Dual-source CT angiography in aortic stent grafting: An in vitro aorta phantom study of image noise and radiation dose

Abstract

Rationale and Objectives: The aim of the study was to investigate the optimal protocols of dual-source CT angiography in aortic stent grafting in terms of image noise and radiation dose, based on a vitro phantom study.

Materials and Methods: A series of helical CT cans were performed on a human aorta phantom using a dual-source CT scanner with kVp of 100, 120 and 140, corresponding mAs of 180, 150 and 100, slice thickness of 1.0, 1.5 and 2.0 mm, pitch value of 0.5, 1.0, and 1.5, respectively. Image quality was determined by measuring the standard deviation (SD) on 3D virtual intravascular endoscopy (VIE) images. Signal to noise ratio (SNR) and contrast to noise ratio (CNR) were measured on 2D axial images at superior mesenteric artery (SMA), renal arteries and aneurysm. Effective dose was determined based on dose length product.

Results: SD measured on VIE images was independent of kVp and pitch values but was determined by the slice thickness ($p<0.05$) at the SMA and renal arteries. SNR and CNR measured on 2D images showed significant differences between variable kVp values and slice thicknesses ($p<0.05$), but were independent of pitch values. The mean estimated effective dose for 120 kVp and 140 kVp protocols were 2.66 $\pm$ 0.21 mSv and 2.68 $\pm$ 0.18 mSv, respectively. The mean estimated effective dose for 100 kVp protocol was significantly lower (1.97 $\pm$ 0.07 mSv, $p<0.0001$). This indicates a reduction of 26.5% radiation dose when the kVp was lowered from 140 to 100.

Conclusion: A scanning protocol of 1.5 mm slice thickness, pitch 1.5 with 100 kVp and 180 mAs is recommended for a dual-source CT angiography in aortic stent grafting as it leads to significant reduction of radiation dose while in the meantime achieving diagnostic images.

Keywords: Multislice CT, aortic stent graft, image noise, radiation dose, 3D visualisation, virtual intravascular endoscopy

Introduction

Helical CT angiography has been recognized as the preferred imaging modality for both pre-operative planning and post-operative follow up of endovascular repair of abdominal aortic aneurysm (AAA) [1, 2]. The diagnostic value of CT angiography has been significantly enhanced with the recent development of multislice CT (MSCT) technique, beginning from initial 4-slice CT to 16-slice, and to the latest 64-slice, dual-source or even more detector row CT scanners [3-5]. Despite its advantages of MSCT angiography, the main concern is radiation exposure associated with the CT scans since radiation dose is gradually increased with the increased number of detector rows and reduction of detector size. Minimization of radiation exposure is of paramount importance for the patients treated with endovascular repair as these patients are normally followed with a series of CT scans during the rest of their life in order to check the position or integrity of aortic stent grafts and exclude any possible complications arising from the endovascular repair. Therefore, the purpose of this study was to investigate the strategies to reduce radiation dose while achieving diagnostic quality images in aortic stent grafting using dual-source CT scans, based on a vitro aorta phantom study.

Particularly, we are interested to examine the relationship between image noise (defined as the standard deviation) visualised on 3D surface rendered images, virtual intravascular endoscopy (VIE) of aortic ostium, as well as signal to noise ratio and contrast to noise ratio which were measured on 2D axial images acquired with variable scanning protocols. VIE has been previously reported valuable for assessment of the treatment outcomes of endovascular repair of patients with AAA [6, 7]. In this study, we applied the same methodology to perform a series of scans on the aorta phantom, but using the latest CT technique, dual-source CT. As CT has become a routine imaging modality and more and more clinical centres are replacing older generation of CT scanners with the recent multislice CT models, it is expected that the study outcomes have practical applications for optimization of the MSCT scanning protocols in the daily clinical practice.

Materials and Methods

Human aorta phantom and MSCT scanning protocols

The experiments were performed on a human abdominal aorta phantom [Fig 1]. The phantom was constructed using medical rapid prototyping based on a sample patient data with AAA [7, 8]. A commercial aortic stent grafting (Zenith, Cook, Europe, Denmark) with a suprarenal component of 2.5 cm was deployed inside the phantom to simulate a repaired aortic aneurysm. The suprarenal stent wires were positioned to cross the renal arteries and superior mesenteric artery (SMA). The phantom was housed in a perspex container, filled with contrast medium having CT attenuation similar to that used in the patient's abdominal CT scan. The contrast medium was diluted to 8% with a CT attenuation of 500 HU so that the attenuation difference between contrast medium and aortic wall (with attenuation of 200 HU) is 300 HU, which ensures the satisfactory vessel enhancement in abdominal CT angiography.

A series of scans were performed on a dual-source multislice CT scanner (Siemens, Definition, Forchheim, Germany) with the scanning protocols as follows: gantry rotation time of 330 milliseconds, slice thickness of 1.0 mm, 1.5 mm and 2.0 mm, pitch of 0.5, 1.0 and 1.5 with 50% reconstruction interval of the slice thickness. Three different tube voltages were selected, including 100 kVp, 120 kVp and 140 kVp, respectively, while the tube current time, mAs values were determined by the tube current modulation of the CT scanner in response to different kV ranges, thus the corresponding mAs values in relation to the kVp ranges were 180, 150 and 100, respectively. As pitch values were taken into account, the mAs values used in the study were actually the effective mAs (effective mAs=mAs/pitch). A field of view of 113 mm, matrix of 512 x 512 and 180^0 linear interpolation algorithms were used to reconstruct the images, resulting in an in-plane resolution of 0.22 mm x 0.22 mm. A total of 27 data sets were generated for inclusion in the study analysis.

Generation of 3D virtual intravascular endoscopy images

All datasets were burned onto CD discs from the MSCT scanner and transferred to a separate workstation for generation of VIE images and performance of image noise measurements. MSCT volume data were converted from original DICOM (Digital Imaging and Communication in Medicine) images with a commercially available software Analyze V 7.0 (Analyze V, AnalyzeDirect, Inc., Lexana, KS, USA). All data sets were reviewed in an unblinded fashion by an experienced radiologist (ZS) who is familiar with axial CT and VIE images of aortic stent grafting. Detailed generation of VIE images of the aortic ostium and suprarenal stent wires has been discussed elsewhere [8]. Similar to our previous studies, we used a CT thresholding technique to produce endoscopic views of the aortic ostium and stent wires with minimal artifacts. This was determined by selecting the appropriate threshold value through measuring the CT attenuation at the level of superior mesenteric artery (SMA) and renal arteries and aortic aneurysm. For generation of VIE images of the suprarenal stent wires, the lower threshold was selected to remove all of the soft tissue while keeping the high density stent wires. An appropriate threshold allows clear visualisation of suprarenal stent wires without showing broken or discontinuous appearance [8].

Quantitative assessment of image quality based on 2D images

To obtain quantitative assessment of image quality of the 2D images, image noise and CT attenuation of the aortic arteries and aneurysm as well as signal to noise ratio (SNR) and contrast to noise ratio (CNR) were determined for each protocol. Image noise was defined as the standard deviation (SD) of CT density in a region of interest (ROI) placed in the abdominal aorta at the levels of SMA, renal arteries and aortic aneurysm [Fig 2]. The ROI was chosen to be placed in the centre of the aorta with a minimum area of 20 mm^2 while carefully avoiding inclusion of the aortic wall or stent wires to prevent partial volume effects. SNR was determined by dividing mean attenuation by image noise. CNR was determined by dividing contrast values (CT attenuation of the ROI at SMA, renal artery and aneurysm minus CT attenuation of the background tissue, which is the aorta phantom wall) by image noise [Fig 2].

Quantitative assessment of image quality based on 3D VIE images

SD of pixel values on surface rendered VIE images was measured to determine the degree of stair-step artifacts in relation to variable scanning protocols. A higher SD indicates more variation in pixel intensity, therefore demonstrating existence of more artifacts leading to poor image quality. Similar to the methodology used in the previous studies [7, 8], a line profile was drawn across each VIE image, with an approximate value of 100 pixels being recorded. The measurements of SD were taken at three different locations, namely, SMA, right renal artery ostium and the aortic aneurysm. Figure 3 shows the method of measuring the SD on VIE images.

Subjective analysis- appearance of aortic ostia and stent wires

The purpose of the subjective assessment was to determine the optimum MSCT VIE scanning protocols from a clinical perspective. All examinations were evaluated by an experienced reviewer (ZS). The reviewer looked at the VIE images of aortic ostium to determined whether the aortic ostium is clearly visualized with normal circular appearance or distorted due to presence of artifacts. Regarding assessment of VIE images of stent wires, the reviewer looked at the appearance of stent wires to decide whether the wires are smooth with regular appearance or became irregular, or distorted due to interference of artifacts. Subjective assessment of configuration of the aortic ostia and stent wires was based on a 4-point scale scoring method:

Configuration of the aortic ostium: Score 1 indicated that the renal ostium was not visualized, 2 visualized but distorted, 3 visualized and normal and 4 visualized and perfect.

Definition of suprarenal stent wires: Score 1 indicated the discontinued stent struts, 2 irregular, 3 smooth and 4 smooth with hooks visible.

Radiation dose measurements

The effective dose of dual-source CT angiography was calculated according to the European Working Group for Guidelines on Quality Criteria in CT [9]. According to these guidelines, effective dose (mSv) can be estimated using the dose length product (DLP) multiplied by a conversion coefficient for the abdomen as the investigated anatomic region (k=0.015 mSv x mGy^{-1} x cm^{-1}). The DLP represents the integrated radiation dose for a specific CT examination and is automatically determined and displayed by the CT scanner. In addition, parameters for volume CT dose index ($CTDI_{vol}$) were obtained from each CT scan protocol and subsequently compared between different protocols.

Statistical analysis

A three-factor factorial design was employed to examine the effects of section thickness (1.0, 1.5 and 2.0 mm), pitch (0.5, 1.0 and 1,5), and voltage (100, 120 and 140 kVp) on SD, SNR and CNR. The SD of signal intensity was measured at three features, namely SMA, renal ostium, and aortic aneurysm. For each feature there was one determination of SD undertaken for each of the 27 cells defined by the factorial design. The analysis of variance model facilitated testing factor main effects and two-factor interaction effects, the three-factor interaction being utilised as residual error. All statistical tests were conducted, minimally, at the 5% level of significance. Analyses were computed with NCSS (Number Cruncher Statistical System) 2007.

Results

Comparison of radiation dose

The table shows the 27 scanning protocols with corresponding $CTDI_{vol}$ and DLP and effective dose. The effective dose was independent of pitch values, since the mAs represents the effective mAs and it remained the same throughout the scans with different pitch ranges. $CTDI_{vol}$ differed significantly between 100 kVp protocol and the other two protocols (120 and 140 kVp) ($p<0.001$). The mean estimated effective dose for 120 kVp and 140 kVp protocols were 2.66 ± 0.21 mSv and 2.68 ± 0.18 mSv, respectively. The mean estimated effective dose for 100 kVp protocol was significantly lower (1.97 ± 0.07 mSv, $p<0.0001$). This corresponds to a reduction of radiation exposure of 26.5% achieved by lowering tube voltage to 100 kVp.

Comparison of image noise and SNR/CNR

The SD measured with 3D VIE images shows that there were significantly differences due to slice thickness at the levels of SMA ($p=0.021$) and renal arteries ($p<0.001$), and no significant difference was reached when the measurement was performed at the aneurysm ($p=0.136$). No significant effects were detected between kVp and SD at the SMA ($p=0.41$), renal artery ($p=0.073$) and aneurysm locations ($p=0.20$) (Fig 4). Similarly, SD was independent of the pitch values at the above same three locations ($p=0.353$, 0.818, 0.619, respectively). The only significant difference of SD in relation to the kVp was noticed between 100 kVp and 140 kVp at the renal arteries between slice thicknesses of 1.5 mm and 2.0 mm ($p=0.035$). Figure 5 is an example of VIE images acquired with different kVp protocols but presenting similar image quality.

Analysis of SNR based on 2D image measurements demonstrates significant difference due to kVp changes at the level of SMA ($p=0.033$), renal arteries ($p=0.031$) and aneurysm ($p<0.001$), and significant differences due to slice thickness changes at the SMA ($p=0.027$) and renal arteries ($p=0.001$). SNR was independent of pitch value changes in all of the above three locations. Figure 6 shows the SNR measured at the renal arteries was increased significantly when the kVp changed from 100 to 140, while

Figure 8 demonstrates that the significant interaction between SNR and slice thickness, but no statistical evidence of interaction with pitch values.

Analysis of CNR based on 2D image measurements also shows significant differences due to kVp changes at the above-mentioned three locations (p=0.033, 0.009, <0.001, for SMA, renal arteries and aneurysm, respectively). The CNR did not change significantly when the slice thickness changed at the SMA and aneurysm (p=0.076 and 0.723, respectively), but reached statistically significant at the renal arteries levels (p=0.001). CNR was independent of pitch value changes in the all of the above three locations. Figure 9 is a graph showing the CNR measured at the aneurysm relative to the variable kVp and pitch values, while Figure 10 demonstrates the relationship between CNR and section thickness measured at the renal arteries.

In summary, both the SNR and CNR measured with thinner slice thickness such as 1.0 mm were significantly lower than those measured with thicker slice thickness such as 1.5 mm or 2.0 mm, indicating higher image noise resulting from thinner slice thickness. Also the SNR and CNR measured at 100 kVp were significantly different from those measured at 140 kVp at the above three locations.

Measurements of the suprarenal stent struts showed that stent wire thickness was independent of the scanning protocols (regardless of kVp, pitch or slice thickness) as the stent wire remained within the same range of thickness, which is between 1.13 and 1.41 mm, while the actual diameter of stent strut is between 0.4 and 0.5 mm. Figure 11 shows the suprarenal stent struts in relation to the SMA and right renal ostia acquired with different scanning protocols.

Subjective assessment of these images did not show difference in the visualization of aortic ostium and stent wires, which both presented with normal and regular appearances. A score of 3 or 4 was given to both aortic ostia and suprarenal stent wires in all of the images acquired with these dual-source CT protocols, and this indicates that images were acceptable for clinical diagnosis while scanning parameters were adjusted to reduce the radiation dose.

Discussion

Our study was designed to investigate the optimal scanning protocols of dual-source CT angiography in aortic stent grafting, with special focus on the image quality and radiation dose. It was found in this study that multislice CT scanning protocol can be optimised with reduction of radiation dose up to 26.5% without compromising image quality significantly.

Multislice CT has become a routine imaging modality in clinical practice due to its less invasiveness, increased spatial and temporal resolution, especially with the recent development of 64-slice and dual-source CT [4, 5, 10, 11]. Despite these advantages of MSCT over other imaging modalities, clinicians are not fully aware of the risk of radiation dose associated with CT angiography when choosing it as the method of choice for imaging patients treated with aortic stent grafts. Patients treated with aortic stent grafts are routinely followed by CT scans over a series of periods, such as 6 months, 12 months, and yearly thereafter, thus, there is a high risk of exposure to radiation dose due to repeat CT scans. Radiation exposure in abdominal CT angiography is influenced by several factors: first, it is dependent on the tube voltage because dose is related to the square of the tube voltage [12]. 120 kVp is the routine protocol for body CT imaging, however, researchers have reported that significant reduction of radiation dose (between 25-40%) can be achieved when lowering tube voltage from 120 kVp to 100 kVp using the same tube current-time product for cardiac imaging [13-16]. A similar decrease up to 26.5% was found in our study when the tube voltage was reduced from 140 or 120 kVp to 100 kVp.

The second factor that affects effective dose is pitch value, the speed of table movement. Dose saving can be achieved by increasing the pitch, as reported in our previous study [17], while still maintaining the similar image noise. Thus, it has become a routine procedure to use a higher pitch value (more than 1.0 but less than 2.0) for helical CT angiography with single slice CT and early type of multislice CT scanners (4 slice or 16 slice scanner) [12, 13]. We did not notice the difference of effective dose when pitch was changed in this study, as the mAs remained the same during these scans, which is the function of tube current modulation. Image noise (SD) and image quality (SNR and CNR) were independent of pitch based on our analysis, so pitch can be increased without compromising image quality. High pitch is also reported in cardiac imaging using dual source CT [18]. Achenbach et al recently reported the feasibility of using high-pitch spiral CT coronary angiography in patients with coronary artery disease with an effective dose less than 1 mSv, while still achieving excellent image quality. Their results contrast significantly to previous studies performed with a very low pitch (0.2-0.4) using 64-slice CT in cardiac imaging, leading to higher radiation dose [19, 20]. Similarly, a very low dose was found in our study and this indicates the advantage of dual-source CT angiography when compared to early type of CT scanners.

The third factor that affects effective dose is the tube current-time product (mAs). Although it is well-known that relationship between mAs and effective dose is linear, reduction of mAs results in higher image noise and thus might negatively affect image quality. In daily practice, lowering tube current can be effectively done by means of tube current modulation. Our study design was based on this function, so the mAs were selected based on the corresponding kV ranges. Thus, we did not investigate the relationship between mAs and image noise and radiation dose as we only focused on the kVp changes, while adjusting the mAs ranges accordingly.

Previous studies investigating the image quality of MSCT scanning protocols with 4-slice and 64-slice CT showed no direct relationship between SD and pitch and slice thickness [8, 17]. Our results in this study using dual-source CT are consistent to these findings to a greater extent. Different from our previous reports, in addition to using the SD criterion to determine image noise, we included another two factors, SNR and CNR to evaluate image quality in our study. Our results corroborated previous findings with regard to the statement that thinner slice thickness produces higher image noise than thicker slice thickness does, thus leading to lower SNR or CNR [7, 8, 17]. Our analysis shows that SNR and CNR were significantly increased when the slice thickness increased from 1.0 mm to 1.5 mm and 2.0 mm. As already well known, thin slice thickness results in higher spatial resolution which leads to improved detection of the tiny structures such as aortic stent wires. This is especially important for 2D or 3D reconstructions such as multiplanar reformation or VIE visualisation. However, the thin slice thickness that is made available with more CT detectors is also associated with unfavourable effects such as increased image noise. In a recent study, we did not find a significant difference between a very thin slice thickness (0.5-0.625 mm) and relatively thin slice thickness (1.0-1.25 mm) in the assessment of fenestrated vessel stents [21]. Therefore, we recommend that a slice thickness of 1.5 mm be the appropriate scanning protocol for abdominal CT angiography in aortic stent grafting.

Most of the current research on MSCT angiography deals with cardiac imaging as it is the main driving force for the CT technical developments. This is due to the less invasiveness of MSCT angiography when compared to invasive coronary angiography, and also the high specificity of MSCT coronary angiography which makes it as an attractive screening technique in patients with suspected coronary artery disease [8-10, 18]. For imaging of aortic stent grafting, helical CT angiography has been well established as the preferred method of choice as it offers additional information when compared to conventional invasive angiography. However, systematic studies on the optimisation of scanning protocols are limited, and studies on reduction of radiation dose are scarce. We believe our results provide guidelines for clinicians to make judicious use of MSCT technique in imaging patients treated with aortic stent grafts.

Some limitations in our study should be mentioned. First, measurements of the degree of artifacts may not reflect the real patient environment as the study was performed in a static model. In vivo, blood is flowing inside the aorta and contrast density varies along the vessel, and these factors affect image quality. However, with dual-source CT acquisition of homogeneous contrast enhancement in the abdominal CT angiography is easily achieved, thus we believe our results are valid for clinical application. Second, there is only one exposure for each protocol, and no replication was performed for these protocols. Thus, an appropriate estimation of random variation is not available with which to estimate the standard error of the difference of SD or radiation dose. Third, although our aorta phantom was constructed based on a sample patient data and its diameters reflected the actual anatomic configurations, no body habitus or body mass index (BMI) was considered in the experiments. Consequently, our results should be interpreted with caution. The BMI or body mass within the scanning field may be a more accurate parameter to decide which patients should be scanned with lower tube voltages. Further studies taking into account patient's BMI are needed to verify our results. Fourth, although the aorta phantom with insertion of aortic stent graft reflects the realistic endovascular repair of AAA, there is no presence of the most common complication, endoleaks in the phantom. Helical CT angiography is reported to be the most sensitive technique for detection of endoleaks in patients treated with aortic stent grafts [22], thus, identification of optimal CT protocol for detection of endoleaks in future experiments allows robust conclusion to be drawn. Last, the reviewer was not blinded to assess the configuration of aortic ostia and stent wires because the aim of this study was to determine the optimal scanning parameters of MSCT VIE by quantitatively assessing the degree of stair-step artifacts. Reader performance in a blinded fashion and interobserver variability were not assessed. Two or more reviewers are preferable to evaluate the image quality.

In conclusion, our results showed that dual-source CT angiography in aortic stent grafting can be optimised with a reduction of radiation dose by 26.5%. A scanning protocol of slice thickness 1.5 mm, pitch 1.5 with 100 kVp and 180 mAs is recommended as the optimal one as it allows for acquisition of acceptable images, leading to significant radiation dose reduction.

Acknowledgment: Authors would like to thank Yazmina Fuentes and Jerad Murphy from Envision Medical Imaging, Perth, Western Australia for their technical assistance in the phantom scanning. We are grateful to Gil Stevenson for his help in the statistical analysis of results.

References

1. Armerding MD, Rubin GD, Beaulieu CF, Slonim SM, Olcott EW, Samuels SL, et al. Aortic aneurysmal disease: Assessment of stent-grafted treatment-CT versus conventional angiography. Radiology 2000; 215: 138-146
2. Rydberg J, Kopecky KK, Lalka SG, Johnson MS, Dalsing MC, Persohn SA. Stent grafting of abdominal aortic aneurysms: pre-and postoperative evaluation with multislice helical CT. J Comput Assist Tomogr 2001; 25: 580-586
3. Nieman K, Oudkerk M, Rensing BJ, van Ooijen P, Munne A, van Geuns RJ, et al. Coronary angiography with multi-slice computed tomography. Lancet 2001; 357: 599-603
4. Raff GL, Gallagher MJ, O'Neill WW, Goldstein JA. Diagnostic accuracy of non-invasive coronary angiography using 64-slice spiral computed tomography. J Am Coll Cardiol 2005, 46: 552-557
5. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, Suss C, et al. First performance evaluation of a dual source CT (DSCT) system. Eur Radiol 2006; 16: 256-268
6. Sun Z, Winder J, Kelly B, Ellis PE, Kennedy PT, Hirst DG. Diagnostic value of CT virtual intravascular endoscopy in aortic stent grafting. J Endovasc Ther 2004; 11:13-25
7. Sun Z, Taylor C. Optimal scanning protocol of multislice CT virtual intravascular endoscopy in pre-aortic stent grafting: in vitro phantom study. Eur J Radiol 2006; 58: 310-316

8. Sun Z, Gallagher E. Multislice CT virtual intravascular endoscopy for abdominal aortic aneurysm stent grafts. J Vasc Intervent Radiol 2004; 15: 961-970
9. Menzel HG, Schibilla H, Teunen D. European guidelines on quality criteria for computed tomography, publications, EUR 16162 EN. Luxembourg: European Commission, 2000
10. Baumuller S, Leschka S, Desbiolles L, Stolzmann P, Scheffel H, Seifert B, et al. Dual-source versus 64-section CT coronary angiography at lower heart rates: comparison of accuracy and radiation dose. Radiology 2009; 253: 65-64
11. Leber AW, Johnson T, Becker A, von Ziegler F, Tittus J, Nikolaou K, et al. Diagnostic accuracy of dual-source multi-slice CT coronary angiography in patients with an intermediate pretest likelihood for coronary artery disease. Eur Heart J 2007; 28: 2354-2360
12. Huda W, Scalzetti EM, Levin G. Technique factors and image quality as function of patient weight at abdominal CT. Radiology 2000; 217: 430-435
13. Leschka S, Stolzmann P, Schimid FT, Scheffel H, Stinn B, Marincek B, et al. Low kilovoltage cardiac dual-source CT: attenuation, noise, and radiation dose. Eur Radiol 2008; 18: 1809-1817
14. Hausleiter J, Meyer T, Hadamitzky M, Huber E, Zankl M, Marttinoff S, et al. Radiation dose estimates from cardiac multislice computed tomography in daily practice. Circulation 2006; 113: 1305-1310
15. Pflederer T, Rudofsky L, Ropers D, Bachmann S, Marvan M, Daniel WG, et al. Image quality in a low radiation exposure protocol for retrospectively ECG-gated coronary CT angiography. AJR Am J Roentgenol 2009; 192: 1045-1050

16. Park EA, Lee W, Kang JH, Yin YH, Chung JW, Park JH. The image quality and radiation dose of 100-kVp versus 120-kVp ECG-gated 16-slice CT coronary angiography. Korean J Radiol 2009; 10: 235-243
17. Sun Z. Multislice CT angiography in post-aortic stent grafting: optimization of scanning protocols for virtual intravascular endoscopy. Int J CARS 2008; 3: 19-26
18. Achenbach S, Marvan M, Ropers D, Schepis T, PfledererT, Anders K, et al. Coronary computed tomography angiography with a consistent dose below 1 mSv using prospective electrocardiogram-triggered high-pitch spiral acquisition. Eur Heart J 2009 (in press)
19. Earls JP, Berman EL. Urban BA, Curry CA, Lane JL, Jennings RS, et al. Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: Improved image quality and reduced radiation dose. Radiology 2008; 246: 742-753
20. Xu L, Yang L, Zhang Z, Li Y, Fan Z, Ma X, et al. Low-dose adaptive sequential scan for dual-source CT coronary angiography in patients with high heart rate: comparison with retrospective ECG gating. Eur J Radiol 2009 (in press)
21. Sun Z, Allen Y, Bibombe P, Hartley D, Lawrence-Brown M. Multislice CT angiography in the follow-up of fenestrated endovascular grafts: Effect of slice thickness on 2D and 3D visualization of the fenestrated stents. J Endovasc Ther 2008; 15: 417-426
22. Stavropoulos SW, Clark TWI, Carpenter JP, Fairman RM, Litt H, Velazquez QC, et al. Use of CT angiography to classify endoleaks after endovascular repair of abdominal aortic aneurysms. J Vasc Interv Radiol 2005; 16: 663-667

Figure legends

Figure 1 A human aorta phantom built with rapid medical prototyping with a suprarenal stent graft placed inside the phantom. Normal aortic branches and cephalad of the aneurysm can be clearly seen (A) and the uncovered suprarenal stent wires are visualized inside the phantom (B). Arrows in Fig 1A refer to the fusion line in the middle of the phantom (as the phantom was initially constructed in two halves), while the arrow in Fig 1B indicates that the suprarenal stent struts crossing the superior mesenteric artery.

Figure 2. Signal to noise ratio (SNR) and contrast to noise ratio (CNR) were measured at the location of superior mesenteric artery. A circle with a minimal area of 20 mm^2 was drawn in the region of interest to measure the CT attenuation and image noise.

Figure 3. Measurement of the standard deviation (SD) using a line profile. A line is drawn on a virtual intravascular endoscopy (VIE) image viewing the superior mesenteric artery (SMA) and right renal ostia (A) with the distance of around 100 pixels being recorded. The corresponding line profile shows the degree of the stair-step artifacts (B), with the SD measured 4.4.

Figure 4 Relationship between SD and kVp and pitch values. The mean SD measured on 3D VIE images of right renal artery ostium was independent of kVp and pitch values.

Figure 5. Relationship between VIE image quality and variable kVp ranges. VIE images of SMA and right renal ostia were acquired with the following scanning protocols: slice thickness 1.5 mm, pitch 1.0 with kVp of 100, 120 and 140, and corresponding mAs was 180, 150 and 100, respectively (A-C). No significant difference was noticed among these 3D images in terms of subjective visualisation of aortic ostium and quantitative measurement of the degree of artifacts. Long arrows point to the SMA, and short arrows

refer to the right renal ostium, while arrowheads indicate the artifacts caused by air bubbles.

Figure 6. Relationship between image quality (SNR) and variable kVp ranges. The mean SNR measured at the renal arteries reached significant difference with kVp changes, especially between 100 kVp and 140 kVp, but was independent of pitch changes.

Figure 7. Relationship between image quality (SNR) and variable slice thicknesses. The mean SNR measured at the renal arteries was significantly different when the slice thickness changed.

Figure 8. Relationship between image quality (CNR) and variable kVp ranges. The mean CNR measured at the aortic aneurysm was determined by the kVp changes, but was independent of pitch changes.

Figure 9. Relationship between image quality (CNR) and variable slice thicknesses. The CNR measured at the renal arteries was determined by the slice thickness, but was independent of pitch changes.

Figure 10. Relationship between VIE image quality and variable kVp ranges. VIE images of SMA and right renal ostia were acquired with scanning protocols of slice thickness 1.5 mm, pitch 0.5, 1.0 and 1.5 with 100 kVp and 180 mAs. No significant difference was found among these three different pitch ranges with regard to the appearance and diameter of the suprarenal stent struts. Long and short arrows point to the SMA and right renal ostia, respectively, while arrowheads refer to the suprarenal struts. The stent wire thickness was measured between 1.1 and 1.4 mm in all of these images.