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FULL PAPER

Diagnostic yield of 90-kVp low-tube-voltage carotid and intracerebral CT-angiography: effects on radiation dose, image quality and diagnostic performance for the detection of carotid stenosis

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Objective: To investigate the impact of low-tube-voltage 90-kVp acquisition combined with advanced modeled iterative reconstruction algorithm (Admirer) on radiation exposure, image quality, artifacts, and assessment of stenosis in carotid and intracranial CT angiography (CTA).

Methods: Dual-energy CTA studies of 43 patients performed on a third-generation 192-slice dual-source CT were retrospectively evaluated. Intraindividual comparison of 90-kVp and linearly blended 120-kVp equivalent image series (M_{0.6}, 60% 90-kVp, 40% Sn-150-kVp) was performed. Contrast-to-noise and signal-to-noise ratios of common carotid artery, internal carotid artery, middle cerebral artery, and basilar artery were calculated. Qualitative image analysis included evaluation of artifacts and suitability for angiographical assessment at shoulder level, carotid bifurcation, siphon, and intracranial by three independent radiologists. Detection and quantification of carotid stenosis were performed. Radiation dose was expressed as dose-length product (DLP).

Results: Contrast-to-noise values of all arteries were significantly increased in 90-kVp compared to M_{0.6} ($p < 0.001$). Suitability for angiographical evaluation was rated excellent with low artifacts for all levels in both image series. Both 90-kVp and M_{0.6} showed excellent accordance for detection and grading of carotid stenosis with almost perfect interobserver agreement (carotid stenoses in 32 of 129 segments; intraclass correlation coefficient, 0.94). dose-length product was reduced by 40.3% in 90-kVp (110.6 ± 32.1 vs 185.4 ± 47.5 mGy-cm, $p < 0.001$).

Conclusion: 90-kVp carotid and intracranial CTA with Admirer provides increased quantitative and similarly good qualitative image quality, while reducing radiation exposure substantially compared to M_{0.6}. Diagnostic performance for arterial stenosis detection and quantification remained excellent.

Advances in knowledge: 90-kVp carotid and intracranial CTA with an advanced iterative reconstruction algorithm results in excellent image quality and reduction of radiation exposure without limiting diagnostic performance.

INTRODUCTION

CT angiography (CTA) is a commonly used cross-sectional imaging technique for the evaluation of carotid and intracranial arteries. It is regularly performed in the emergent management for suspected stroke to assess acute vascular occlusion, bleeding, or aneurysm. It is also an alternative modality to duplex ultrasound to evaluate large-artery atherosclerosis, which is cause of ischemic stroke in approximately 20%.¹

As CTA of the supraaortic arteries is performed routinely before a potential angiographic intervention and might make the intervention redundant, a robust protocol providing

excellent image quality is crucial. It has become more and more common that automatic and semi-automatic software support technicians in performing CT scans aiming in maintaining image quality while reducing radiation exposure.^{2–5} The effort of introducing low-dose CT protocols is based on the concern of an increased risk for radiation-induced carcinoma of repetitive CT scans,⁶ especially when the scan field involves radiation-sensitive organs.⁷

The benefit of low-tube-voltage CTA scans is not only a lower radiation exposure, but also an increased attenuation, especially of iodinated contrast-filled vessels. However, increased

image noise is a drawback of that technique.^{8,9} To overcome this limitation, iterative reconstruction (IR) algorithms have been proven to beneficially lower image noise without dose penalties. The combination of low-tube-voltage CT scans and IR allows for an increased contrast with significantly lower radiation exposure compared to routine 120-kVp images.^{10,11} A newly introduced IR algorithm, advanced modeled IR algorithm (Admire, Siemens Healthcare, Forchheim, Germany), has shown beneficial results in CTA scans of several body regions and venous contrast-enhanced CT scans of the head and neck region.^{12–17} To our knowledge, the diagnostic yield of low-tube-voltage CTA with Admire for the evaluation of supraaortic stenosis has not been investigated so far.

Therefore, the purpose of this study was to evaluate the impact of 90-kVp acquisition with Admire on quantitative and qualitative image quality, radiation dose, and diagnostic yield on the detection and quantification of vessel stenosis in CTA of the carotid and intracranial arteries compared to 120-kVp equivalent acquisition.

METHODS AND MATERIALS

Patients

This retrospective study was approved by our local institutional review board with a waiver for written consent. A radiologist with more than 6 years of experience in CTA reviewed all dual-energy CTA scans ($n = 48$) of supraaortic arteries of patients with indication of stenosis, stroke, dissection, bleeding, or tumor, which had been performed between July 2015 and June 2016 (12 months). Cases with severe motion artifacts were excluded.

Image acquisition

All CTA scans were performed on a third-generation 192-slice dual-source CT scanner (Somatom Force, Siemens Healthcare, Forchheim, Germany). The X-ray tubes operated in dual-energy mode at 90-kVp (95 mAs) and Sn-150-kVp (59 mAs). The tube operating at 150 kVp was equipped with a tin filter for dose saving (Selective Photon Shield II, Siemens Healthcare, Forchheim, Germany). All scans were acquired in caudocranial direction with a pitch of 0.7 and a collimation of 192×0.6 mm. Automatic tube current modulation software (Caredose 4D, Siemens Healthcare) was used to adapt tube current to the patient's habitus throughout the examination.

Non-ionic contrast medium (Ultravist®, Iopromide 300 mg iodine ml^{-1} ; Bayer Healthcare, Berlin, Germany) at a dose of 0.9 ml kg^{-1} body weight with a maximum of 90 ml were injected with a flow-rate of 2 ml s^{-1} , followed by 30 ml saline flush. Bolus-tracking technique with a region of interest (ROI) in the ascending aorta and a threshold of 140 Hounsfield Units (HUs) triggered the scan.

Image reconstruction

Images were reconstructed using Admire (Siemens Healthcare, Forchheim, Germany) at a strength level of 3 of 5 with a medium smooth reconstruction kernel (Bv36). Linearly-blended M_{0.6} image series merging 60% of the 90-kVp and 40% of the 150-kVp spectrum were reconstructed to resemble standard

single-energy 120-kVp equivalent image series. Additional 90-kVp image series were reconstructed manually in less than 2 min. All data were calculated as transverse and coronal images with a slice thickness of 2.0 mm and increment of 2.0 mm.

Radiation dose

Cumulative radiation dose of each dual-energy CTA scan, expressed as dose-length product (DLP) and CT dose index (CTDI_{vol}), were displayed in the patient's protocols, which were available within our picture archiving and communication system (PACS). DLP was multiplied with the International Commission on Radiological Protection conversion factor for head CT ($0.0021 \text{ mSv mGy.cm}^{-1}$; 16 cm head phantom) to calculate effective dose (ED). Radiation doses of the 90-kVp acquisition were extracted from the data set by validated and previously used software developed in-house in co-operation with Fraunhofer Institute Darmstadt, Germany.¹⁸

Quantitative image analysis

All quantitative measurements were performed by a radiologist with 4 years of experience in CTA, who was not involved with subsequent subjective image analysis, using a commercially available picture archiving and communication system workstation (Centricity 5.0, General Electric Healthcare, Milwaukee, WI). Circular two-dimensional ROIs were drawn in the aorta, common carotid artery, internal carotid artery (ICA) extracranial 2 cm above carotid bifurcation, middle cerebral artery (MCA), basilar artery, and sternocleidomastoid muscle to measure attenuation in HU. In the case of an occluded vessel with, then, filling defect, ROIs were placed in the same vessel at the contralateral side. Image noise was recorded as standard deviation (SD) for each ROI. All ROIs were drawn as large as possible avoiding surrounding anatomical structures. All measurements were performed three times and values for each ROI were averaged to provide data consistency. Contrast-to-noise ratio (CNR) and signal-to-noise ratio (SNR) were calculated using the following formulas: $\text{CNR} = (\text{attenuation}_{\text{artery}} - \text{attenuation}_{\text{muscle}}) / \text{noise}_{\text{artery}}$ and $\text{SNR} = \text{attenuation}_{\text{artery}} / \text{noise}_{\text{artery}}$

Qualitative image analysis

Both 90-kVp and M_{0.6} image series were independently reviewed by three radiologists with 4–6 years of experience in CTA who were blinded to the radiology reports. Window settings (preset values: width, 800 HU; level, 300 HU) could be freely modified. Only a single image series in random order was evaluated during each readout session. A time interval of at least 2 weeks was kept between readings to reduce possible recall bias. Readers rated artifact and suitability for the arterial assessment at shoulder level, carotid bifurcation, carotid siphon, and intracranial using 5-point Likert scales, ranging from 1 = extensive artifacts to 5 = no artifacts, and 1 = non diagnostic to 5 = excellent. Assessment of stenosis was performed for common carotid artery at bifurcation and ICA within the carotid siphon according to NASCET criteria, and graded as relevant stenosis with 50–69% and 70–99%, and occlusion.¹⁹ The reference standard for this study was based on the same CTA acquisition. Other imaging modalities were not included in this study.

Statistical analysis

Statistical analysis was performed using dedicated software (Medcalc statistical software version 12.7.2; Medcalc Software bvba, Ostend, Belgium). Kolmogorov–Smirnov test was applied to evaluate normality of data distribution. For normal variances, Student's *t*-test was used, while Wilcoxon signed-rank test was applied to analyze unequally distributed data. 5-point Likert scales were averaged and analyzed using the non-parametric Friedman test with *post-hoc* tests to calculate subjective artifacts and suitability. Interobserver agreement was calculated using the intraclass correlation coefficient (ICC) in a two-way mixed-effects model, with ICC 0–0.20, slight; 0.21–0.40, fair; ICC 0.41–0.60, moderate; ICC 0.61–0.80, substantial; and ICC 0.81–1, almost perfect agreement. A *p*-value ≤ 0.05 was interpreted as a significant result.

RESULTS

A total of 43 patients (33 male; mean age, 61.7 ± 16.8 years; mean BMI 25.8 kg m^{-2}) were enrolled in this study. Five cases with severe motion artifacts were excluded.

Radiation dose

Extracted DLP, CTDI_{vol} , and ED of the 90-kVp acquisition were 40.3% lower than the cumulative radiation doses of the dual-energy CTA scan (DLP, 110.6 ± 32.1 vs $185.4 \pm 47.5 \text{ mGy}\cdot\text{cm}$; CTDI_{vol} 2.7 ± 1.0 vs $2.8 \pm 0.7 \text{ mGy}$; ED, 0.2 ± 0.1 vs $0.4 \pm 0.1 \text{ mSv}$; all $p < 0.001$).

Quantitative image analysis

Attenuation (all, $p < 0.001$) and image noise (aorta, $p = 0.284$; all others $p < 0.001$) were increased in all measured arteries in 90-kVp compared to M_0.6. Calculated CNR values of all measured arteries were significantly higher in 90-kVp image series compared to linearly-blended 120-kVp equivalent image series (all, $p < 0.001$) (Figure 1). SNR were significantly higher in 90-kVp compared to M_0.6 in all arteries except of ICA and

Figure 1. Axial reformatted, linearly-blended 120-kVp equivalent (M_0.6) (a) and 90-kVp (b) CTA images of an 80-year-old male patient with occlusion of the right internal carotid artery (arrows). 90-kVp image provided increased contrast with slightly, but not diagnostically limiting increased noise, while suitability for carotid artery assessment remained similarly excellent at 40.3% lower radiation doses (DLP, 110.6 ± 32.1 vs $185.4 \pm 47.5 \text{ mGy}\cdot\text{cm}$; ED, 0.2 ± 0.1 vs $0.4 \pm 0.1 \text{ mSv}$; $p < 0.001$). DLP, dose-length product; ED, effective dose.

Table 1. Quantitative image analysis

Parameters	90-kVp	M_0.6	<i>p</i> -value
Attenuation			
Aorta	454.2 ± 138.5	292.0 ± 83.3	<0.001
CCA	442.9 ± 133.2	281.7 ± 79.8	<0.001
ICA	421.7 ± 121.1	269.5 ± 72.3	<0.001
BA	369.7 ± 88.1	235.4 ± 52.4	<0.001
MCA	330.6 ± 77.5	211.2 ± 46.0	<0.001
Noise			
Aorta	21.5 ± 6.7	20.7 ± 4.7	0.284
CCA	35.3 ± 26.6	26.8 ± 16.1	<0.001
ICA	66.3 ± 40.6	42.4 ± 23.7	<0.001
BA	69.1 ± 43.8	45.8 ± 36.3	<0.001
MCA	73.7 ± 34.1	47.7 ± 21.2	<0.001
SNR			
Aorta	22.7 ± 9.1	14.9 ± 5.7	<0.001
CCA	17.0 ± 9.6	13.3 ± 7.9	<0.001
ICA	10.7 ± 9.4	8.7 ± 5.9	0.151
BA	7.2 ± 5.1	6.3 ± 3.4	<0.001
MCA	5.3 ± 2.2	5.1 ± 1.9	0.223
CNR			
Aorta	44.1 ± 23.4	25.0 ± 9.5	<0.001
CCA	43.1 ± 22.8	23.9 ± 9.5	<0.001
ICA	38.2 ± 13.5	22.4 ± 8.0	<0.001
BA	34.2 ± 15.4	18.7 ± 5.9	<0.001
MCA	30.2 ± 14.8	16.5 ± 6.5	<0.001

BA, basilar artery; CCA, common carotid artery; CNR, contrast-to-noise ratio; ICA, internal carotid artery; MCA, middle cerebral artery; SNR, signal-to-noise ratio.

Values are mean $\pm$ standard deviation.

MCA (ICA, $p = 0.151$; MCA, $p = 0.223$; all others, $p < 0.001$). Detailed quantitative measurements are displayed in Table 1.

Qualitative image analysis

Image series of both, 90-kVp and M_0.6, had excellent ratings for suitability for carotid and intracranial artery assessment without poor or non-diagnostic cases (4.8 ± 0.4 vs 5.0 ± 0.3 ; $p \geq 0.096$). Bar graphs illustrating results of qualitative image analysis are displayed in Figure 2. Both image series showed similar excellent ratings with low level of artifacts and without cases of high or extensive artifacts for carotid bifurcation level and carotid siphon ($p \geq 0.11$) (Figure 3). In comparison, ratings of artifacts at shoulder level were slightly lower in both image series (90-kVp, 4.6 ± 0.5 ; M_0.6, 4.7 ± 0.5 ; $p = 0.008$).

Detection of stenosis

Interobserver agreement was excellent for the detection (ICC, 1.00) and grading of stenosis at carotid bifurcation level (ICC, 1.00) and within the carotid siphon (ICC, 0.989 and 1.00) for

Figure 2. Median scores for qualitative image analysis including artifacts (a) and suitability for angiographic evaluation (b) of 90-kVp and 120-kVp equivalent linearly-blended (M_0.6) image series.

both 90-kVp and M_0.6 images. All three raters detected 12 carotid stenoses greater 50% at bifurcation level, and 10 stenoses greater 50% within the carotid siphon (ICC, 1.00, respectively). There was no significant difference for detection and grading of stenosis between 90-kVp and M_0.6 image series (all, $p \geq 0.317$) (Figure 4). There was a grading discrepancy of one patient of carotid siphon with one observer. All results for detection and grading of stenosis are displayed in Table 2.

DISCUSSION

The results of our study demonstrated that 90-kVp CTA acquisition of the supraaortic arteries provided increased quantitative image quality and similarly, excellent qualitative image quality compared to 120-kVp equivalent linearly-blended image series, while radiation dose was reduced by 40.3%. Further, low-tube-voltage CT acquisition did not limit diagnostic performance, but showed similar excellent diagnostic yield for the detection and grading of carotid stenosis.

Reduction of tube voltage is a commonly used technique to lower radiation exposure in CT imaging. The limitation of increased noise at lower kV levels has been overcome by new CT scanner hardware with increased tube current capacity and new reconstruction techniques such as IR algorithms. Thus, low-tube voltage scans in combination with IR algorithms allow substantial lower radiation doses while preserving image quality.^{11–13,20–22} Whole body CTA

on a third-generation 192-slice dual-source CT using a combination of several dose saving strategies such as automated tube voltage selection (70- to 150-kVp) and Admire resulted in a tube voltage reduction in 75% of all patients, improved image quality, and 19% lower radiation doses compared to second-generation 128-slice dual-source CT.²³ Further, quantitatively improved image quality with, simultaneously, 34% lower radiation doses have been reported for contrast-enhanced venous neck CT when reduced tube voltages of 70-kVp to 90-kVp were used on a third-generation dual-source CT scanner compared to 100-kVp on a second-generation dual-source CT scanner.²⁴ Our study could show that 90-kVp CTA of the supraaortic vessels demonstrated a mean dose reduction of 40.3%. Almost similar radiation doses for carotid and cerebral CTA were reported by Kayan *et al* using 80-kVp (DLP, 116.60 mGy.cm) and Chen *et al* using 70-kVp scans (DLP, 116.0 mGy.cm).^{25,26} In both studies, qualitative image analysis revealed similar good ratings compared to standard 120-kVp images. However, diagnostic accuracy for carotid stenosis was not assessed within these studies.

Imaging of the lower part of the neck per CT remains still a critical area due to superimposition of the shoulder region and consecutive

Figure 3. Axial reformatted, 120-equivalent (M_0.6) (a) and 90-kVp (b) CTA images of a 76-year-old male patient with a high-grade stenosis (90%) of the right internal carotid artery (arrows). While metallic artifacts due to dental filling were slightly increased in 90-kVp image series, visualization of carotid arteries remained excellent. CTA, CT angiography.

Figure 4. Axial reformatted images of a 56-year-old female patient with a 60% stenosis of the right internal carotid artery (arrows), and a < 50% stenosis of the left internal carotid artery (arrowheads). In comparison to 120-kVp equivalent linearly-blended (M_0.6) images (a) 90-kVp images (b) showed greater iodine attenuation resulting in higher contrast, while depiction of carotid arteries remained excellent. Radiation dose was reduced by 40.3% (DLP, 110.6 ± 32.1 vs 185.4 ± 47.5 mGy.cm; ED, 0.2 ± 0.1 vs 0.4 ± 0.1 mSv; $p < 0.001$). DLP, dose-length product; ED, effective dose.

Table 2. Diagnostic performance

	90-kVp (n = 43)	M_0.6 (n = 43)	p-value
Bifurcation			
Stenosis > 50%	12/12/12	12/12/12	1.00
ICC for stenosis > 50%	1.00	1.00	
Grading of stenosis			
0–49%	31/31/31	31/31/31	1.00
50–69%	9/9/9	9/9/9	
70–99%	3/3/3	3/3/3	
100% (occlusion)	0	0	
ICC for stenosis grading	1.00	1.00	
Siphon			
Stenosis > 50%	10/10/10	10/10/10	1.00
ICC for stenosis > 50%	1.00	1.00	
Grading of stenosis			
0–49%	33/33/33	33/33/33	0.317
50–69%	7/6/6	6/6/6	
70–99%	2/3/3	3/3/3	
100% (occlusion)	1	1	
ICC for stenosis grading	0.989 (0.981, 0.994)	1.00	

ICC, intraclass correlation coefficient.

Quantification of stenoses at carotid bifurcation and within the carotid siphon for 90-kVp and linearly-blended 120-kVp equivalent M_0.6 image series.

artifacts. Despite of a steadily improvement of CT hardware and new IR algorithms, prior studies pointed out increased artifacts at the lower neck/shoulder level in venous contrast-enhanced neck CT at 70-kVp scans.^{12,27} As CTA scans in the head and neck region are generally scanned with lower tube current settings than venous CT scans, risk of non-diagnostic images due to streak artifacts at shoulder level might be higher and, thus, 70-kVp CTA scans should be used with caution to prevent non-diagnostic examinations. However, application of advanced IR algorithms in 80-kVp cervical CTA and 90-kVp venous neck CT lowered image noise substantially and increased CNR compared to filtered back projection reconstruction, even at shoulder level.^{12,28} The present study was conducted using a single vendor's equipment. However, CT scanners from other vendors are equipped with manufacturer specific IR software.

To our knowledge, this study is the first which proved similar diagnostic performance for stenosis evaluation of supraaortic low-tube-voltage CTA scans as in comparison to 120-kVp equivalent CT scan. These beneficial results with similar good diagnostic performance and improved quantitative image quality might be seen as a solid base for further studies which might vary contrast medium volume to achieve similar quantitative image quality than 120-kVp scans, but with significant lower volume of iodine.

We acknowledge that the current study has some limitations apart from the vendor-specific nature of our results that need to be mentioned. First, the number of patients in this study was small and results should be confirmed in a bigger cohort. We compared 90-kVp image series with 120-kVp equivalent linearly-blended image series, but did not perform comparison with true 120-kVp acquisition. Prior studies have shown equal image quality of linearly-blended dual-energy image series and 120-kVp acquisition.²⁹ The comparison of two image series reconstructed from a single acquisition allowed an intraindividual comparison without contrast medium- or patient-related confounders which might have an influence on contrast bolus and, therefore, image quality. For evaluation of stenosis detection and grading, we did not compare findings to alternative modalities such as ultrasound or MRI. The reference standard of this study was not independent, as it was based on the same CTA study. We performed an interrater agreement analysis, based on ratings of three radiologists, to compare both image series. Fourth, with a BMI of 25.8 kg m⁻², our patient cohort is in a normal weight range. Further studies are warranted to evaluate whether our results also apply for overweight patients, as low-kVp imaging might be impaired in this patient cohort.

In conclusion, our study demonstrated that 90-kVp acquisition with an advanced IR algorithm resulted in excellent image quality in carotid and intracranial CTA without limitation in the diagnostic performance for the detection and quantification of carotid stenosis while reducing radiation exposure by 40.3% compared to 120-kVp images.

CONFLICT OF INTEREST

Julian L Wichmann received speakers' fees from GE Healthcare and Siemens Healthcare. The other authors have no potential conflict of interest to declare. Data was controlled by authors with no potential conflict of interest.

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