AJNR

Comparison of Image Quality and Radiation Dose between Fixed Tube Current and Combined Automatic Tube Current Modulation in Craniocervical CT Angiography

E.J. Lee, S.K. Lee, R. Agid, P. Howard, J.M. Bae and K. terBrugge

AJNR Am J Neuroradiol 2009, 30 (9) 1754-1759
doi: https://doi.org/10.3174/ajnr.A1675
http://www.ajnr.org/content/30/9/1754

ORIGINAL RESEARCH

Comparison of Image Quality and Radiation Dose between Fixed Tube Current and Combined Automatic Tube Current Modulation in Craniocervical CT Angiography

E.J. Lee
S.K. Lee
R. Agid
P. Howard
J.M. Bae
K. terBrugge

BACKGROUND AND PURPOSE: The combined automatic tube current modulation (ATCM) technique adapts and modulates the x-ray tube current in the *x-y-z* axis according to the patient's individual anatomy. We compared image quality and radiation dose of the combined ATCM technique with those of a fixed tube current (FTC) technique in craniocervical CT angiography performed with a 64-section multidetector row CT (MDCT) system.

MATERIALS AND METHODS: A retrospective review of craniocervical CT angiograms (CTAs) by using combined ATCM ($n = 25$) and FTC techniques ($n = 25$) was performed. Other CTA parameters, such as kilovolt (peak), matrix size, FOV, section thickness, pitch, contrast agent, and contrast injection techniques, were held constant. We recorded objective image noise in the muscles at 2 anatomic levels: radiation exposure doses (CT dose index volume and dose-length product); and subjective image quality parameters, such as vascular delineation of various arterial vessels, visibility of small arterial detail, image artifacts, and certainty of diagnosis. The Mann-Whitney *U* test was used for statistical analysis.

RESULTS: No significant difference was detected in subjective image quality parameters between the FTC and combined ATCM techniques. Most subjects in both study groups (49/50, 98%) had acceptable subjective artifacts. The objective image noise values at shoulder level did not show a significant difference, but the noise value at the upper neck was higher with the combined ATCM ($P < .05$) technique. Significant reduction in radiation dose (18% reduction) was noted with the combined ATCM technique ($P < .05$).

CONCLUSIONS: The combined ATCM technique for craniocervical CTA performed at 64-section MDCT substantially reduced radiation exposure dose but maintained diagnostic image quality.

Recent technical advances have greatly increased the clinical applications of CT, especially since the introduction of the spiral scanning techniques and the subsequent developments in multidetector-row CT (MDCT) technology. Sixty-four-section MDCT allows craniocervical CT angiography (CTA) to be performed with increased coverage, from the aortic arch to the vertex, with improved spatial resolution, shorter acquisition times, and lower doses of contrast material.[1] Craniocervical CTA is now routinely used as a noninvasive alternative to conventional angiography for the evaluation and detection of intracranial aneurysms and intracranial and extracranial vascular occlusive disease, particularly in emergency situations (eg, stroke, subarachnoid hemorrhage).[2-6]

However, the major disadvantage with the increased use of MDCT is associated radiation exposure. Greater use of craniocervical CTA has the potential to increase the radiation burden in general. Induction of cancer is a stochastic event; however, the risk for cancer in humans proceeds in a linear fashion at lower doses without a "safe" threshold, and even the smallest dose has the potential to cause a small increase in risk to humans.[7,8] A recent survey showed that CT now accounts for about 11% of all radiology procedures in the United States and constitutes approximately two thirds of the collective medical radiation dose.[9] In standard CT of the head and neck, direct radiation effects relative to the eye lenses and the thyroid gland have been documented, likely resulting in cataract formation and the development of thyroid malignancies, respectively.[4,10]

The automatic tube current modulation (ATCM) technique enables automatic adjustment of the tube current in various planes (*x-y* or *z*) based on the size and attenuation of the body area scanned, to achieve constant image quality. Angular or *x-y* modulation decreases the selected tube current in the projection (in the *x-y* plane) that causes less attenuation, whereas the *z*-axis modulation technique adjusts the tube current from section to section, depending on regional body anatomy. A combination of the angular and *z*-axis modulations involves varying the tube current both during gantry rotation and along the *z*-axis of the patient. This is one of the most comprehensive approaches to CT dose reduction because the x-ray dose is adjusted according to patient-specific attenuation in all 3 planes.[11-16]

Despite these pronounced technical advances, little is known about the optimal imaging parameters for MDCT in craniocervical CTA. In this study, we compared image quality and radiation doses of 64-section MDCT craniocervical CTA obtained with the ATCM technique of the combined type with those obtained with a fixed tube current (FTC) technique.

Received February 5, 2009; accepted after revision April 17.

From the Department of Medical Imaging (E.J.L., S.K.L., R.A., P.H., K.t.), Toronto Western Hospital, Toronto, Ontario, Canada; Department of Radiology (S.K.L.), Lahey Clinic Medical Center, Burlington, Mass; Department of Radiology (E.J.L.), Myong Ji Hospital, Kwandong University, Goyang-shi, South Korea; and Department of Preventive Medicine (J.M.B.), Jeju National Univeristy, Jeju, South Korea.

Please address correspondence to: Seon Kyu Lee, MD, PhD, Staff Interventional Neuroradiologist, Department of Radiology, Lahey Clinic Medical Center, Burlington, MA, 01805; e-mail: seonkyu.lee@lahey.org

DOI 10.3174/ajnr.A1675

Materials and Methods

Patient and Examination Protocol

The institutional review board approved the study.

We retrospectively reviewed 50 consecutive adult patients who underwent contrast-enhanced craniocervical CTA at our institution between December 2006 and November 2007. All patients had a craniocervical CTA from the aortic arch to the vertex by using a 64-section MDCT scanner (Aquilion 64; Toshiba Medical Systems, Tokyo, Japan).

Patients were divided into 2 groups. In the first group of 25 consecutive subjects (median age, 61 years; range, 32–90 years; 11 men, 14 women), an FTC of 300 mA was used because this was the standard protocol for craniocervical CTA on our scanner. Members of the other group, composed of 25 consecutive subjects (median age, 59 years; range, 18–84 years; 10 men, 15 women) were scanned with the combined ATCM technique. In all except 1 patient, the range of tube currents in the combined ATCM technique was 101–300 mA (the maximum tube current in 1 obese patient was 400 mA). The tube current at the shoulder level was the same (300 mA) for the 2 groups, except for the 1 obese patient with the combined ATCM technique.

The combined ATCM system used was the ^{SURE}Exposure 3D (Toshiba Medical Systems); it controls and modulates the current in the *x*, *y*, and *z* directions to achieve and maintain a uniform user-selected noise level in the images. For a homogeneous object with a circular cross section, attenuation is constant over all of the projections and all measured values contribute equally. However, because the human body is not perfectly round or uniform in size or attenuation, different milliampere-second (tube current–time product) settings are required to achieve the same image quality in different parts of the body. More current is typically needed when x-rays are passing laterally through the body than when they are passing anteroposteriorly, because patients are shaped approximately elliptically, particularly in the shoulders. The ^{SURE}Exposure 3D software automatically and rapidly adjusts the current during scanning to adapt to and compensate for changes in the attenuation level. Using data from the anteroposterior and lateral scanograms, the software determines exactly how much current is necessary to maintain a user-defined level of image quality. The software does this in all 3 dimensions (*x*-, *y*-, and *z*-axes). Thus, as the scanning moves from the shoulders to the head, more current is needed to penetrate attenuated and large areas, like the shoulders and head, whereas lower current is adequate in less attenuated and smaller areas like the neck (*z*-axis modulation). Furthermore, as the tube rotates around the patient, less current is used anteroposteriorly than laterally (*x*-*y*—axis modulation) (Fig 1).

Other scanning parameters were held constant, with a tube voltage of 120 kilovolt (peak), a matrix size of 512 × 512, FOV of 28–32 cm, a section thickness of 0.5 mm, a pitch of 1.0, and an isotropic voxel size of 0.5 mm. The acquisition time was 11–16 seconds. CTA images were acquired following intravenous timed injection of contrast agent (iodixanol, Visipaque 270; Amersham Health, Oslo, Norway) by using an autotriggered mechanical injector. The injection rate was 4 mL/s to a total injection volume of 40 mL of contrast agent, followed by an injection of 20 mL of contrast agent at 3 mL/s.

Image processing consisted of standardized axial, coronal, and sagittal multiplanar volume-reformatted maximum intensity projections (MIP; 8-mm thickness, 2-mm reconstruction interval) and 3D volume-rendered reconstructions (performed on an Advantage Windows, Version 4.2 workstation; GE Healthcare, Milwaukee, Wis).

Indications for craniocervical CTA were the detection of aneurysms and possible atherosclerotic disease of the intracranial and extracranial vascular system in patients with a transient ischemic attack or ischemic stroke. Patients with poor-quality CTA due to patient movement and those who had undergone carotid stent placement or coiling or clipping for an aneurysm were excluded from the study. Patients who simultaneously underwent craniocervical CTA with standard head CT or cerebral perfusion were also excluded because we could not separate radiation doses from the craniocervical CTA from those of the combined imaging.

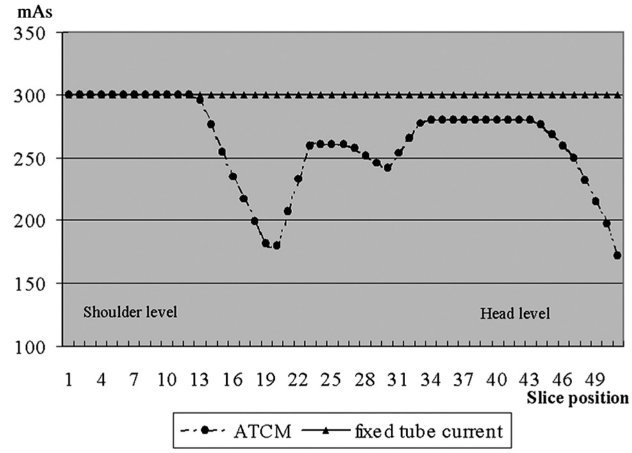

Fig 1. Graph illustrating tube current reduction by combined ATCM, which tailors the radiation dose to the individual patient. A higher dose is needed to penetrate attenuated areas like the shoulder and head, whereas a lower dose is adequate for less attenuated areas such as the neck. The overall radiation dose with combined ATCM is less than that with FTC.

Image Analysis

To compare patient sizes in the groups, we used 2 measurements. The length of scan coverage and the maximum transverse neck diameter at the level of the hyoid bone were recorded because these patient-related factors may affect image quality or the radiation dose.

Objective evaluation of image quality was based on an evaluation of image noise. Image noise was recorded for each examination in the muscles at 2 anatomic levels: the sternocleidomastoid muscle in the upper neck (submandibular gland level, possibly the lowest current site) and the pectoralis major muscle, at shoulder level. For measurement of image noise, circular or ovoid regions of interest with a size of 0.5–1.0 cm^2 (0.5 cm^2 in the sternocleidomastoid muscle and 1.0 cm^2 in the pectoralis major muscle) were placed in a homogeneous region of muscle without fat. SDs of the attenuation in these regions of interest were recorded. The SD, in Hounsfield units, of the attenuation in a particular region of interest can be used as a noise measurement.[13]

Qualitative image scoring was performed independently by 2 staff neuroradiologists with experience in craniocervical CTA. Scanning parameters were removed at the PACS workstation; thus, the readers were blinded with regard to the scanning parameters used. The readers evaluated subjective image quality at standardized axial, coronal, and sagittal multiplanar volume-reformatted MIP and 3D volume-rendered reconstructions of craniocervical CTA. The readers evaluated and independently scored the image quality parameters of the vascular delineation in various arterial vessels, the visibility of small arterial detail, image artifacts, and the certainty of diagnosis.

The readers were asked to evaluate the vascular delineation of various arterial vessels, such as the common carotid arteries, bifur-

Table 1: Age, scanning length, and maximum transverse neck diameter of subjects for examinations performed using FTC and combined ATCM			
	FTC*	Combined ATCM*	*P* Value†
Age	61.6 ± 15.35 (61.0)	58.96 ± 16.62 (59.0)	.669
Scanning length (cm)	43.90 ± 55.87 (32.40)	44.39 ± 55.79 (33.60)	.336
Maximum transverse neck diameter (cm)	12.91 ± 1.36 (12.70)	12.67 ± 1.60 (12.30)	.503

Note:—FTC indicates fixed tube current; ATCM, automatic tube current modulation.
* Mean ± SD (median).
† From the Mann-Whitney *U* test.

Table 2: The scores for image quality parameters for examinations performed using FTC and combined ATCM						
	Reader 1			Reader 2		
	FTC*	Combined ATCM*	*P* Value†	FTC*	Combined ATCM*	*P* Value†
Vascular delineation	4.92 ± 0.40 (5.0)	4.92 ± 0.40 (5.0)	1.00	4.48 ± 0.59 (5.0)	4.40 ± 0.58 (4.0)	.61
Visibility of small arterial detail	4.92 ± 0.27 (5.0)	5.00 ± 0.00 (5.0)	.16	4.92 ± 0.28 (5.0)	4.80 ± 0.41 (5.0)	.23
Subjective image noise	4.28 ± 0.74 (4.0)	4.52 ± 0.65 (5.0)	.21	4.08 ± 0.57 (4.0)	4.00 ± 0.50 (4.0)	.60
Certainty of diagnosis	4.96 ± 0.20 (5.0)	4.92 ± 0.28 (5.0)	.57	4.72 ± 0.46 (5.0)	4.80 ± 0.41 (5.0)	.52

* Mean ± SD (median).
† From the Mann-Whitney *U* test.

cation of the carotid arteries, the internal carotid arteries (ICAs), external carotid arteries, intraosseous portion of the ICAs, vertebral arteries, the basilar artery, anterior cerebral arteries, middle cerebral arteries, and posterior cerebral arteries by using a 5-point scale. A score of 5 corresponded to excellent vessel delineation; 4, to good vessel delineation; 3, to adequate vessel delineation; 2, to marginally acceptable vessel delineation; and 1, to unacceptable vessel delineation.

The readers were asked to evaluate the visibility of small arterial detail on the basis of the depiction of small arteries, such as the ophthalmic, the superior cerebellar, and pericallosal arteries with a 5-point scale. A score of 5 corresponded to excellent vessel delineation; 4, good vessel delineation; 3, adequate vessel delineation; 2, marginally acceptable vessel delineation; and 1, unacceptable vessel delineation.

The readers were asked to assess subjective image artifacts on a 5-point scale. Five corresponded to a complete absence of imaging artifacts; 4, to mild artifacts not interfering with diagnostic decision making; 3, to moderate artifacts slightly interfering with diagnostic decision-making; 2, to pronounced artifacts interfering with diagnostic decision-making, though it was still possible to arrive at a diagnosis; and 1, to a situation in which artifacts completely hindered diagnostic decision making.

In addition, the readers were asked to rate their certainty of diagnosis on a 5-point scale. Five corresponded to a full and confident certainty of diagnosis based on the results of CT angiography alone; 4, a good certainty of diagnosis based on the results of CT angiography alone, though additional imaging would increase the certainty of diagnosis; 3, an adequate certainty of diagnosis based on the results of CT angiography alone, though additional imaging would be desirable; 2, a marginal certainty of diagnosis based on the results of CT angiography alone, though additional imaging would be required to establish the diagnosis; and 1, a situation in which the diagnosis was uncertain on the basis of the results of CT angiography alone. A score of ≥3 was considered as an acceptable level of artifacts or as constituting adequate diagnostic acceptability.

Radiation Dose

The fundamental radiation dose parameter in CT is the CT dose index (CTDI). The volume CTDI ($CTDI_{vol}$), a derivative of the CTDI, can be used to express the average dose delivered to the scan volume in a specific examination. The dose-length product (DLP) provides an indication of the energy imparted to the organs and can be used to assess the overall radiation burden associated with a CT study.

To compare radiation exposure with combined ATCM and FTC techniques, we recorded the DLP, as a CT radiation dose descriptor, for each study. The $CTDI_{vol}$ was calculated from the following equation: $DLP = CTDI_{vol} \times$ scan length (cm).

Statistical Analysis

The ages, maximum transverse diameter, and scan lengths between combined ATCM and FTC were compared for study homogeneity. Image quality scores for the delineation of various arterial vessels, visibility of small arterial details, subjective image artifacts, and certainty of diagnosis were compared between combined ATCM and FTC. Furthermore, quantitative image noise values in the muscles at 2 anatomic levels, $CTDI_{vol}$ and DLP, for examinations performed with the different techniques were also compared. The Mann-Whitney *U* test was used to assess differences between these values (Statistical Package for the Social Sciences, Version 12.0; SPSS, Chicago, Ill). A value of $P < .05$ indicated a statistically significant difference.

Results

The ages, length of scan coverage, and maximum transverse neck diameters of the subjects between the combined ATCM and FTC were not significantly different ($P > .05$, Table 1).

The scores of subjective image-quality parameters, such as vascular delineation of various arterial vessels, visibility of small arterial detail, image artifacts, and certainty of diagnosis, for studies performed with FTC and combined ATCM are summarized in Table 2. Again, no significant difference was detected in image quality parameters for examinations performed with the 2 different techniques (Fig 2 and Table 2). All subjects in both study groups had acceptable subjective artifacts or adequate diagnostic acceptability according to both readers, but reader 1 reported a suboptimal study for subjective artifacts in 1 subject with the FTC due to mild motion artifacts and metallic artifacts from the teeth.

We found no significant difference in the objective image noise values at the shoulder level between the study groups ($P = .077$). However, mean noise measurements at the upper neck were significantly greater with combined ATCM ($P =$

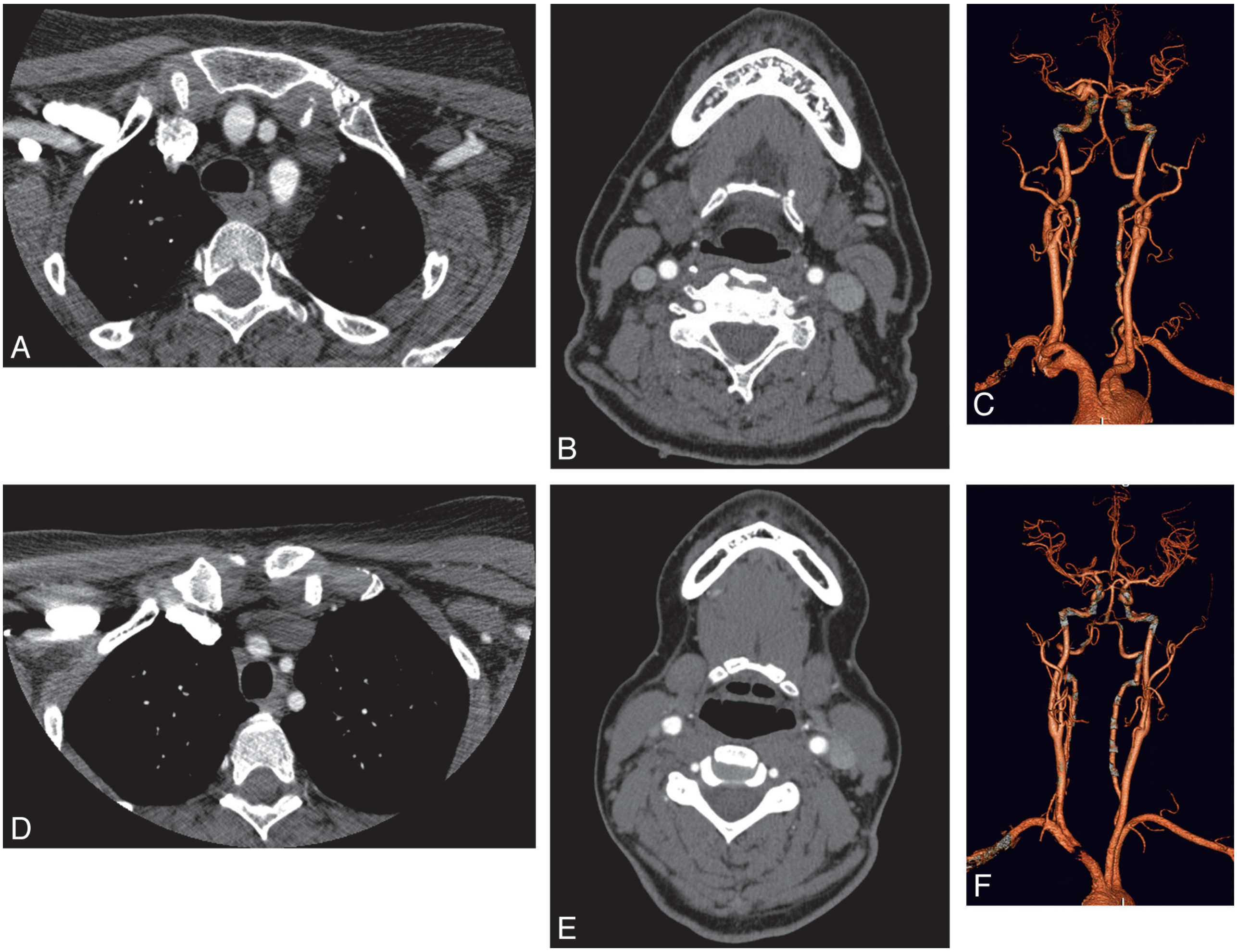

Fig 2. Evaluation of craniocervical CTA with combined ATCM (*A–C*) and FTC (*D–F*). Transverse images through the shoulder level and upper neck and 3D reconstructions of CTA show that the subjective image quality of the 2 techniques is comparable.

Table 3: Objective image noise for examinations performed using FTC and combined ATCM

	FTC*	Combined ATCM*	*P* Value†
Objective image noise (HU)			
Upper neck	8.82 ± 2.53 (9.10)	10.50 ± 1.37 (10.30)	.003
Shoulder	22.78 ± 4.16 (22.40)	25.23 ± 3.84 (25.60)	.077
$CTDI_{vol}$ (mGy)	53.85 ± 17.28 (57.10)	42.97 ± 11.67 (47.00)	.001
DLP (mGy × cm)	1756.07 ± 560.05 (1835.50)	1423.92 ± 390.03 (1507.00)	.002

Note:—$CTDI_{vol}$ indicates CT dose index volume; DLP, dose-length product.
* Mean ± SD (median).
† From the Mann-Whitney *U* test.

.003, Table 3). Noise measurements at the shoulder level were much greater than those at the upper neck for both the combined ATCM and FTC groups.

A significant reduction in radiation dose (18% reduction for both $CTDI_{vol}$ and DLP) was noted with the combined ATCM compared with the FTC ($P = .001$ for $CTDI_{vol}$ and $P = .002$ for DLP, Table 3).

Discussion

With the rapid development of MDCT technology and increasing concern over the associated radiation dose, optimization of scanning techniques to maintain diagnostic image quality at the lowest possible radiation dose has become very important.[17-20]

Scanning parameters that affect CT radiation dose include x-ray beam energy (tube potential, kilovolt [peak]), tube current–time product (milliampere-second), pitch, section thickness, and scanning volume. Tube current is an important determinant of radiation dose and image quality in x-ray–based examinations. The radiation dose is linearly related to the current-time (milliampere-second) value when all other factors are held constant. However, a reduction of radiation dose will increase image noise, which may compromise image quality to a variable extent.[2,12,17,19,21,22]

Previous studies on CT of the head and neck, chest, abdomen, and pediatric pelvis have suggested the possibility of reducing tube currents without jeopardizing imaging quality,[17,19,23-28] but the tube current in those studies was adjusted manually.

Such manual adjustment of tube current, based on patient weight or dimensions, can aid in establishing an appropriate balance between image noise and radiation exposure. However, these adjustments do not guarantee constant image quality throughout the examination.

Recent advances in CT technology, including implementation of combined ATCM, allow reduced radiation exposure during CT examinations. ATCM techniques allow maintenance of constant image quality with a reduced radiation exposure level because ATCM responds rapidly to large variations in beam attenuation. ATCM is based on the principle that x-ray attenuation and quantum image noise are determined by the size of the object and its tissue attenuation. Thus, the technique aims to modulate the tube current on the basis of regional body anatomy for adjustment of x-ray quantum noise to maintain constant image noise, with improved dose efficiency.

Compared with the chest and abdomen, craniocervical CTA by using a 64-detector MDCT spans a body region with wide variations in body size and attenuation patterns. With an FTC technique, a low-dose CT may result in suboptimal-quality images at the shoulders, whereas a higher tube current may result in greater exposure in the neck region. Because ATCM automatically adjusts the tube current on the basis of size and attenuation of the body region, it can automatically increase the tube current for the shoulder region and head and reduce it for the neck.

In previous studies, investigators have reported a substantial reduction in radiation dose with the ATCM technique. One study reported a 33% mean tube current–time product reduction, with similar artifacts and diagnostic acceptability, for abdominal and pelvic CT by using *z*-axis tube current modulation compared with an FTC technique.[29] A radiation dose reduction of 56%–77% has been reported for urinary tract stone CT studies by using *z*-axis modulation.[20] Kalra et al[16] reported an 18%–26% radiation dose reduction for a chest CT study by using *z*-axis modulation. Namasivayam et al[11] compared the radiation dose and image quality of *z*-axis tube current modulation with those of FTC for MDCT evaluations of the neck. They reported a significant radiation dose reduction in the *z*-axis tube current modulation technique, with similar subjective artifacts and diagnostic acceptability.

Rizzo et al[13] reported that the use of a combined modulation technique resulted in a substantial reduction in the radiation dose, with acceptable image artifacts and diagnostic acceptability, compared with using a constant tube current, in scans of the abdomen and pelvis. Graser et al[30] compared the radiation dose and image quality of combined ATCM with angular tube current modulation alone in CT colonography. They showed that combined ATCM resulted in a significant reduction in radiation exposure in CT colonography, without loss of image quality. Implementation of the *x-y-z* axis dose modulation (combined dose modulation) technique for neuroradiology CT examinations also revealed substantial dose reduction while maintaining image quality, compared with no dose modulation or z-axis dose modulation only.[31] However, this study could not provide the magnitude of dose reduction on 64-section MDCT scanning because the comparison studies were performed on 16-section MDCT.

To our knowledge, no previous report has included comparisons of image quality and radiation doses on craniocervical CTA at 2 different tube current settings, the FTC and a combined ATCM. Our study showed that the combined modulation technique for craniocervical CTA provided similarly acceptable levels of depiction of the craniocervical vessels and diagnostic acceptability, as well as a reduction in radiation dose, compared with the FTC technique. In our results, objective noise at the shoulder level was greater than that in the upper neck for both the combined ATCM and FTC groups. This was due to the wide and higher beam-attenuating shoulders being in the scanning field. Because the shoulders were not the primary area of interest, we believe that better image quality of the shoulders need not be obtained by using a higher tube current. We saw no significant difference in the objective image noise values at shoulder level between the study groups, but objective noise in the upper neck was significantly higher with combined ATCM. The tube current in the shoulder level was the same (300 mA) for the 2 groups, but the combined ATCM technique automatically lowered the tube current for the neck, whereas the FTC had a constant tube current. We believe that this caused an increase in objective noise in the upper neck with the combined ATCM.

Our study has following limitations: First, different patients were assessed with combined ATCM and FTC modulation techniques because radiation concerns prohibited evaluating the same patients by using >1 method. However, the scanning length, maximum transverse neck diameter, and ages of the patients who underwent craniocervical CTA with the 2 different techniques were not significantly different. Second, our study was targeted at the efficacy of combined ATCM for craniocervical CTA in showing depictions of vascular structures. Its effects on diagnostic information, such as vascular stenosis or aneurysms, remain to be evaluated. Third, we neither included a comparison of the mean tube current–time product nor estimated the effective dose for combined ATCM and FTC techniques. However, currently, $CTDI_{vol}$ and DLP are the standard parameters used to describe CT-associated radiation doses; thus, we considered these useful in assessing the radiation dose.[32,33] Last, the cross-sectional dimensions and weight (or body mass index) of the patients may provide better criteria for optimizing scanning parameters without losing relevant diagnostic information because the distance of the pathway traversed by the x-ray beam determines its attenuation.

In this study, we did not correlate the objective image noise, subjective image quality, and radiation exposure with patient weight or cross-sectional dimensions. We believe that such correlations should be assessed in a larger population study. Lowering the tube potential (kilovolt [peak]) can effectively reduce the radiation dose at MDCT examinations without substantially decreasing image quality.[34-37] Other scanning parameters such as pitch, section thickness, and scanning volume can also affect radiation dose. Therefore, in addition to the combined ACTM technique, there may still be some room to reduce the radiation dose further though kilovolt (peak), pitch, section thickness, and scanning time optimization.

Recently, GE Healthcare introduced a new CT reconstruction technique, the Adaptive Statistical Iterative Reconstruction (ASIR) algorithm. The ASIR algorithm uses statistical noise profiles in an iterative manner to ramp image clarity and suppress noise compared with traditional filtered back-projection (FBP) techniques. The ASIR algorithm may significantly improve the reconstructed image quality of certain examinations that usually are regarded as very limited for proper interpretations due to image noise such as large patient and low-dose examinations compared with traditional FBP. In other words, use of the ASIR can provide comparable image quality even with a significantly reduced radiation dosage. However, the ASIR algorithm needs substantial computational processes and may require longer reconstruction time than the FBP technique. Therefore, although the ASIR algorithm has theoretic benefits of less noisy reconstructed images and the potential for significant radiation dose reduction on CT examinations, further clinical study is needed to determine its efficacy.

In conclusion, combined ATCM for craniocervical CTA resulted in a substantial dose reduction (18%), with similar diagnostic acceptability and subjective image artifacts compared with the FTC technique, though a small increase was observed in objective image noise in the upper neck with combined ATCM.

Acknowledgments

We thank Dr Dae Sub Choi and Toronto Western Hospital CT technologists, including Behruz Karasfi, Christina Sinclair, and Mike Verrall, for assistance in data collection and valuable advice.

References

1. de Monye C, Cademartiri F, de Weert TT, et al. **Sixteen-detector row CT angiography of carotid arteries: comparison of different volumes of contrast material with and without a bolus chaser.** *Radiology* 2005;237:555–62
2. Sahani DV, Kalva SP, Hahn PF, et al. **16-MDCT angiography in living kidney donors at various tube potentials: impact on image quality and radiation dose.** *AJR Am J Roentgenol* 2007;188:115–20
3. Teksam M, McKinney A, Casey S, et al. **Multi-section CT angiography for detection of cerebral aneurysms.** *AJNR Am J Neuroradiol* 2004;25:1485–92
4. Cohnen M, Wittsack HJ, Assadi S, et al. **Radiation exposure of patients in comprehensive computed tomography of the head in acute stroke.** *AJNR Am J Neuroradiol* 2006;27:1741–45
5. Jayakrishnan VK, White PM, Aitken D, et al. **Subtraction helical CT angiography of intra- and extracranial vessels: technical considerations and preliminary experience.** *AJNR Am J Neuroradiol* 2003;24:451–55
6. Lell MM, Anders K, Uder M, et al. **New techniques in CT angiography.** *Radiographics* 2006;26:S45–S62
7. Russell MT, Fink JR, Rebeles F, et al. **Balancing radiation dose and imaging quality: clinical applications of neck volume CT.** *AJNR Am J Neuroradiol* 2008;29:727–31
8. Tubiana M, Aurengo A, Averbeck D, et al. **The debate on the use of linear no threshold for assessing the effects of low doses.** *J Radiol Prot* 2006;26:317–24
9. Mettler FA, Wiest PW, Locken JA, et al. **CT scanning: patterns of use and dose.** *J Radiol Prot* 2000;20:353–59
10. Mazonakis M, Tzedakis A, Damilakis J, et al. **Thyroid dose from common head and neck CT examinations in children: is there an excess risk for thyroid cancer induction?** *Eur Radiol* 2007;17:1352–57. Epub 2006 Sep 21
11. Namasivayam S, Kalra MK, Pottala KM, et al. **Optimization of Z-axis automatic exposure control for multidetector row CT evaluation of neck and comparison with fixed tube current technique for image quality and radiation dose.** *AJNR Am J Neuroradiol* 2006;27:2221–25
12. Kalra MK, Maher MM, Toth TL, et al. **Techniques and applications of automatic tube current modulation for CT.** *Radiology* 2004;233:649–57
13. Rizzo S, Kalra M, Schmidt B, et al. **Comparison of angular and combined automatic tube current modulation techniques with constant tube current CT of the abdomen and pelvis.** *AJR Am J Roentgenol* 2006;186:673–79
14. McCollough CH, Bruesewitz MR, Kofler JM. **CT dose reduction and dose management tools: overview of available options.** *Radiographics* 2006;26:503–12
15. Mulkens TH, Marchal P, Daineffe S, et al. **Comparison of low-dose with standard-dose multidetector CT in cervical spine trauma.** *AJNR Am J Neuroradiol* 2007;28:1444–50
16. Kalra MK, Rizzo S, Maher MM, et al. **Chest CT performed with z-axis modulation: scanning protocol and radiation dose.** *Radiology* 2005;237:303–08
17. Prasad SR, Wittram C, Shepard JA, et al. **Standard-dose and 50% reduced-dose chest CT: comparing the effect on image quality**. *AJR Am J Roentgenol* 2002;179:461–65
18. Mullins ME, Lev MH, Bove P, et al. **Comparison of image quality between conventional and low-dose nonenhanced head CT.** *AJNR Am J Neuroradiol* 2004;25:533–38
19. Kalra MK, Prasad S, Saini S, et al. **Clinical comparison of standard-dose and 50% reduced-dose abdominal CT: effect on image quality.** *AJR Am J Roentgenol* 2002;179:1101–06
20. Kalra MK, Maher MM, D'Souza RV, et al. **Detection of urinary tract stones at low-radiation-dose CT with z-axis automatic tube current modulation: phantom and clinical studies.** *Radiology* 2005;235:523–29
21. Kalra MK, Maher MM, Toth TL, et al. **Strategies for CT radiation dose optimization**. *Radiology* 2004;230:619–28
22. McNitt-Gray MF. **AAPM/RSNA Physics Tutorial for Residents: topics in CT—radiation dose in CT.** *Radiographics* 2002;22:1541–53
23. Brem MH, Zamani AA, Riva R, et al. **Multidetector CT of the paranasal sinus: potential for radiation dose reduction.** *Radiology* 2007;243:847–52
24. Cohnen M, Fischer H, Hamacher J, et al. **CT of the head by use of reduced current and kilovoltage: relationship between image quality and dose reduction.** *AJNR Am J Neuroradiol* 2000;21:1654–60
25. Marmolya G, Wiesen EJ, Yagan R, et al. **Paranasal sinuses: low-dose CT**. *Radiology* 1991;181:689–91
26. Husstedt HW, Prokop M, Dietrich B, et al. **Low-dose high-resolution CT of the petrous bone**. *J Neuroradiol* 2000;27:87–92
27. Sohaib SA, Peppercorn PD, Horrocks JA, et al. **The effect of decreasing mAs on image quality and patient dose in sinus CT.** *Br J Radiol* 2001;74:157–61
28. Takahashi M, Maguire WM, Ashtari M, et al. **Low-dose spiral computed tomography of the thorax: comparison with the standard-dose technique.** *Invest Radiol* 1998;33:68–73
29. Kalra MK, Maher MM, Toth TL, et al. **Comparison of Z-axis automatic tube current modulation technique with fixed tube current CT scanning of abdomen and pelvis.** *Radiology* 2004;232:347–53
30. Graser A, Wintersperger BJ, Suess C, et al. **Dose reduction and image quality in MDCT colonography using tube current modulation.** *AJR Am J Roentgenol* 2006;187:695–701
31. Smith A, Dillon W, Lau B, et al. **Radiation dose reduction strategy for CT protocols: successful implementation in neuroradiology section.** *Radiology* 2008;24:499–506
32. Smith AB, Dillon WP, Gould R, et al. **Radiation dose-reduction strategies for neuroradiology CT protocols.** *AJNR Am J Neuroradiol* 2007;28:1628–32
33. Morin RL, Gerber TC, McCollough CH. **Radiation dose in computed tomography of the heart**. *Circulation* 2003;107:917–22
34. Hurwitz LM, Yoshizumi TT, Goodman PC, et al. **Radiation dose savings for adult pulmonary embolus 64-MDCT using bismuth breast shields, lower peak kilovoltage, and automatic tube current modulation.** *AJR Am J Roentgenol* 2009;192:244–53
35. Heyer CM, Lemburg SP, Kagel T, et al. **Evaluation of chronic infectious interstitial pulmonary disease in children by low-dose CT-guided transthoracic lung biopsy.** *Eur Radiol* 2005;15:1289–95
36. Suess C, Chen X. **Dose optimization in pediatric CT: current technology and future innovations.** *Pediatr Radiol* 2002;32:729–34
37. Heyer CM, Mohr PS, Lemburg SP, et al. **Image quality and radiation exposure at pulmonary CT angiography with 100- or 120-kVp protocol: prospective randomized study.** *Radiology* 2007;245:577–83