence of hypertension, diabetes mellitus, or dyslipidemia, in the smoking rate, or in the percentage of patients with a family history of coronary artery disease.

The mean number of rows did not differ significantly, at 276.5±24.8 rows, 278.2±21.5 rows, and 278.1±26.1 rows, respectively. Tube current, which was adjusted according to the reconstruction protocol selected, differed significantly among the 3 groups, at 535.6±57.7 mA for half reconstruction, 305.8±70.8 mA for APMC reconstruction, and 215.3±46.8 mA for full reconstruction (P<0.0001).

Image quality assessments were A for 110 patients, B for 6 patients, and C for 2 patients undergoing half reconstruction, A for 46 patients, B for 1 patient, and C for 1 patient undergoing APMC reconstruction, and A for all 43 patients undergoing full reconstruction. Quality was thus good for each imaging protocol.

Comparison of image noise

The CT numbers for the ascending aorta were 443.9±89.8 HU (half reconstruction), 426.9±133.0 HU (APMC reconstruction), and 485.9±88.7 HU (full reconstruction). The numbers differed significantly for APMC and full reconstruction (P=0.0225), but no other significant differences were observed. The CT numbers for the left atrium were 387.5±112.5 HU, 377.4±155.1 HU, and 408.7±113.3 HU, respectively, and those for the left ventricle were 406.4±90.7 HU, 389.4±137.7 HU, and 439.4±99.0 HU, respectively. There were no significant differences (Figure 1A).

The SD values were 26.1±3.7 HU (half reconstruction), 24.5±3.0 HU (APMC reconstruction), and 22.7±3.2 HU (full reconstruction) for the ascending aorta, 31.1±4.9 HU, 28.4±3.9 HU, and 26.0±3.8 HU for the left atrium, and 30.1±4.8 HU, 27.6±3.6 HU, and 25.5±4.2 HU for the left ventricle. At each region of interest, SD values were significantly lower for APMC reconstruction compared with half reconstruction and again significantly lower for full reconstruction compared with APMC reconstruction (Figure 1B).

Comparison of radiation dose

DLP.e values were 141.7±48.7 mGy·cm (half reconstruction), 93.0±60.9 mGy·cm (APMC reconstruction), and 54.8±22.3 mGy·cm (full reconstruction). Effective doses were 2.0±0.7 mSv, 1.3±0.9 mSv, and 0.8±0.3 mSv, respectively. The values differed significantly among the three groups, which indicates that full reconstruction allowed imaging with significantly less radiation exposure than with the other two protocols (Figure 2).

Evaluation of diagnostic accuracy

Twenty-eight of the 209 patients (13.4%) subsequently underwent coronary angiography (after a mean of 34.6±20.4 days (2-88 days)). On vessel-based analysis**,** sensitivity, specificity, positive predictive value, negative predictive value, and accuracy were 94.4.%, 82.9%, 72.3%, 96.9%, and 86.6% for all patients (N=28), 90.9%, 83.0%, 78.9%, 92.9%, and 86.3% for half reconstruction (N=20), 100.0%, 80.0%, 50.0%, 100.0%, and 83.3% for APMC reconstruction (N=3), and 66.7%, 82.4%, 40.0%, 93.3%, and 80.0% for full reconstruction (N=5), respectively (Table 2).

Representative Cases

Representative images from Full and APMC are shown in Figures 3 and 4.

Discussion

RR-PQ times were evaluated in patients for whom 1-rotation scanning with half reconstruction was theoretically indicated to determine if dose reduction with APMC or full reconstruction was possible. The aggressive use of beta-blockers except when contraindicated enabled 1-rotation scanning with half reconstruction for 74% of the patients, and exposure was reduced with APMC or full reconstruction in 43.5% of this patient subset. With full reconstruction, the effective dose was submillisievert at 0.8±0.3 mSV. Image quality assessments were A for 93.2%, B for 5.1%, and C for 1.7% of the patients undergoing half reconstruction, A for 95.8%, B for 2.1%, and C for 2.1% of the patients undergoing APMC reconstruction, and A for 100% of the patients undergoing full reconstruction. Quality was thus acceptable in almost all patients. The diagnostic accuracy of the scans obtained with each type of reconstruction in the present study was generally comparable to that in the previous reports (1-3), which indicates that this protocol is acceptable for clinical use. The line represented by -443+0.742 (RR-PQ) as an approximation for -95% prediction of slow filling phase over an RR-PQ range of 600 to 1500 ms was used in the protocol (14), and excellent image quality over the slow-filling phase was obtained when this procedure was used to select the optimal type of reconstruction.

The projection data obtained in half reconstruction are about half those obtained in full reconstruction, and the quantity of data and motion artifact reduction achieved with APMC reconstruction rank between half and full reconstruction. Doubling the tube current brings image noise to $1/\sqrt{2}$, while holding tube current steady should greatly reduce image noise in full reconstruction compared with half reconstruction.

Given that AIDR3D tends to reduce image noise in the low-dose range, we decided to perform APMC reconstruction at 50% of the tube current of half reconstruction and full reconstruction at 30% of the tube current of half reconstruction. Although CT numbers did not differ significantly among the types of reconstruction at these settings, SD values in each region of interest were significantly lower for APMC reconstruction than for half reconstruction and again significantly lower for full reconstruction than for APMC reconstruction. The noise associated with each type of reconstruction was clinically acceptable. These findings indicate that APMC and full reconstruction could be performed at even lower tube current to further reduce the dose.

Factors affecting the radiation dose also include tube voltage, tube current, scanning range, and heart beats during scanning. Our protocol was designed not only to select the optimal type of reconstruction, but also to minimize dose by, for example, limiting tube voltage to 100 kV in patients with a BMI less than 30 kg/m^2, keeping the scanning range at a minimum, and limiting X-ray exposure to the mid-diastolic phase. Moreover, AIDR3D was used for all patients. Radiation dose reduction has been achieved with recently developed next-generation adaptive iterative reconstruction procedures (6-11). The use of these and other adaptive iterative reconstruction procedures could help further reduce the radiation dose.

Subtraction CT angiography with 320-ADCT scanners has recently been used to improve diagnostic accuracy in patients with severe calcification or stent placement (20, 21). Subtraction CT, however, delivers a higher dose, because a mask scan is performed before the scan performed following contrast agent administration. Since the clinical usefulness of APMC and full reconstruction has been shown in the present study, our protocol could possibly be used to lower the radiation dose in subtraction CT.

Limitations

This study was a single-center study with a limited sample size. Not all patients underwent invasive coronary angiography, which was performed at the discretion of the attending physician. Featuring high negative predictive values, coronary CT angiography is an established procedure for excluding coronary artery disease (1). This made invasive coronary angiography in all patients unfeasible. No accurate physical property evaluations have been performed for the use of 50% of half reconstruction tube current for APMC reconstruction and 30% of half reconstruction tube current for full reconstruction. Image quality, image noise, and diagnostic accuracy assessments, however, indicate that the scans are acceptable for clinical use. Proper tube current settings for APMC and full reconstruction must be further investigated.

Conclusion

RR-PQ times were used to select the optimal reconstruction type, half, APMC, or full, in patients for whom half reconstruction with 1 rotation scanning on a 320-ADCT scanner was indicated. APMC and full reconstruction scans were obtained at a radiation dose lower than and maintained an image quality comparable to conventional half reconstruction.

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Disclosures

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Tables

Table 1. Comparison of patient characteristics, image acquisition protocols, and image quality among various reconstruction groups

BMI: body mass index, APMC: automatic patient motion correction

Table 2. Evaluation of diagnostic accuracy among various reconstruction groups

APMC: automatic patient motion correction

Figure legends

Figure 1. Comparison of CT number (A) and standard deviation (B) in the ascending aorta, left atrium, and left ventricle among various reconstruction groups

APMC: automatic patient motion correction

Figure 2. Comparison of DLPe (A) and effective dose (B) among various reconstruction groups

DLPe: extended dose length product, APMC: automatic patient motion correction

Figure 3. Representative case of a full reconstruction image

This 68-year-old man was 158 cm tall, weighed 58 kg, and had a BMI of 21.4 kg/m^2. He achieved a heart rate of 50 beats per minute following oral metoprolol and breathing practice. RR-PQ values indicated that full reconstruction was possible. Imaging was performed at a heart rate of 41 beats per minute. Tube voltage was 100 kV. Tube current was 150 mA, which was 30% of the mean tube current calculated with automatic exposure control for a standard deviation of 20. Imaging was performed over 240 rows (120 mm). Prospective CTA was used. The X-ray exposure range was 75% of the RR interval, and imaging was performed for 1 beat. DLP.e was 42.9 mGy·cm, and the effective dose was 0.6006 mSV. Excellent image quality was achieved at these less-than-conventional doses.

DLPe: extended dose length product

Figure 4. Representative case of an APMC reconstruction image

This 60-year-old man was 149 cm tall, weighed 46 kg, and had a BMI of 20.7 kg/m^2. He achieved a heart rate of 55 beats per minute following oral metoprolol and breathing practice. RR-PQ values indicated that APMC reconstruction was possible. Imaging was performed at a heart rate of 57 beats per minute. Tube voltage was 100 kV. Tube current was 300 mA, which was 50% of the mean tube current calculated with automatic exposure control for a standard deviation of 20. Imaging was performed over 240 rows (120 mm). Prospective CTA was used. The X-ray exposure range was 75% of the RR interval**,** and imaging was performed for 1 beat. DLP.e was 58.1 mGy·cm, and the effective dose was 0.8134 mSV. Excellent image quality was achieved even though the dose was lower than that used for half reconstruction.

APMC: automatic patient motion correction, DLPe: extended dose length product

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Figure 1A

(Figure 1A)

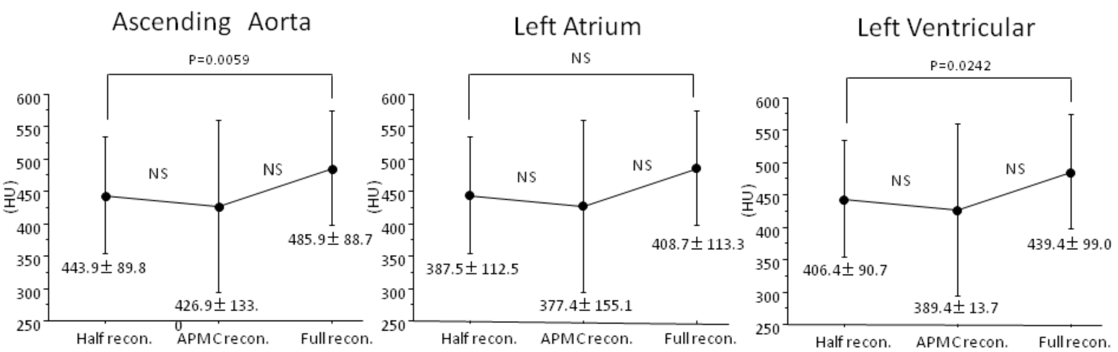

Figure 1B

(Figure 1B)

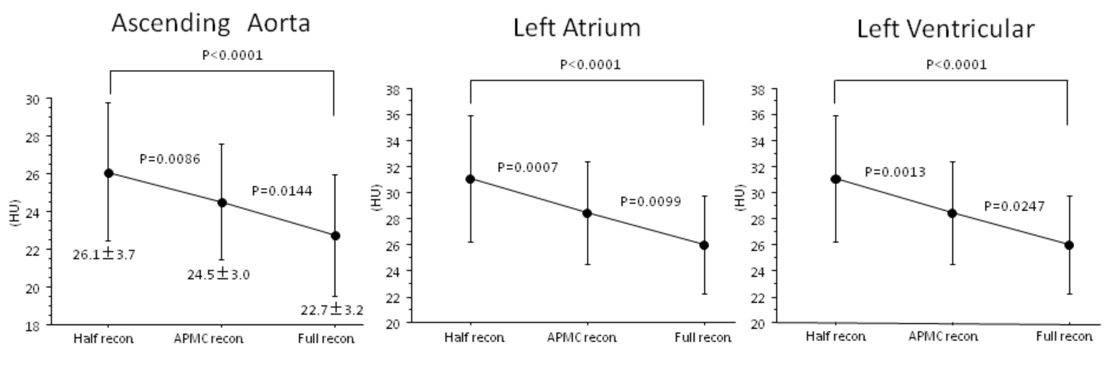

Figure 2A

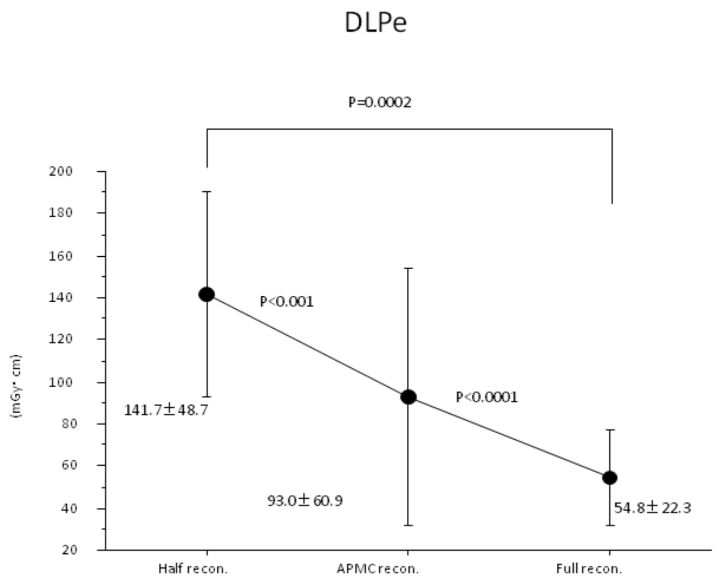

Figure 2B

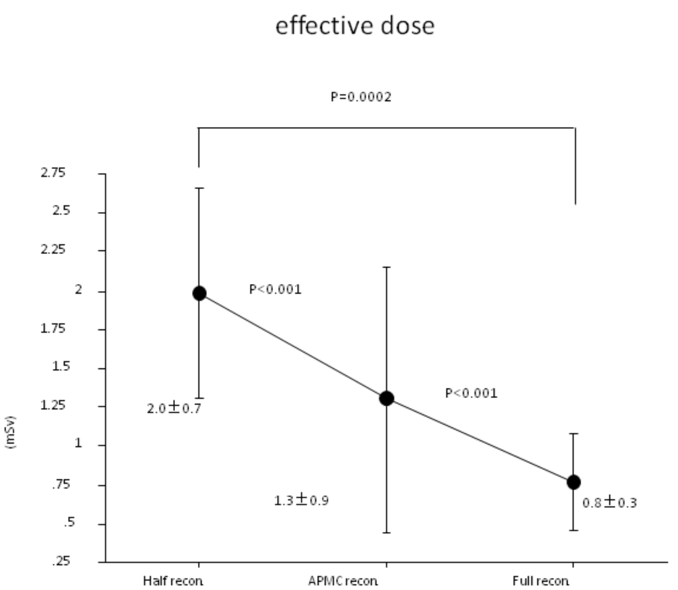

Figure 3

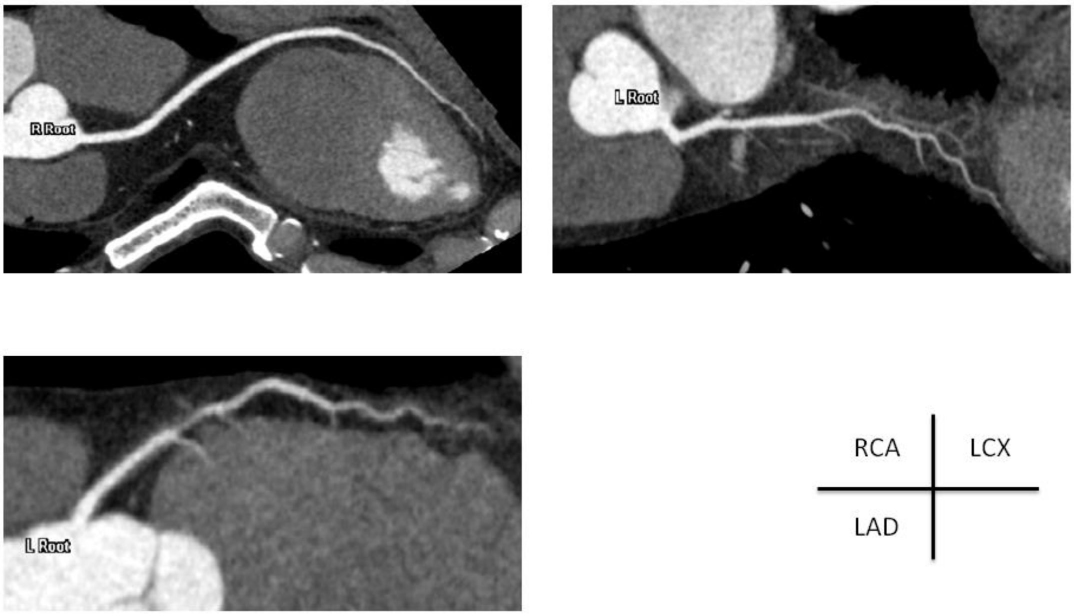

Figure 4

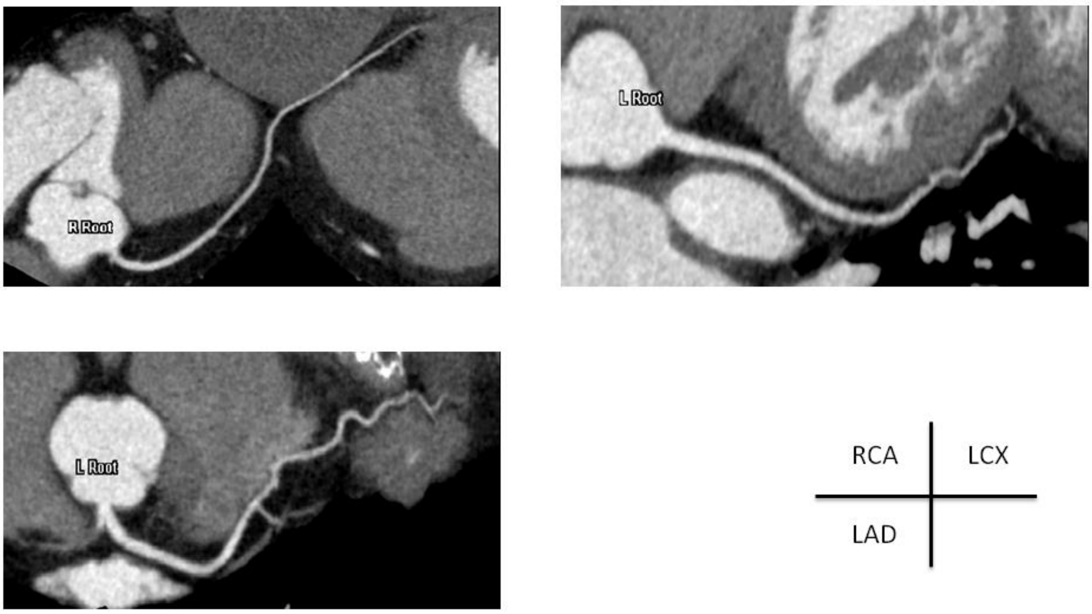

Table1

	HALF (N=118)	APMC (N=48)	FULL (N=43)	P value
Age	64.4±10.0	65.1±11.2	66.3±9.3	N.S.
No. of men	79(66.9%)	33(68.8%)	29(67.4%)	N.S.
Height (cm)	163.2±9.5	163.6±10.6	162.9±9.5	N.S.
Weight (kg)	66.3±14.2	64.1±12.0	62.9±9.8	N.S.
BMI (kg/m2)	24.7±3.7	23.8±3.0	23.7±3.2	N.S.
HR (beats/min)	55.3±6.2	52.6±3.3	47.7±4.7	<0.001
Coronary risk factor (No. of patients)				
Hypertension	80	31	27	N.S.
Diabetes mellitus	34	11	13	N.S.
Dyslipidemia	86	27	28	N.S.
Smoking	20	3	6	N.S.
Received oral β-blocker	105(89.0%)	41(85.4%)	36(83.7%)	N.S.
Imaging range(raw)	276.5±24.8	278.2±21.5	278.1±26.1	N.S.
Tube current (mA)	535.6±57.7	305.8±70.8	215.3±46.8	<0.0001

Table2

	Total (N=28)	HALF (N=20)	APMC (N=3)	FULL (N=5)
Sensitivity (%)	94.4	90.3	100.0	66.7
Specificity (%)	82.9	82.2	80.0	82.3
Positive Predictive Value (%)	72.3	77.8	50.0	40.0
Negative Predictive Value (%)	96.9	92.5	100.0	93.3
Accuracy (%)	86.6	85.5	83.3	80.0