Strategies to reduce radiation dose in cardiac PET/CT

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Abstract

Background: Our aim was to investigate CT dose reduction strategies on a hybrid PET⁄CT scanner for cardiac applications.

Materials: Image quality and does estimate of different CT scanning protocols for CT coronary angiography (CTCA) and CT-based attenuation correction for PET imaging were investigated. Fifteen patients underwent CTCA, perfusion PET imaging at rest, under stress, and FDG PET for myocardial viability. These patients were divided into three groups based on the CTCA technique performed: retrospectively gated helical (RGH), ECG tube current modulation (ETCM) and prospective gated axial (PGA) acquisitions. All emission images were corrected for photon attenuation using CT images obtained using default setting and an ultra low dose CT (ULDCT) scan.

Results: Radiation dose of RGH technique was 22.2±4.0 mSv. It was reduced to 10.95±0.82 mSv and 4.13±0.31 mSv when using ETCM and PGA techniques, respectively. Radiation dose in CT transmission scan was reduced by 96.5% (from 4.53±0.5 mSv to 0.16±0.01 mSv) when applying ULDCT as compared to the default CT. No significant difference in terms of image quality was found among various protocols.

Conclusion: The proposed CT scanning strategies, i.e. ETCM or PGA for CTCA, ULDCT for PET attenuation correction, could reduce radiation dose up to 47% without degrading imaging quality in an integrated cardiac PET/CT coronary artery examination.

Introduction

Coronary artery disease (CAD) is the leading cause of death around the world. For the diagnosis of CAD, medical imaging emerges as a powerful method over the past decade. PET imaging is one of the well-established tools for the evaluation of ischemic heart, blood flow quantification, myocardial perfusion and viability [1, 2]. Clinical protocols usually include cardiac PET with ^{13}N-ammonia and ^{18}F-FDG to assess myocardial perfusion and viability, respectively. On the other hand, cardiac CT has enabled not only the detection and quantification of coronary artery calcification by using CT calcium scoring, but also the grading of coronary stenosis through contrast-enhanced CT coronary angiography (CTCA). PET/CT is a hybrid imaging instrumentation that can perform these examinations in one patient exam session (Fig. 1) [3-5]. Moreover, the CT image can be used to correct PET scans for photon attenuation [6]. So the integrated system offers the abilities to decrease overall scanning time and improve localization of vessels or regions-of-interest in cardiac imaging. However, radiation dose of these cardiac PET/CT examinations shown in Fig. 1 can be up to 37.67 mSv, while the proportion of CT radiation dose is about 75.0 % (28.27 mSv) [2, 7]. The rationale of our study was to investigate CT dose reduction strategies on a hybrid PET⁄CT scanner for cardiac applications.

Materials and Methods

Patient population

A total of 15 consecutive patients (9 male, 6 female; mean age 50.8±8.4 years; range 39-68 years) were enrolled for this cardiac PET/CT study between November 2009 and May 2010. All patients underwent the cardiac PET/CT scanning protocol as shown in Fig.1. Patients with prior allergic reaction to iodinated contrast media or atrial fibrillation were excluded. This study was institutional review board-approved, and written informed consent was obtained for all subjects.

PET/CT Acquisition Protocols

All studies were performed on a PET/CT scanner (Discovery^{TM} VCT, Germany, GE). Data acquisitions in the CT and PET studies were performed with a matrix of 512×512×64 and 128×128×47, respectively. Patients with heart rate (HR) >70 bpm prior to CTCA were administered 40 mg of propranolol orally after the scout scans and returned for CTCA after their HR decreased to <70 bpm. For those enrolled 15 patients, 5 patients (HR = 60±8 bpm, height = 1.6±0.16 m, weight = 65.5±7.78 kg) underwent CTCA with retrospectively gated helical (RGH) acquisitions, and 5 patients (HR = 59±8 bpm, height = 1.6±0.08 m, weight = 63.0±9.85 kg) underwent CTCA with ECG tube current modulation (ETCM) acquisitions, 5 patients (HR = 59±6 bpm, height = 1.6±0.03 m, weight = 66.2±9.65 kg) underwent CTCA with prospectively gated axial (PGA) acquisitions. Based on the weight of the patients, 70-90 mL of a nonionic contrast medium (Optiray 350, Tyco

Healthcare, Montreal, Quebec, Canada) was injected at a flow rate of 5 mL/s, followed by a 25 mL bolus of saline at the same rate using a dual-head injector (Stellant D; Medrad, Warrendale, PA, USA). PET imaging examinations include ^{13}N-labeled NH_3 rest-stress perfusion PET and ^{18}F-FDG viability scan. All patients received 700-900 MBq and 298-458 MBq injections of ^{13}N-labeled NH_3 and ^{18}F-FDG via the peripheral vein before the start of serial transaxial tomographic imaging of the heart, respectively. To compensate effects of photon attenuation in PET imaging, two CT scanning protocols were applied: the default setting and the ultra low-dose CT (ULDCT). Table 1 lists the parameters of CT scanning protocols for coronary angiography and CT-based attenuation correction.

CT Data Analysis

Coronary arteries were classified into 15 segments according to the scheme proposed by the American Heart Association [8] and the intermediate artery was designated segment 16, if present. Images were analyzed and graded randomly by 2 independent cardiovascular radiologists, each with >5 years experience. Images included transverse source images, (curved) multi-planar reformations, thin-slab maximum intensity projections, and volume-rendering mode, and were presented to the observers to identify coronary image quality. After the optimal reconstruction interval was determined, we used motion artifact as the figure-of-merit for assessing image quality. We performed semi-quantitative analysis by using a 4-point ranking scale (1 = no motion artifacts; 2 = mild blurring; 3 = moderate blurring without structure discontinuity; 4 = severe artifacts and doubling). For any disagreement in data assessment, the 2 readers reviewed the data together until consensus was obtained. The image quality at the best reconstruction interval from RGH, ETCM and PGA patients was then compared with Wilcoxon signed ranks test (NCSS version 2007, NCSS).

PET Data Analysis

The mutual information and the correlation coefficient were computed to characterize similarity between PET images corrected for photon attenuation using CT images obtained with default setting and ULDCT. Mutual information (MI) was applied to estimate the non-linear intensity distribution between two sets of images. The random variables X and Y are defined as sum of all grey value pairs at corresponding positions between two sets of images. Their intensity value at a certain coordinate in the images is the joint outcome of a random experiment. The MI between X and Y, denoted as $I(X, Y)$ is defined as equation (1):

$$I(X,Y)=\sum_{x\in X}\sum_{y\in Y}p(x,y)\log\frac{p(x,y)}{p(x)p(y)} \qquad (1)$$

where $p(x)$ is the histogram of X, $p(y)$ is the histogram of Y, and $p(x,y)$ is the joint histogram of X and Y. The larger $I(X,Y)$, the more similar two images are [9,10].

Correlation coefficient (CC) was applied to calculate the intensity relationship point by point between two image sets. The CC value represents the linear information about intensity difference between two imaging sets of n voxels in each. The equation defining the correlation coefficient is:

$$CC = \frac{S_{u,v}}{S_u * S_v} = \frac{\sum_{i=1}^{n} \left(u_i - \bar{u}\right) * \left(v_i - \bar{v}\right)}{\sqrt{\sum_{i=1}^{n} \left(u_i - \bar{u}\right)^2} * \sqrt{\sum_{i=1}^{n} \left(v_i - \bar{v}\right)^2}} \quad (2)$$

where S_u is the standard deviation of object *u*, S_v is the standard deviation of object *v*, $S_{u,v}$ is the covariance of object *u* and *v*, *CC* is the correlation coefficient of *u* and *v*, which is between -1 and 1.

Radiation Dose

The volume CT dose index ($\mathrm{CTDI_{vol}}$) was displayed after each scan on the scanner's console. To obtain the effective dose, the $\mathrm{CTDI_{vol}}$ was multiplied by the scan length to get the dose-length product (DLP), an indicator of the integrated radiation dose of an entire CT examination. Values of DLP were converted into effective dose using a conversion factor of 0.017 $\mathrm{mSv \cdot mGy^{-1} \cdot cm^{-1}}$ for adult chest CT [11].

Result

A total of 220 segments were evaluated in the 15 patients. Twelve segments were missing because of anatomic variants and 8 segments were too small to visualize. When the best reconstruction interval was used, images without motion artifacts (score 1) were obtained in 40 of the 76 segments for RGH group, 38 of the 74 segments for ETCM group and 38 of the 70 segments for PGA group. No statistical significance was seen among image quality obtained from the three CTCA groups. Fig. 2 shows curved multiplanar reconstruction images of the right coronary artery, reconstructed from RGH, ETCM and PGA acquisitions.

For PET acquisitions of ^{13}N-NH$_3$ for perfusion (rest/stress) and FDG for viability with two different CT attenuation corrections, we got 0.878±0.041, 0.764±0.037, 0.833±0.037 for the mutual information and 0.976±0.006, 0.974±0.009, 0.982±0.005 for the correlation coefficient, respectively. These results indicate that the PET data sets corrected for photon attenuation using two different CT acquisition protocols provide similar image quality and information. Fig. 3 shows CT images for CT-based attenuation correction and corresponding FDG-PET images with attenuation correction using these CT images. Image noise is more noticeable in CT image obtained using ULDCT because of the reduced photon flux. However, no significant difference is observed between the two sets of PET images.

The effective dose of patients underwent a cardiac PET⁄CT examination are show in Fig. 4. Radiation dose of RGH technique was 22.2±4.01 mSv. It was reduced to 10.95±0.82 mSv and 4.13±0.31 mSv when using ETCM and PGA techniques, respectively, leading to a dose reduction of

50-83%. Radiation dose in CT transmission scan was reduced by 96.5% from 4.53±0.5 mSv to 0.16±0.01 mSv when applying ULDCT protocol. When CT images for attenuation correction were obtained using ULDCT, radiation dose of the whole cardiac PET/CT examination using ETCM and PGA for CTCA could be reduced by 29.8-47.9%.

Discussion

Radiation dose is becoming a major issue for cardiac imaging. The current PET/CT growth leads to the volume of cardiac diagnostic procedures involving the use of ionizing radiation – within both emission and transmission scanning – increased considerably. Due to improved accuracy, the number of cardiac PET/CT scans is growing rapidly [2,12]. A number of techniques can be used to minimize dose from integrated cardiac PET/CT examination. For CTCA, PGA should be employed when it is expected that multiple reconstructions at different positions of the cardiac cycle will not be necessary for diagnosis. This is generally the case for patients with regular rhythm, little or no ectopy, and well-controlled HR after administration of beta-blockers such as metoprolol. Beta-blockers play an important role in dose reduction in addition to improving image quality by decreasing coronary artery velocity.

Another important consideration is the optimization of tube current and voltage. In modern PET imaging, CT has replaced Ge-68 for the transmission scan. However, the drawback of the helical CT technology is the higher radiation dose to patients. Effective dose increases linearly with tube current [13], and therefore tube current should be minimized to the lowest level yet still providing acceptable image quality for performing attenuation correction on PET images. Therefore, we use 10 mA tube current for ULDCT in our study. The low tube current causes low photon flux thus leading to low signal-to-noise ratio in the images. However, these CT images are mainly for attenuation correction purpose thus diagnostic image quality is not needed. Our results of MI and CC showed that there is actually no significant difference between the PET images with attenuation correction using default CT and ULDCT. Thus, the diagnostic accuracy of PET images corrected using ULDCT should not be affected. Pascal Koepfli *et al.*[14] once compared the usage of conventional Ge-68 external source and CT with different tube currents (120 mA, 80 mA, 40 mA and 10 mA) as the transmission scans for PET myocardial perfusion scans. Their study shows that for the assessment of qualitative and quantitative myocardial blood flow (MBF) with a hybrid PET/CT scanner, the use of CT with a tube current of 10 mA, instead of Ge-68, can provide accurate results for attenuation correction in PET images. However, the effective doses for the CT using tube current of 80 mA and 10 mA are 0.38 mSv and 0.05 mSv respectively. Thus, the radiation dose can be lowed by 8-fold by using tube current of 10 mA as compared to 80 mA without compromising diagnostic information. On the other hand, Michael Souvatzoglou *et al.*[15] assessed the image quality and radiation dose for 3 different CT scans: (1) LDCT(low dose CT)：120 kV，26 mA; (2) SCT(slow CT)：120 kV，99 mA; (3) ULDCT(ultra low dose CT)：80 kV，13 mA for the attenuation correction in cardiac PET/CT scans. Their results showed that all 3 types of CT can provide PET images with good image quality and the ULDCT showed the least radiation dose. It is thus feasible to use 80 kV, a value that is lower than that used in the clinical setting, for CT attenuation correction purpose for dose reduction. Although using ULDCT as attenuation correction does not affect the diagnosis in the PET images, our results showed that there are still some minor discrepancies between ULDCT and default CT in terms of MI and CC analysis. It is probably because CT images are usually a snap shot of a respiration cycle, while PET scans are results of average of respiration cycles. This temporal difference between the scans often introduces misalignment artifacts in PET images. These artifacts will cause registration errors and affect the quantitative results.

In conclusion, this study demonstrated that radiation dose in cardiac PET/CT can be significantly reduced without degrading imaging quality. The proposed imaging protocol, with radiation dose reduction up to 47.9% for an integrated cardiac PET/CT coronary artery examination, should be able to provide unique insight into diagnosis and management of coronary heart disease.

Reference

[1] Achenbach S, Anders K, Kalender WA. Eur Radiol. 18(2008) 1188–1198.

[2] Berman DL, Hachamovitch R, Shaw LJ, et al. J Nucl Med. 47(2006) 74–82.

[3] Earls JP, Berman EL, Urban BA, et al. Radiology. 246 (2008) 742–753.

[4] Paul J-F, Abada HT. Eur Radiol. 17(2007) 2028–2037.

[5] Prinak AN, McCollough CH, Bruesewitz MR, et al. Radiographics. 26(2006) 1785–1794.

[6] EC99. Report EURO 16262 EN (1999) 69–78.

[7] Annals of the ICRP. Recalculated data for frequently used radiopharmaceuticals. (1998). Publ. 80, Vol 28, No 3.

[8] Austen WG, Edwards JE, Frye RL, et al. Circulation. 51(1975) 5-40.

[9] Maes F, Collignon A, Vandermeulen D, et al. IEEE trans med imag. 16(1997) 187-198.

[10] Rangarajan A, Chui H, Duncan JS. Med Image Anal. 3(1999) 425-440.

[11] Morin RL, Gerber TC, McCollough CH. Circulation. 107(2003) 917-922.

[12] Einstein AJ, Moser KW, Thompson RC, et al. Circulation. 116(2007) 1290–1305.

[13] Gerber TC, Stratmann BP, Kuzo RS, Kantor B, Morin RL. Invest Radiol. 40(2005) 556 –563.

[14] Pascal Koepfli, Thomas F. Hany, Christophe A. Wyss. et al. J Nucl Med. 45(2004)537–542.

[15] Michael Souvatzoglou, Frank Bengel, Raymonde Busch. et al. Eur J Nucl Med Mol Imaging. 34(2007)1991-2000.

Figure

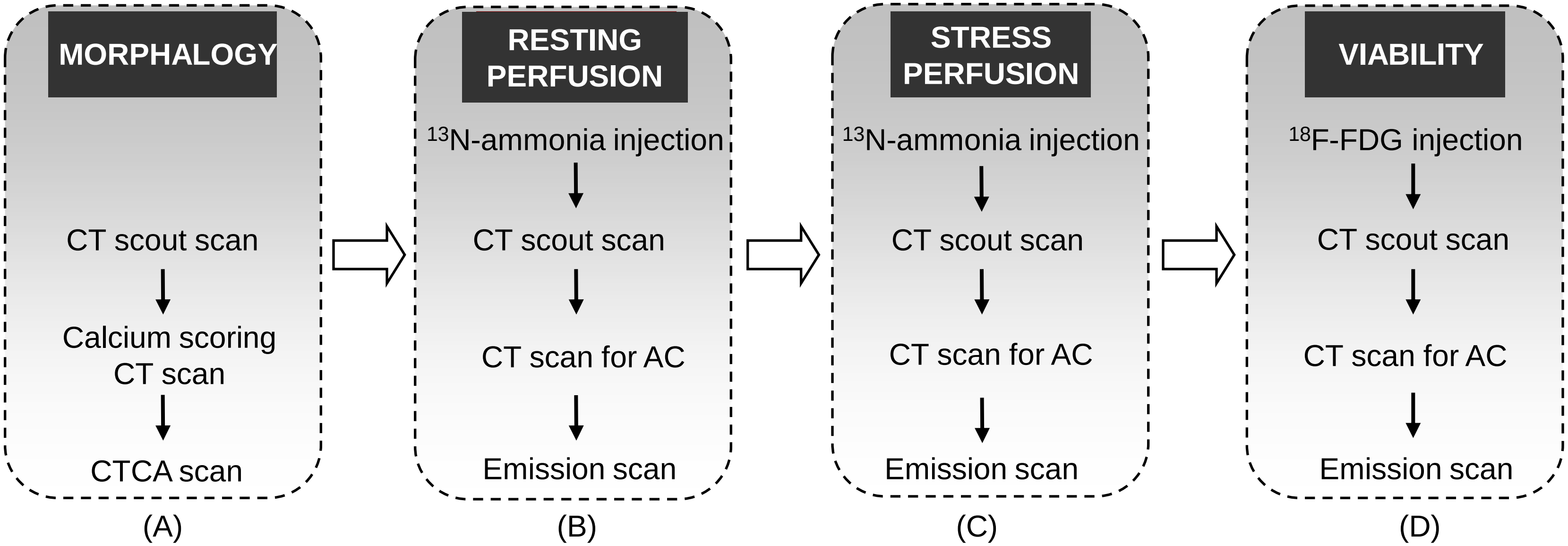

Fig.1 Flowchart of cardiac PET/CT scanning procedures, including cardiac CT imaging (A), cardiac perfusion PET imaging at rest (B) and under stress (C), and FDG PET for myocardial viability (D).

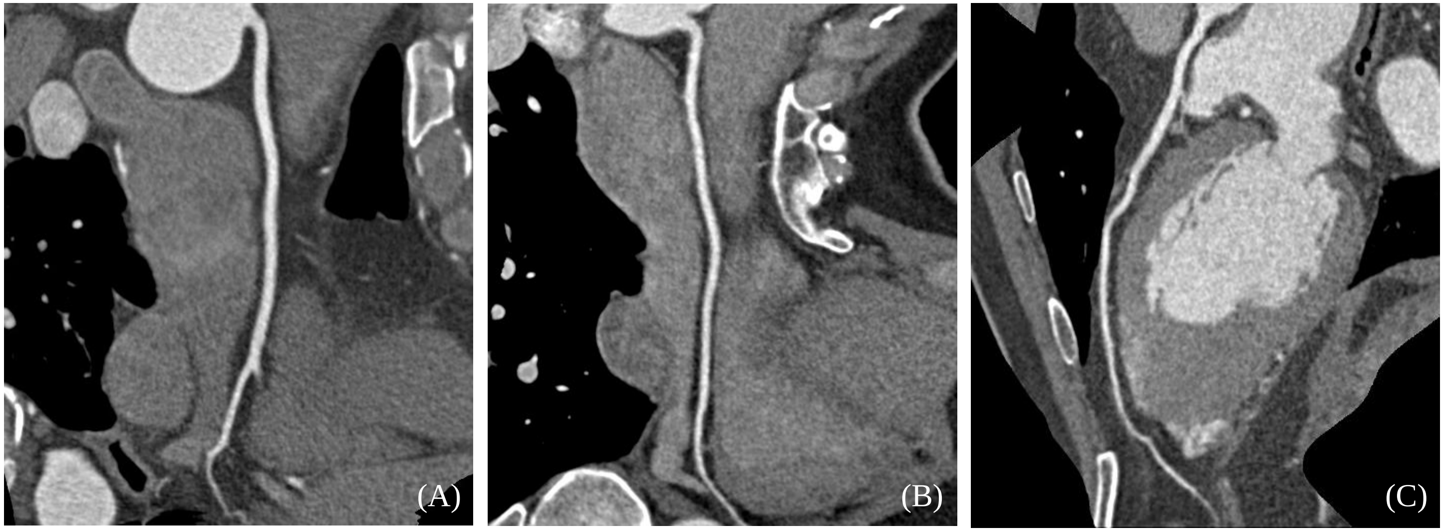

Fig. 2. Curved multiplanar reconstruction images show no motion artifact (score 1) of the RCA, reconstructed from RGH (A), ETCM (B) and PGA (C) acquisitions.

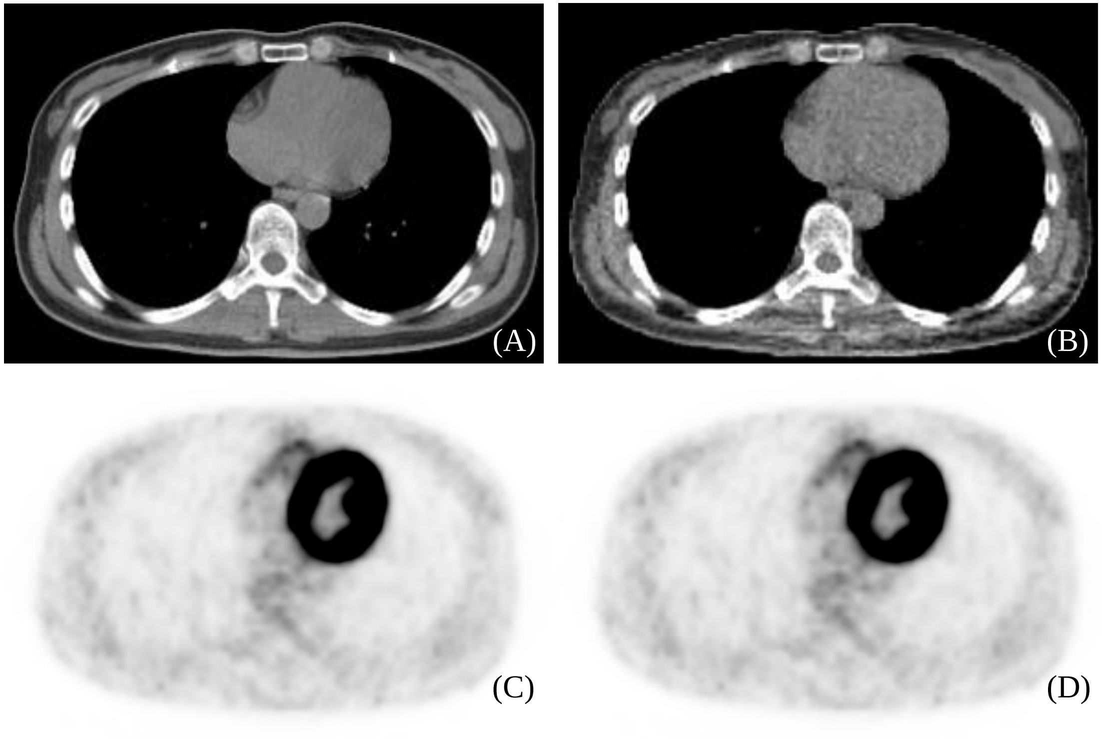

Fig. 3. CT images for CT-based attenuation correction obtained using default scan parameters (A) and ULDCT (B). FDG-PET images with attenuation correction using CT images in (A) and (B) are shown in (C) and (D), respectively.

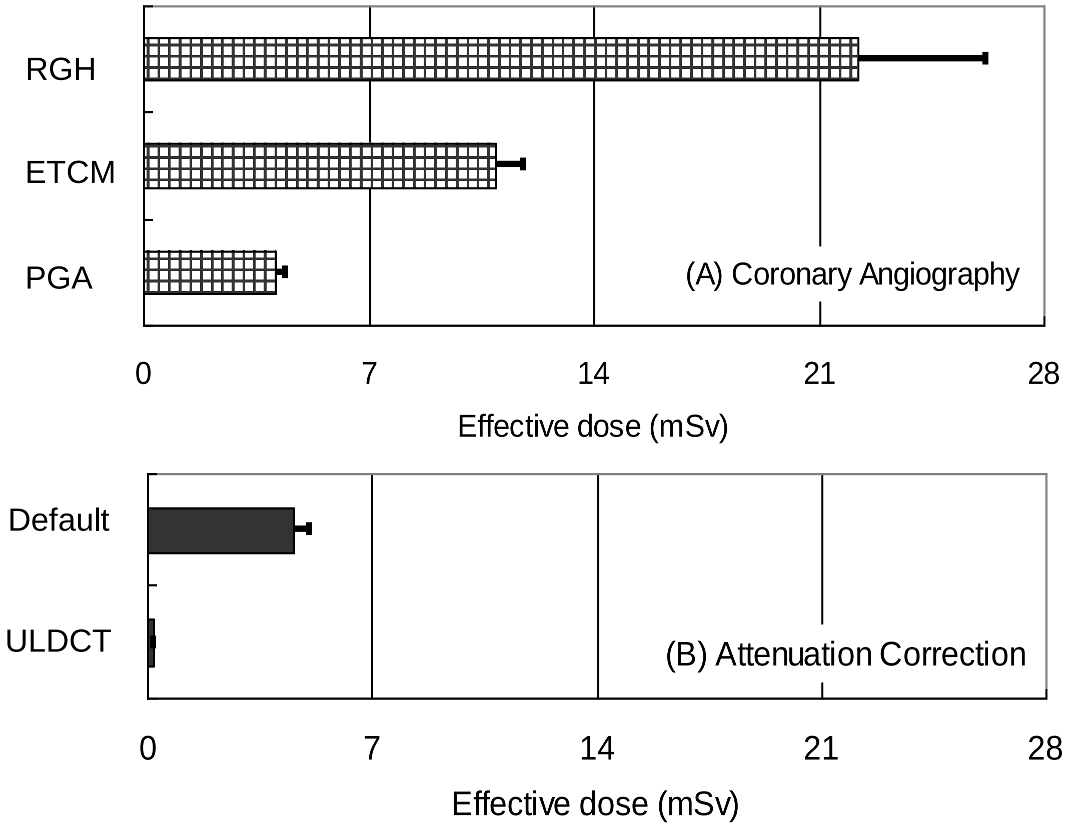

Fig. 4. Effective dose obtained from CT scans for CT coronary angiography (A) and CT-based attenuation correction (B).

Table

Table 1. Parameters of the CT scanning protocols for coronary angiography and CT-based attenuation correction

	Coronary Angiography			Attenuation Correction	
	RGH[a]	ETCM[b]	PGA[c]	Default	ULDCT[d]
Tube voltage (kV)	120	120	120	120	80
Tube current (mA)	624.5±34.65	633±28.58	639.2±40.99	20-210[e]	10
Rotation time (ms)	350	350	350	500	500
Pitch[f]	0.18-0.22	0.18-0.22	1	0.516	0.516
Acquisition window	0%-100%	30%-80%	75% ±5%	NA	NA

[a] RGH = retrospectively gated helical

[b] ETCM = electrocardiogram tube current modulation

[c] PGA = prospectively gated axial

[d] ULDCT = ultra low dose CT

[e] Variable tube current was delivered based on patient's scout image to maintain an appropriate balance between image quality and radiation dose (Smart mA).

[f] Pitch depends on the patient's heart rate.