Received:
5 April 2016

Revised:
26 October 2016

Accepted:
10 November 2016

<https://doi.org/10.1259/bjr.20160308>

Cite this article as:

Merzan D, Nowik P, Poludniowski G, Bujila R. Evaluating the impact of scan settings on automatic tube current modulation in CT using a novel phantom. *Br J Radiol* 2017; **90**: 20160308.

FULL PAPER

Evaluating the impact of scan settings on automatic tube current modulation in CT using a novel phantom

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Objective: The aim of this study was to make a comprehensive evaluation of how variable scan settings can affect the performance of automatic tube current modulation (ATCM) in recent CT scanners from the four major manufacturers.

Methods: A phantom was designed and manufactured for the purpose of evaluating ATCM. The phantom was scanned with four categories of systematically varied settings (scan projection radiograph, technique and reconstruction parameters and phantom miscentring). The performance of ATCM, in terms of applied tube current and noise uniformity, for the scans with varied settings was compared with a reference scan using subjective and quantitative approaches.

Results: The ATCM implemented by each manufacturer is based on different principles and any affect to the performance of the ATCM, when varying scan settings,

will manifest differently among the vendors. The results are summarized in four tables corresponding to the categories of varied settings.

Conclusion: The developed phantom proved useful for evaluating the ATCM. It is important to understand how different implementations (vendor specific) of ATCM perform in order to make informed decisions about the selection of scan settings when designing protocols. The resulting tables can serve as a reference for understanding the different implementations of ATCM and highlight settings that should be taken into consideration when adjusting an imaging protocol.

Advances in knowledge: The results from this work can serve as a reference for how changes in geometry or scan settings can affect the performance of ATCM, in terms of tube current and noise.

INTRODUCTION

With the increasing number of CT examinations being performed worldwide, and the relatively high doses associated with CT, the development and implementation of technical solutions for dose optimization is important to mitigate excessive radiation exposure to patients. Automatic tube current modulation (ATCM) aims at adapting the X-ray tube current to account for different attenuations to achieve a target image quality throughout a scan. ATCM was first discussed by Haaga et al¹ in 1981 and introduced for clinical use in a single-slice CT scanner in 1994.²

Today, ATCM has been implemented by every major CT manufacturer and is widely used to optimize the required dose to maintain a target image quality for the large range of patients who are scanned with CT. However, the ATCM that each vendor provides is based on different principles. It can therefore be difficult for operators of CT scanners to fully understand how different selections in the imaging protocol will affect the applied ATCM, such that the ATCM might not always be optimally used. Some studies^{3,4} have

emphasized the need for CT users to have full knowledge of how ATCM operates and to be aware of the differences between systems from various vendors. The way certain scan settings affect the ATCM from different vendors has been an area of interest for many years.^{3,5–12} The focus has been on the effect of a limited number of scan settings or on a specific vendor ATCM. However, an extensive study investigating the influence of all variable scan settings and covering all of the vendor implementations of ATCM is, to our knowledge, missing in the literature. Furthermore, earlier reports have presented unexpected results,⁵ which further suggests the usefulness of a complete evaluation of the influence of scan settings on the modulation systems from different vendors.

The purpose of this study was to characterize the ATCM in recent scanners from the four major CT manufacturers, with a phantom specifically designed for this purpose. The characterization is made by investigating how the applied tube current and image noise are affected when systematically varying scan settings, including the settings used for

acquiring the scanned projection radiograph (SPR), scan technique and reconstruction parameters and phantom miscentring. This work aimed at providing a comprehensive list of how different scan settings can influence the ATCM. This list is intended to serve as a reference for CT users, to inform the selection of scan settings with the aim of making the most effective use of ATCM. Furthermore, this work can help CT users understand the differences between how different vendors have implemented ATCM.

METHODS AND MATERIALS

General description of automatic tube current modulation

ATCM provides a mechanism to obtain a target image quality for varying local patient attenuations throughout a scan. In order to use ATCM, the scanner needs to estimate the attenuation characteristics of the patient over the range of the scan. This is provided through one or two SPRs.¹³ An SPR is a projection image that is acquired with a fixed tube angle while the patient table moves through the gantry. The attenuation of a patient is estimated as water-equivalent cylinders or ellipsoids at different table locations. Owing to the divergence of the X-ray beam, a magnification or demagnification of the patient may occur if the patient is miscentred, leading to the attenuation of the patient being misjudged.¹⁴

An operator-controlled image quality reference parameter (IQ reference parameter) is used to adjust the amount of applied ATCM during a scan. Prior to a scan, the CT scanner determines which tube current to apply at different locations throughout a scan from the attenuation characteristics of the patient, the IQ reference parameter and the selected technique parameters. The tube current can be modulated based on the patient attenuation characteristics along the scan direction (longitudinal modulation). The tube current can also be modulated at different angles during each rotation to account for the patient attenuation characteristics for different projection angles (angular

modulation). Certain CT scanners characterize attenuation during a scan (online) and use attenuation data acquired in the previous half or whole revolution to modulate the tube current angularly. Longitudinal and angular modulation can be used in combination in recent CT systems.¹³ Whether this is by default or not depends on the vendor as well as the target region of the scan. Table 1 summarizes the different implementations of ATCM investigated in this work.

CT scanners and vendor specific approaches to automatic tube current modulation

Revolution CT (GE Healthcare, Waukesha, WI)

The ATCM system in this scanner is called SmartmA and provides noise index (NI) as the IQ reference parameter. According to the Technical Reference Manual,¹⁵ the NI is related to the standard deviation (SD) of pixel values at the centre of an image of a uniform phantom with the same attenuation characteristics as the patient, reconstructed with the standard reconstruction kernel. This system aims at achieving constant image noise throughout a scan. The ATCM is planned with information from the latest SPR, from which the patient attenuation and shape (oval ratio) are estimated. The scanner decides which tube current to apply at each anteroposterior (AP) and lateral (LAT) projection during each rotation and varies the tube current smoothly between the target values. The scanner used in this work had software v. rev01_m3_mdcp1.4 and rev01_m3.171 during the course of the measurements.

Brilliance iCT 256 (Philips Healthcare, Cleveland, OH)

The ATCM system in this scanner is referred to as DoseRight and it is part of the iPatient user interface.¹⁶ The IQ reference parameter is the dose right index, which is a relative level of dose. According to Philips,¹⁶ the patient attenuation at different longitudinal positions is calculated from an SPR and is converted into a water-equivalent diameter (WED). The average WED over the scan range is compared with a preset reference

Table 1. Specification of the automatic tube current modulation systems of the CT scanners investigated in the study

	GE Revolution CT	Philips Brilliance iCT 256	Siemens SOMATOM® Force	Toshiba Aquilion One™
Name	SmartmA	DoseRight	CareDose4D	SureExposure 3D
Number of SPRs used	1	1	1 (2 ^a)	1 or 2, as specified
IQ reference parameter	NI	DRI	Quality ref.mAs	SD
Minimum/maximum tube current adjustable	Yes	Yes ^b	No	Yes
Online feedback	No	No	Yes	No
Aims at same noise level for all patients	Yes	No	No	Yes
Aims at constant noise throughout each scan	Yes	Yes	No	Yes

DRI, dose right index; IQ reference parameter, image quality reference parameter; NI, noise index; Quality ref.mAs, quality reference tube current-time product; SD, standard deviation; SPR, scanned projection radiograph.

^aCombines SPRs if multiple available.

^bAdjustable when creating the protocol only.

WED and the tube current is adjusted accordingly. The Dose-Right system is based on the hypothesis that different-sized patients require different levels of image noise. For angular ATCM, the scanner estimates the patient shape at each longitudinal position from a posteroanterior (PA) SPR. The scanner used in this work had software v. 4.1.

SOMATOM® Force (Siemens Healthcare, Forchheim, Germany)

The ATCM in this scanner is called CareDose4D¹⁷ and the IQ reference parameter is the quality reference tube current–time product (Quality ref.mAs). The Qref mAs is the effective mAs (mAs divided by pitch) that would be applied to a given body part of a reference patient (70–80 kg). The longitudinal ATCM is planned based on one or two SPRs, from which the patient size is estimated and compared with the reference patient. The angular ATCM is “online” where attenuation information is acquired half a rotation earlier during a scan. Similar to Philips DoseRight, the CareDose4D system does not aim at achieving the same level of image noise for different-sized patients. Further, the CareDose4D system does not aim at obtaining constant image noise for different patient attenuations throughout a scan. However, the degree to which the tube current is modulated for different patient cross-sections can be adjusted with a global adaption strength parameter, ranging from “very weak” to “very strong”. The size of the reference cross-section and the relation between patient cross-section size and mAs depend on the target region in the selected protocol. The scanner used in this work was Syngo CT VA50A.

Aquilion one™ Vision Edition (Toshiba Medical Systems, Otawara, Japan)

The ATCM in this scanner is referred to as SureExposure 3D and it provides the desired SD of pixel values in the reconstructed images as the IQ reference parameter. The tube current is modulated to achieve the stated value throughout the scan. There are five predefined values of the SD to aid the user, ranging from “extra high quality” to “extra low dose”. For longitudinal ATCM, the applied mAs is adapted to the patient WED at different longitudinal positions estimated from the first SPR. Angular modulation is adapted to an estimation of the patient AP LAT ratio if only one SPR is acquired and measured AP LAT ratio if two SPRs are acquired (private communication with Toshiba, 2015). The reconstruction settings that the system considers when determining what tube current to apply at different locations are set in the SureIQ tool and are not necessarily the same as the ones set in the imaging protocol. The scanner used in this work had software v. 6.

Phantom

Currently, there exists no standardized approach or phantom for the characterization of ATCM performance and therefore, a phantom was developed for this purpose. Figure 1 shows a three-dimensional rendering of the developed phantom. Multiple studies of feasible phantom designs for ATCM evaluations have been made.^{5,8,9,18,19} From those studies, it is concluded that an ideal phantom should be applicable to use for the evaluation of longitudinal as well as angular ATCM and provide a means for quantifying image quality. Sookpeng et al¹⁸ have

Figure 1. A three-dimensional rendering of the developed phantom: the phantom was milled from a solid block of poly (methylmethacrylate). It consists of three sections, between which are smooth transitions. The cross-section of the phantom is elliptical with an aspect ratio of 2:3.

used phantoms with sharp discontinuities and air gaps, concluding that these properties should be avoided. Further, the phantom should have regions with constant geometry wider than the total beam collimation to allow the modulation to stabilize. It is in these regions with constant geometry that it is appropriate to quantify performance. The CelT phantom (Medical Physics, BCUHB, Wales) offers other useful features, such as the possibility of measuring internal dose, and fulfils most of the above-mentioned properties.²⁰ However, the CelT phantom has sharp discontinuities that can induce strange responses in some ATCM systems. These previous studies from other researchers were taken into consideration in the design of the phantom developed in this work. The phantom consists of three sections, with different major axes (25, 30 and 35 cm) to evaluate longitudinal ATCM. Each section is 15-cm long in the longitudinal direction. Between each section is a smooth transition of 10 cm and both ends of the phantom are rounded to avoid abnormal responses of the ATCM. The phantom has an elliptical cross-section with an aspect ratio of 3:2 to permit evaluation of angular ATCM. The phantom was milled from a solid block of poly(methylmethacrylate) to minimize any non-uniformities in the phantom. The shape of the phantom does not aim at representing the human anatomy, but rather having sufficient longitudinal and angular variations in attenuation so that these aspects of the modulation can be evaluated.

Testing procedure

For each CT scanner, a reference scan protocol was set up using the settings displayed in Table 2. During the reference scans, the phantom was centred in the gantry and the SPR covered the entire scan region. The phantom was then repeatedly scanned while systematically varying one or more settings at a time. The intention was to vary only one or a few parameters of interest and otherwise use the same settings as in the reference scan. However, this was not always possible, and in cases where parameters other than those of interest have been changed, this

Table 2. Settings used for the reference scans on the investigated CT scanners

Standard scans Common parameters				
SPR tube voltage (kV): 120 kV	Scan direction: in		Rotation time (s): 0.5 s	Slice thickness (mm): 5 mm
SPR tube current (mA): 50 mA	Scan mode: helical/spiral		CFOV (mm): 500 mm	Increment (mm): 5 mm
Patient orientation: HFS	Tube voltage (kV): 120 kV		RFOV (mm): 440 mm	Iterative reconstruction: off
	GE	Philips	Siemens	Toshiba
SPR angle	0°	180°	0°	0°
SPR reconstruction filter	—	—	—	Standard
IQ reference parameter	NI 15	DRI 15	Quality ref.mAs 160	SD 12.5
Pitch	0.984	0.921	1	0.813
Collimation (mm)	64 × 0.625	64 × 0.625	96 × 0.6	80 × 0.5
Shaped filter	Large	Large	wedge ₃	Large
Reconstruction kernel	Standard	Standard B	Br36	FC08
Other	—	—	Average modulation	—

DRI, dose right index; HFS, head-first supine; IQ reference parameter, image quality reference parameter; NI, noise index; Quality ref.mAs, quality reference tube current-time product; RFOV, reconstructed field of view; SD, standard deviation; SPR, scanned projection radiograph. The phantom is centred in the gantry and the SPR covers the entire scan region for the reference scans. CFOV, collected field of view.

will be noted. The reference scans were compared with the scans with varied settings and were divided into tests of varied SPR settings, scan technique parameters, reconstruction parameters and miscentring of the phantom in the gantry. From the acquired images, the normalized root mean square error (NRMSE) of tube current curves, visual evaluation of tube current curves and image noise were used in the comparison.

A MATLAB® script (The Mathworks® Inc., Natick, MA) was developed for the ATCM evaluations. The images from a scan were read into the script and the image data, longitudinal position and applied tube current were extracted. The NRMSE of tube current values between an arbitrary scan and a reference scan is expressed as:

$$\text{NRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^n (x_i - x_i^{\text{ref}})^2}{n}}}{\max(x_i^{\text{ref}}) - \min(x_i^{\text{ref}})}, \quad (1)$$

where x_i and x_i^{ref} represent the tube current values for the arbitrary scan and reference scan, respectively, at the longitudinal position i . The NRMSE value is stated as a percentage. In cases where the axial images and thus the extracted tube current data of the two scans did not correspond to the same longitudinal positions, interpolated tube current values were used. Some variation of the applied ATCM can be expected between independent scans that have identical scan settings. From measurements, NRMSEs between reproduced scans with identical settings were determined, where the phantom had either been repositioned between the scans or not. It should be noted that certain tests required the repositioning of the phantom between

scans with identical settings, *e.g.* miscentring. Owing to clinical constraints on certain scanners, the tests were split over multiple occasions, which also required repositioning of the phantom during other tests. A criterion was established (two times the determined NRMSE between reproduced scans) for determining whether the ATCM had been affected by a change in scan settings. When visually analyzing ATCM curves, the criterion that was chosen agreed well with a noticeable difference between arbitrary scans and the reference scan. The criteria for NRMSEs for each scanner are displayed in [Tables 3–6](#).

Volume data were projected to the coronal plane, by summing along columns of pixels, to visualize the phantom attenuation in the longitudinal direction resembling the AP SPR. The tube current at each slice position of the scan was plotted over the projection of volume data, visualizing the modulation over the phantom. For some tests, it is of interest to analyze the effective mAs applied at each slice position, since it is pitch and rotation time independent and will allow for a comparison of scans where a different pitch or rotation time has been used. It should be noted that the tube current and effective mAs at each slice location determined from the information in the digital imaging and communications in medicine header correspond to the average of all the projections used to reconstruct the image, and the curves will therefore not give insight into the angular modulation.

For each image, noise was analyzed by measuring the SD of pixel values in a circular region of interest (ROI) placed at the centre of the phantom. The ROI had a radius of 39 pixels, approximately 40%²¹ of the minor half axis of the smallest phantom section when a reconstructed field of view (RFOV) of 440 mm

Table 3. The result of how varied scanned projection radiograph (SPR) settings affect the automatic tube current modulation (ATCM)

Varied SPR setting	GE Revolution CT	Philips Brilliance iCT 256	Siemens SOMATOM® Force	Toshiba Aquilion One™
Criteria for the NRMSE (%), phantom not repositioned	0.8	2.6	1.6	3.3
Criteria for the NRMSE (%), phantom repositioned	1.0	2.7	1.9	10.2
SPR angle (degrees)	90 (+, 26.4) 180 (+, 5.4) 270 (+, 26.0)	90 (+, 1.6) 90/180 (+, 1.0)	90 (±, 4.2) 180 (+, 12.0) 0/90 (±, 4.6)	90 (+, 11.3) 180 (+, 12.8) 270 (+, 6.2)
SPR tube current (mA)	20 (±, 0.1) 80 (±, 0.5)	10 (±, 0.5) 80 (±, 1.0)	20 (±, 1.6) 80 (±, 1.4)	20 (−, 3.3) 80 (−, 3.3)
SPR tube voltage (kV)	70 (−, 3.8) 80 (−, 3.1) 100 (−, 2.2) 140 (±, 3.8)	80 (+, 3.8) 100 (−, 11.1) 140 (−, 10.3)	70 (±, 1.5) 80 (±, 1.8) ^a 90 (±, 1.6) 100 (±, 1.0) 110 (±, 0.7) 130 (±, 1.6) 140 (±, 0.8) 150 (±, 1.8) ^a 150Sn (±, 1.7) ^a	80 (±, 4.7) 100 (+, 3.8) 135 (−, 3.4)
SPR tube voltage (kV), tube current (mA)	70 kV/20 mA (−, 1.5) 70 kV/80 mA (−, 3.8)	80 kV/10 mA (+, 2.9) 80 kV/80 mA (+, 4.1)	70 kV/20 mA (±, 1.8) ^a 70 kV/80 mA (±, 1.7) ^a	80 kV/20 mA (±, 5.3) 80 kV/80 mA (±, 4.3)
SPR angle (degrees), tube current (mA)	90°/20 mA (+, 30.1) 90°/80 mA (+, 25.9)	90°/10 mA (+, 13.4) 90°/80 mA (+, 17.8)	90°/20 mA (±, 4.5)^b 90°/80 mA (±, 4.3)^b	90°/20 mA (+, 10.0)^{b,c} 90°/80 mA (+, 9.8)^{b,c}
SPR angle (degrees), tube voltage (kV), tube current (mA)	90°/70 kV/10 mA (±, 15.4) 90°/70 kV/30 mA (+, 11.5) 90°/70 kV/80 mA (+, 19.4)	90°/80 kV/10 mA (+, 61.3) 90°/80 kV/30 mA (+, 38.7) 90°/80 kV/80 mA (+, 15.2)	90°/70 kV/20 mA (−, 22.9)^b 90°/70 kV/30 mA (−, 18.2)^b 90°/70 kV/80 mA (−, 9.0)^b	90°/80 kV/10 mA (−, 8.2)^b 90°/80 kV/30 mA (+, 10.4)^b 90°/80 kV/80 mA (+, 14.6)^b
SPR length	Starts 2.5 cm before phantom (±, 0.7) ^d Starts 12.5 cm before phantom (±, 0.6) ^d	Starts 2.5 cm before phantom (±, 2.3) Starts 12.5 cm before phantom (±, 1.6)	Starts 2.5 cm before phantom (±, 1.1) Starts 12.5 cm before phantom (±, 1.4)	Starts 2.5 cm before phantom (+, 3.3) Starts 12.5 cm before phantom (+, 3.2)
SPR image filter	—	—	—	Smooth (+, 16.6) Sharp (+, 9.7)
Scan outside SPR	Starts with first or continues with last determined mA value where SPR exists	Starts with first or continues with last determined mA value where SPR exists	Scans with close to first or last determined mA value where SPR exists	Starts with first or continues with last determined mA value where SPR exists

NRMSE, normalized root mean square error.

The cells with italicized values are indicating that the ATCM was unaffected by the change in parameter; the cells with bold values are indicating that the ATCM was affected by the change in parameter. The NRMSE of the tube current between each scan and the reference scan is displayed between parentheses and given in %. Plus or minus signs before the NRMSE value refers to an increase/decrease in the overall tube current at different longitudinal positions throughout the scan, compared with the reference scan. Plus and minus signs (±) refer to a combination of increased and decreased tube current at different longitudinal positions throughout the scan. For the evaluation process, the NRMSEs are compared with the determined criteria shown at the top of the table, and combined with a visual assessment of the tube current modulation curves.

^aVisual assessment of tube current modulation curves suggests that there was no effect on ATCM.

^bTable and/or phantom repositioned between scans.

^cVisual assessment of tube current modulation curves suggests that there was an effect on ATCM.

^dSoftware v. rev01_m3.171.

was used. Plots showing the variation of SD with longitudinal position can be used for evaluating the longitudinal ATCM. In order to evaluate the angular ATCM, the local SD of pixel values was analyzed in axial images of the phantom. The local SD was

determined in an area of 3×3 pixels, since it approximately corresponds to the width of the point spread function of the reconstruction kernels used in the reference scans. In order to avoid dependence of the X-ray tube position, the mean pixel

Table 4. The result of how varied scan technique parameters affect the automatic tube current modulation (ATCM)

Varied scan technique parameter	GE Revolution CT	Philips Brilliance iCT 256	Siemens SOMATOM® Force	Toshiba Aquilion One™
Criteria for the NRMSE (%), phantom not repositioned	0.8	2.6	1.6	3.3
Criteria for the NRMSE (%), phantom repositioned	1.0	2.7	1.9	10.2
IQ reference parameter	NI 10 (+, 99.6) NI 20 (–, 32.5) NI 25 (–, 46.2) NI 30 (–, 52.9)	DRI 5 (–, 51.3) DRI 10 (–, 31.6) DRI 20 (+, 59.9)	Ref mAs 80 (–, 36.2) Ref mAs 120 (–, 18.4) Ref mAs 200 (+, 18.1) Ref mAs 240 (+, 36.2)	SD 7.5 (+, 85.0) SD 10.0 (+, 27.2) SD 15.0 (–, 17.9)
Patient orientation	FFS (+, 0.8)	FFS (±, 1.9)	FFS (±, 1.7) ^a	FFS (±, 0.0)
Scan direction	Out (±, 3.8)	Out (±, 3.9)	Out (±, 28.3)	Out (±, 14.3)
Tube voltage (kV)	70 (+, 62.5) 80 (+, 58.4) 100 (+, 17.0) 140 (–, 14.1)	80 (+, 221.5) 100 (+, 53.8) 140 (–, 25.1)	70 (±, 15.8) 80 (±, 9.1) 90 (±, 4.9) 100 (±, 2.7) 110 (±, 1.9) 130 (±, 1.3) 140 (±, 2.8) 150 (±, 5.1) 150Sn (±, 9.3)	80 (+, 209.0) 100 (+, 38.6) 135 (–, 16.1)
Collimation (mm)	0.625 × 128 (mA: +, 6.7) (Effective mAs: +, 6.5) (Pitch 0.992)	0.625 × 16 (mA: –, 7.2) (Effective mAs: –, 7.8) (Pitch 0.935) 0.625 × 32 (mA: ±, 5.4) (Effective mAs: ±, 4.9) (Pitch 0.908) 0.625 × 128 (mA: ±, 7.6) (Effective mAs: ±, 7.8) (Pitch 0.915) 1.25 × 64 (mA: –, 7.4) (Effective mAs: –, 7.4)	1.2 × 48 (mA: ±, 1.6) (Effective mAs: ±, 1.6) ^b	0.5 × 32 (mA: ±, 12.8) (Effective mAs: ±, 12.8) (Pitch 0.844) 0.5 × 64 (mA: ±, 10.1) (Effective mAs: ±, 9.8) (Pitch 0.828) 0.5 × 100 (mA: +, 22.8) (Effective mAs: +, 23.2) (Pitch 0.810) 0.5 × 160 (mA: +, 27.1) (Effective mAs: +, 28.0) (Pitch 0.806)
Pitch	0.516 (mA: –, 38.4) (Effective mAs: +, 29.4) 1.375 (mA: +, 33.0) (Effective mAs: +, 5.5)	0.609 (mA: –, 26.8) Effective mAs: –, 2.1) 0.798 (mA: –, 11.9) (Effective mAs: –, 2.6)	0.5 (mA: –, 38.0) (Effective mAs: ±, 9.5) 1.5 (mA: +, 40.4) (Effective mAs: ±, 7.0)	0.639 (mA: –, 9.7) (Effective mAs: +, 11.3) 1.388 (mA: +, 49.7) (Effective mAs: ±, 11.5)
Rotation time (s)	0.28 (mA: +, 51.7) (Effective mAs: ±, 0.6) 0.35 (mA: +, 28.1) (Effective mAs: ±, 0.1) 1.0 (mA: –, 33.1) (Effective mAs: ±, 1.5)	0.4 (mA: +, 18.3) (Effective mAs: ±, 1.8) 0.75 (mA: –, 26.2) (Effective mAs: ±, 1.6) 1.0 (mA: –, 38.3) (Effective mAs: ±, 1.5)	0.25 (mA: +, 73.1) (Effective mAs: ±, 15.5) 1.0 (mA: –, 36.6) (Effective mAs: ±, 2.0)	0.275 (mA: +, 61.2) (Effective mAs: ±, 3.7) 1.0 (mA: –, 36.0) (Effective mAs: +, 9.5)
Shaped filter	Medium (–, 9.9)	Trauma (open) (±, 1.6)	—	Small (±, 0.3) (SFOV/RFOV 240 mm) Medium (±, 0.3) (SFOV/RFOV 320 mm)
Scan mode	Axial (±, 10.1)	—	Axial (±, 13.2)	Axial (–, 24.6) (Slice thickness 1 mm)

DRI, dose right index; FFS, feet-first supine; IQ reference parameter, image quality reference parameter; NI, noise index; NRMSE, normalized root mean square error; Ref mAs, reference tube current-time product; RFOV, reconstructed field of view; SD, standard deviation; SFOV, scanned field of view. For an explanation of the format, Table 3 footnote can be referred. For some tests where this could be of interest, the NRSME of the effective mAs (tube current-time product divided by pitch) is also displayed.

^aVisual assessment of tube current modulation curves suggests that there was no effect on ATCM.

^bThe results of varying the total collimation on the Siemens SOMATOM Force are not included in the table, since the scans were not comparable with the reference scan.

Table 5. The table displays the result of how varied reconstruction parameters affect the automatic tube current modulation (ATCM)

Varied reconstruction parameter	GE Revolution CT	Philips Brilliance iCT 256	Siemens SOMATOM® Force	Toshiba Aquilion One™
Criteria for the NRMSE (%), phantom not repositioned	0.8	2.6	1.6	3.3
Criteria for the NRMSE (%), phantom repositioned	1.0	2.7	1.9	10.2
Reconstructed slice thickness (mm)	2.5 (+, 63.1) 3.75 (+, 18.9)	2.5 (±, 1.0) 10.0 (±, 0.9)	1.0 (±, 1.4) 3.0 (±, 0.6) 10.0 (±, 1.1)	2.0 (±, 1.4) 3.0 (±, 0.5) 10.0 (±, 1.3)
RFOV (mm)	300 (+, 25.9) ^a 350 (+, 25.9) ^a 400 (+, 18.5) ^a 450 (-, 4.3) ^a 500 (-, 23.2) ^a	320 (±, 1.7) 410 (±, 1.8) 500 (±, 1.8)	380 (±, 1.1) 500 (±, 1.3)	320 (±, 0.0) 380 (±, 0.0) 500 (±, 0.0)
Reconstruction kernel	Edge (-, 0.5)	Smooth A (±, 1.6) Sharp C (±, 1.2) Detail D (±, 1.4)	Br32 (±, 1.7) ^b Br44 (±, 0.9) Br64 (±, 0.9)	FC11 (±, 0.0) FC15 (±, 0.0) FC18 (±, 0.0)
Iterative reconstruction	ASiR-V 30% (-, 30.8) ASiR-V 60% (-, 50.7) ASiR-V 90% (-, 60.8)	IR level 1 (±, 1.0) IR level 3 (±, 1.7) IR level 6 (±, 0.8)	ADMIRE (±, 1.7) ^b	AIDR 3D mild (±, 0.0) AIDR 3D standard (±, 0.0) AIDR 3D strong (±, 0.0)

NRMSE, normalized root mean square error; RFOV, reconstructed field of view.

For an explanation of the format, Table 3 footnote can be referred.

^aSoftware v. rev01_m3.171.

^bVisual assessment of tube current modulation curves suggests that there was no effect on ATCM.

values from images corresponding to an entire revolution of the tube was used, *i.e.* 12 images in the Siemens scanner and 8 images in other scanners. The local SD images can be used

for evaluating the angular ATCM, since they visualize how well the systems can achieve a constant image quality in each axial image.

Table 6. The table displays the result of how phantom miscentring affects the automatic tube current modulation

Varied phantom positioning	GE Revolution CT	Philips Brilliance iCT 256	Siemens SOMATOM® Force	Toshiba Aquilion One™
Criteria for the NRMSE (%), phantom not repositioned	0.8	2.6	1.6	3.3
Criteria for the NRMSE (%), phantom repositioned	1.0	2.7	1.9	10.2
Horizontal miscentring, 90° SPR	4 cm left (+, 18.7) ^a 4 cm right (+, 33.3) ^a	4 cm left (+, 15.2) 4 cm right (+, 23.5)	4 cm right (±, 6.8) 4 cm left (±, 5.1)	3 cm left (+, 4.8) 3 cm right (+, 15.5) 4 cm table left (NRMSE: 3.1)+
Vertical miscentring, 0 or 180° SPR	+3 cm (+, 10.0) +1 cm (+, 4.0) -1 cm (-, 4.5) -3 cm (-, 10.5) -5 cm (-, 12.3)	+3 cm (±, 1.2) +1 cm (-, 3.5) ^b -1 cm (±, 2.1) -3 cm (±, 1.0) -5 cm (±, 2.0)	+3 cm (+, 9.2) +1 cm (+, 3.2) -1 cm (-, 3.2) -3 cm (-, 8.9) -5 cm (-, 13.4)	+3 cm (±, 0.0) +1 cm (±, 0.0) -1 cm (±, 0.0) -3 cm (-, 1.7) -5 cm (±, 0.0)

NRMSE, normalized root mean square error; SPR, scanned projection radiograph.

For an explanation of the format, Table 3 footnote can be referred. The table height has been adjusted for all the above scans and therefore, the NRMSE criteria for repositioned phantom were used in the evaluation

^aSoftware v. rev01_m3.171.

^bOnly when the table was raised by 1 cm on the Philips scanner, the tube current was decreased and the NRMSE exceeded the criteria. The reason for this is unknown.

RESULTS

A summary of the results are displayed in Tables 3–6. The tables show the NRMSE of the applied tube current (and in some cases the NRMSE of the applied effective mAs) between the reference scan and a scan where one or more settings have been changed. The criteria that are compared with the NRMSE of each test to indicate whether the ATCM has been affected are displayed in the same tables. The cells with italicized values indicate that a test did not affect the ATCM, while the cells with bold values indicate that the test affected the ATCM, based on the confidence level indicated by the established NRMSE criteria. Figure 2a–d show the modulation of tube current over the phantom for three scans with different settings of the IQ reference parameter in each of the investigated scanners. In Figure 3a–d, the SD of pixel values in a central ROI is plotted along the phantom for scans with and without ATCM. Figure 4a–h show the local SD of pixel values for scans with and without ATCM in the largest phantom section. It should be noted that everything except for the phantom has been masked out of those images. The Toshiba scanner exhibits more non-uniform noise even with ATCM, compared with the other three scanners. Figure 5 shows a selection of results of particular interest, one from each of the investigated scanners. Figure 5a shows how the selected percentage of iterative reconstruction affects the applied ATCM on the GE scanner. The iterative reconstruction

that is used on the GE Revolution CT is called ASIR-V. Figure 5b shows how the tube voltage used during SPR acquisition affects the ATCM in the Philips scanner. Figure 5c shows how the ATCM is affected by the scan direction in the Siemens scanner and Figure 5d shows how the selected reconstruction filter for the SPR affects the ATCM in the Toshiba scanner.

The results of this work are valid for the specified software versions. It is important to be aware that there might be a difference in ATCM between different software versions in the same CT scanner.

Influence of scanned projection radiograph settings on automatic tube current modulation

Scanned projection radiograph tube position

SPRs can be acquired only at 90° (right LAT) and 180° (PA) in the Philips scanner and angular ATCM will not be available if only a 90° SPR is acquired; however, the longitudinal ATCM was invariant of SPR angle. In the GE scanner, the highest tube current was applied when the SPR was acquired with lateral projections and a 180° SPR resulted in an increased tube current compared with a 0° (AP) SPR. 180° SPRs resulted in the highest applied tube currents in the Siemens scanner. Further, a 0° SPR resulted in the lowest tube current applied to the largest phantom section, whereas a 90° SPR resulted in the lowest tube

Figure 2. Figures (a–d) are showing the variation of tube current throughout the scans of the phantom with different settings of the image quality reference parameter on each of the investigated CT scanners: other parameters used for the scans are specified in Table 2. (a) Scans with the noise index (NI) set to 10, 15 and 20, respectively, on the GE Revolution CT; (b) scans performed on the Philips Brilliance iCT, where the dose right index (DRI) has been set to 10, 15 and 20, respectively; (c) scans with the quality reference tube current–time product (Quality ref.mAs) set to 120, 160 and 200 on the Siemens SOMATOM® Force (Siemens Healthcare, Forchheim, Germany); and (d) scans performed on the Toshiba Aquilion One™ scanner (Toshiba Medical Systems, Otawara, Japan), where the standard deviation (SD) has been set to 7.5, 12.5 and 15.0.

Figure 3. For each investigated CT scanner, a comparison of standard deviation (SD) of pixel values in a central region of interest for a scan with automatic tube current modulation (ATCM) and a scan without ATCM (constant tube current of 100 mA was used) has been shown: (a) GE Revolution CT—for the scan with ATCM turned on, the noise index (NI) has been set to 15; (b) Philips Brilliance iCT—for the scan with ATCM, the dose right index (DRI) has been set to 15; (c) for Siemens SOMATOM® Force (Siemens Healthcare, Forchheim, Germany), the quality reference tube current–time product (Quality ref.mAs) has been set to 160 when ATCM was used; (d) Toshiba Aquilion One™ scanner (Toshiba Medical Systems, Otawara, Japan)—when ATCM was used, an SD of 12.5 has been requested.

current at the small and medium phantom sections. It should be noted that a 270° SPR is not available in the Siemens scanner. In the Toshiba scanner, the lowest tube current was applied following the 0° SPR and the highest tube current was applied following the 180° SPR. Both lateral SPR projections resulted in tube current values in between for the large and medium sections of the phantom. For the small section, all SPR acquisition angles lead to the same tube current being applied.

Scanned projection radiograph tube current

An isolated change in tube current during the SPR did not affect the ATCM in any of the scanners. For the Siemens and Toshiba scanners, the tube current in the ATCM decreased with decreasing SPR tube current when combined with a low SPR tube voltage and/or a lateral projection angle. In the GE and Philips scanners, a low SPR tube current in combination with a low SPR tube voltage and/or a lateral projection angle affected the ATCM in an unpredictable manner. However, in most cases, the tube current in the ATCM decreased with decreasing SPR tube current in the GE scanner and increased in the Philips scanner.

Scanned projection radiograph tube voltage

In the Philips scanner (Figure 5b), SPR acquisitions using 80 and 120 kV had the highest and next highest tube currents in the ATCM. SPRs acquired with 100 and 140 kV resulted in the lowest

overall tube current in the ATCM. For the GE and Toshiba scanners, the SPR tube voltage had a minimal and inconsistent effect on the ATCM. The ATCM in the Siemens scanner was unaffected by the choice of tube voltage during the acquisition of SPRs, accounting for the established NRMSE criteria.

Scanned projection radiograph length

If the SPR covered the entire scan, the ATCM was invariant of SPR length in all scanners. Scanning outside the SPR was possible in all scanners and if the SPR covered approximately two-thirds or more of the scan, no warning was given. When scanning outside the SPR, the GE, Philips and Toshiba scanners will start/continue the scan with the first/last tube current that the scanner's ATCM derived from the SPR, depending on whether the scan starts or ends without SPR information. In the Siemens system, the tube current will start/continue with a value close to the first/last value from the SPR, possibly owing to the online modulation.

Scanned projection radiograph image filter

In the Toshiba scanner, the smooth and occasionally the sharp SPR image filter led to ATCM tube current spikes at the ends of the phantom where the smooth filter had the greatest spikes (Figure 5d). The ATCM tube current between the ends of the phantom was invariant of the SPR filter. The other scanners do not have SPR filters.

Figure 4. The local standard deviation (SD) of pixel values for a scan with constant tube current of 100 mA and a scan with automatic tube current modulation (ATCM) for each investigated CT scanner: in order to eliminate dependence on the X-ray tube position, the mean pixel values from axial images corresponding to an entire revolution of the tube have been used. The local SD was determined in an area of 3×3 pixels and all other features in the image, e.g. the couch, have been masked out. All other scan settings were set equal to those of the reference scan, as shown in Table 2. (a, b) GE Revolution CT; (c, d) Philips Brilliance iCT; (e, f) Siemens SOMATOM® Force (Siemens Healthcare, Forchheim, Germany); and (g, h) Toshiba Aquilion One™ (Toshiba Medical Systems, Otawara, Japan).

Influence of scan technique parameters in automatic tube current modulation

Image quality reference parameter

The IQ reference parameter in each of the scanners had the expected effect on the ATCM. The tube current increased with decreased NI (GE) and SD values (Toshiba) or with increased dose right index (Philips) and Quality ref.mAs (Siemens).

Patient orientation

Selecting head-first supine and feet-first supine, starting at the small phantom section for each scan, did not affect ATCM in any scanner.

Scan direction

The scan direction (craniocaudal or caudocranial) affected the ATCM in all scanners. Changing the scan direction in the GE

Figure 5. A selection of results of particular interest from each of the investigated scanners: (a) variation of tube current in scans with different selected percentages of iterative reconstruction (ASiR-V) that is blended into the reconstructed images on the GE Revolution CT. (b) Variation of tube current throughout the scan depending on the tube voltage used for scanned projection radiograph (SPR) acquisition on the Philips Brilliance iCT. All scans were performed with 120 kV and only the tube voltage during the SPR was varied. (c) Effect of scan direction on automatic tube current modulation on the Siemens SOMATOM® Force (Siemens Healthcare, Forchheim, Germany). (d) Variation of tube current depending on the image filter used for the SPR on the Toshiba Aquilion One™ (Toshiba Medical Systems, Otawara, Japan). All other scan settings were set equal to those of the reference scan, as shown in Table 2.

and Toshiba scanners resulted in a small shift in the ATCM curves, while the shift was more apparent in the Siemens scanner (Figure 5c). The Philips scanner did not display a shift in ATCM curves; however, the scanner started each scan with higher tube currents.

Scan tube voltage

In the GE, Toshiba and Philips scanners, lower tube voltages resulted in significantly higher tube currents in the ATCM. The ATCM was affected less by tube voltage in the Siemens scanner; however, the effects were not consistent in all sections of the phantom. For decreased tube voltage, the small and medium sections experienced lower tube currents, while the larger section experienced higher tube currents. There were large fluctuations in the ATCM curve in the uniform sections of the phantom when 150 kV was used. In the Siemens and Toshiba scanners, the noise level increased with decreased tube voltage, despite adjustments in tube current. In the GE scanner, the noise level was maintained for 80–120 kV; however, the 70 and 140 kV resulted in increased noise in the large phantom section. The noise level was consistent for 100–140 kV scans in the Philips scanner; however, a higher noise level was obtained when using 80 kV throughout the entire scan.

Beam collimation

All scanners displayed improved ATCM at regions of varying attenuation when smaller total collimations were used, which was expected, since the local attenuation characteristics covered by the beam became less varying. In the GE, Siemens and Philips scanners, the ATCM was unaffected in regions of constant attenuation. The ATCM varied at regions of constant attenuation in the Toshiba scanner where the highest tube currents resulted from 50- and 80-mm total collimations and a consistent lower tube current was observed for total collimations under 50 mm. It should be noted that the pitch was slightly affected by total collimation in the GE, Philips and Toshiba scanners. Further, detector elements were binned (varying single collimation width) on the Philips and Siemens scanners, which did not affect the ATCM.

Pitch

Higher pitches resulted in higher tube currents in the ATCM in all scanners. The effective mAs was affected by pitch in all scanners except for Philips. The NRMSE of effective mAs was lower than that of tube current in all cases except for Toshiba with pitch 0.639. The noise level remained constant with pitch in the Philips and Toshiba scanners, while the noise level varied slightly with pitch in the Siemens scanner. In the GE scanner, increased pitch resulted in an increased level of noise.

Rotation time

In all scanners, when rotation time decreased, the tube current increased, the NRMSE of effective mAs was less than that of tube current and the level of noise was constant.

Scan mode

It was not possible to scan in axial mode with ATCM in the Philips scanner. In the other scanners, the axial-mode ATCM differed from helical-mode ATCM (most apparent in sections of non-uniform attenuation). In the GE and Siemens scanners, the tube current in the uniform sections of the phantom was comparable between axial and helical modes. In the Toshiba scanner, a lower tube current was used in axial mode compared with helical mode in uniform sections of the phantom.

Shaped filter

Shaped filters were not selectable from the protocol in the Siemens scanner. The ATCM in the Toshiba and Philips scanners was unaffected by the selection of the shaped filter. In the GE scanner, the ATCM was affected by shaped filter; however, shaped filters are coupled with a selected scanned field of view. The tube current increased when using a small-shaped filter compared with a medium-shaped filter using an RFOV of 320 mm. It should be noted that this result is omitted from Table 4, since the reference RFOV is 440 mm. The tube current increased for the large-shaped filter compared with the medium-shaped filter.

Influence of reconstruction settings on automatic tube current modulation

Reconstruction slice thickness

Reduced slice thickness in the first reconstruction resulted in a higher tube current being applied in the GE scanner. Despite this, the noise level increased with decreasing slice thickness. It should be noted that in older GE scanners, the NI is adjusted instead of tube current for changes in slice thickness in the first reconstruction, and the resulting noise level will vary more. The other scanners did not adjust the tube current with different slice thicknesses and the noise level in the reconstructed images varied greatly with slice thickness.

Reconstruction field of view

In the GE scanner, the applied tube current increased with decreasing RFOV up to a certain diameter; thereafter, the tube current was not increased. Despite the increased tube current, the noise level increased for the smaller RFOV. In the other scanners, the selected RFOV did not affect the ATCM. In the Philips scanner, the noise level increased with decreasing RFOV. In the Siemens and Toshiba scanners, the noise level was invariant of the selected RFOV.

Reconstruction kernel

The choice of reconstruction kernel did not affect the ATCM in any of the scanners. However, sharper kernels resulted in greater image noise.

Iterative reconstruction

In the GE scanner, an increased ASIR-V strength generally led to a decrease in the applied tube current and image noise

(see Figure 5a). For the 90% ASiR-V scans, the minimum mA in the protocol was used throughout the scan and the image noise was greater compared with other ASiR-V scans. In the remainder of the scanners, the use of iterative reconstructions did not affect the ATCM; however, image noise decreased.

Influence of phantom miscentring on automatic tube current modulation

Miscentring in the vertical direction

Vertical miscentring was investigated by adjusting the table height. SPRs were acquired at 0° (AP projection) in the GE, Siemens and Toshiba scanners and at 180° (PA projection) in the Philips scanner. In the GE and Siemens scanners, a lower tube current resulted when the phantom was positioned further from the X-ray tube during SPR acquisition, caused by demagnification of the phantom in the SPR, and vice versa when positioned closer to the X-ray tube. For Philips and Toshiba scanners, ATCM was unaffected by vertical miscentring, since these systems incorporate table height correction. For all scanners, miscentring increased the intrimage noise variation.

Miscentring in the horizontal direction

Horizontal miscentring was investigated by acquiring an SPR and scan, while the phantom was positioned in a different horizontal position on the couch. In the Toshiba scanner, it was also possible to move the couch horizontally. SPRs acquired with a lateral projection angle caused the tube current to decrease in the scan as a function of the distance between the phantom and the X-ray tube in all scanners.

DISCUSSION

GE Revolution CT

When acquiring SPRs, it is important to consider the position of the X-ray tube, as PA SPRs resulted in higher tube currents in the ATCM compared with AP SPRs, which could be explained by the magnification of the couch. Lateral SPRs (greatest phantom attenuation) resulted in the highest tube currents in the ATCM (the only scanner to do so). It is therefore important to consider the order in which SPRs (different projections) are acquired, as only the latest SPR is used for the ATCM. Noisy SPRs (low tube current/voltage and LAT projections) potentially inhibited the scanner ability to accurately determine the attenuation characteristics of the phantom and affected the ATCM.

The scan technique parameters that affected the ATCM the greatest were rotation time (because of the tube current–time product), pitch and tube voltage. Different rotation times did not affect the image noise level; however, the noise level decreased with decreasing pitch, indicating that the ATCM did not adequately compensate with tube current. This inadequate tube current modulation could also be seen in scans with 70 or 140 kV.

The ATCM acted on changes in reconstructed slice thickness, RFOV and the selection of iterative reconstruction, in an attempt at keeping the image noise level more constant with changes in the imaging protocol; it should be noted that this is the only scanner to do so. Despite this feature, the noise level increased with decreased reconstructed slice thickness and

RFOV, which indicates that the tube current modulation was insufficient. ATCM adjustments based on changes in the RFOV have, however, been removed in later software versions in the Revolution CT. The intention of implementing this feature was to reduce patient dose by taking advantage of the inherent reduction in image noise with increased RFOV (private communication with GE Healthcare, January 2016). When using 90% ASiR-V, the noise level increased compared with other strengths, indicating that the decrease in tube current was too aggressive.

Accurate centring of the phantom (or patient) is important, since it affects both the ATCM and image noise. The effects on image noise could be due to changes in tube current and misalignment with the shaped filter.

Philips Brilliance iCT

During SPR acquisition, this was the only scanner where tube position did not affect the ATCM and where the tube voltage used during SPR acquisition had the greatest and most variable effect. The ATCM could be affected, like the GE scanner, when SPRs are acquired with a low tube current/voltage and lateral projections.

The scan technique parameters that affected the ATCM the greatest were rotation time, pitch and tube voltage. The scanner was generally able to compensate with tube current to maintain a constant level of image noise when changes in rotation time, pitch and tube voltage were made. An increase in image noise was observed for scans with 80 kV.

This scanner provides a correction for table height when SPRs are acquired and therefore, the ATCM was unaffected by vertical miscentring. However, it still recommended that patients are carefully centred, as shaped filter misalignments can affect the patient dose distribution as well as image noise.

Siemens SOMATOM Force

The highest tube currents in the ATCM were observed following a PA SPR and the ATCM was affected by noisy SPRs (low tube current/voltage and LAT projections). Despite this scanner online modulation, the ATCM will not function optimally without an SPR and scanning outside the SPR should be avoided (as with the other scanners in this study).

The scan direction affected the ATCM significantly (Figure 5c), which could have been caused by online modulation. A caudocranial scan direction, compared with a craniocaudal scan direction, caused the tube current to modulate earlier at regions of non-uniform attenuation. This could be taken into consideration to minimize exposure to radiosensitive organs, e.g. the thyroid, which are longitudinally situated between regions of higher attenuation. Tube voltage, rotation time and pitch were other scan parameters that impacted the ATCM significantly. The compensation (increase or decrease) of tube current for different tube voltages was less than the other scanners, resulting in greater variations of image noise.

Miscentring the phantom in the vertical or horizontal direction affected the ATCM and led to high fluctuations in image noise.

Toshiba Aquilion One

The position of the tube and low tube currents used in combination with a low tube voltage and lateral projection angles during SPR acquisitions affected the ATCM. There are indications that the ATCM is based on (image) filtered SPRs.

Tube voltage, rotation time and pitch were the scan technique parameters that had the greatest impact on the ATCM. This scanner displayed an adequate tube current compensation for variations in rotation time and pitch to achieve a constant level of noise. The scanner was not able to maintain a constant level of noise for different tube voltages (inadequate tube current). The total collimation affected the tube current at regions of uniform attenuation in the phantom; however, it is unclear why this happened.

This ATCM was not affected by changes of reconstruction parameters in the protocol; however, if reconstruction settings are changed in the SureIQ interface, it is expected to have an effect on the ATCM (private communication with Toshiba, 2015). It should be noted that the purpose of this study was to investigate how the ATCM is affected by changes in the imaging protocol.

The ATCM was not affected by vertical miscentring for AP and PA SPR acquisitions, as table height corrections are made (similar to the Philips scanner). However, the level of image noise was impacted.

CONCLUSION

The ATCM in recent CT scanners from four major manufacturers has been evaluated using a novel phantom. The novelty of the phantom lies in the ability to evaluate both longitudinal and angular ATCM and the possibility of analyzing how the tube current stabilizes over regions of constant geometry in scanners with wide collimations. Further, the smooth transitions between sections prevent abnormal responses of the ATCM. Since the modulation of tube current directly affects the patient dose and image quality, it is of great importance that CT users are aware of the differences between the ATCM systems implemented in different scanners and have proper knowledge of how each system operates and will respond to changes in scan settings. It is also important to remember that there might be differences in how the ATCM systems work between different software versions in the same CT scanner. Tables 3–6 can serve as a reference for CT users by highlighting scan settings that when changed will induce a response in the ATCM systems and therefore should be taken into extra consideration when altered. The phantom designed in this study could potentially be used for determining the baseline performance of an ATCM system and it can be used for regular quality controls to study the performance over time.

ACKNOWLEDGMENTS

We would also like to thank each of the vendors (GE Healthcare, Philips Healthcare, Siemens Healthcare and Toshiba Medical Systems) for helping us understand their specific implementation of ATCM and answering questions that arose under the duration of this work. This work is part of the XQuality project at Karolinska University Hospital in Stockholm, Sweden, which aims to improve patient and staff radiation safety in clinical practice.

REFERENCES

1. Haaga JR, Miraldi F, MacIntyre W, LiPuma JP, Bryan PJ, Wiesen E. The effect of mAs variation upon computed tomography image quality as evaluated by *in vivo* and *in vitro* studies. *Radiology* 1981; **138**: 449–54. doi: <https://doi.org/10.1148/radiology.138.2.7455129>
2. McCollough CH, Bruesewitz MR, Kofler JM Jr. CT dose reduction and dose management tools: overview of available options. *Radiographics* 2006; **26**: 503–12. doi: <https://doi.org/10.1148/rg.262055138>
3. Sookpeng S, Martin CJ, Gentle DJ. Investigation of the influence of image reconstruction filter and scan parameters on operation of automatic tube current modulation systems for different CT scanners. *Radiat Prot Dosimetry* 2015; **163**: 521–30. doi: <https://doi.org/10.1093/rpd/ncu236>
4. Gudjónsdóttir J, Ween B, Olsen DR. Optimal use of AEC in CT: a literature review. *Radiol Technol* 2010; **81**: 309–17.
5. Tsalafoutas IA, Varsamidis A, Thalassinou S, Efsthathopoulos EP. Utilizing a simple CT dosimetry phantom for the comprehension of the operational characteristics of CT AEC systems. *Med Phys* 2013; **40**: 111918. doi: <https://doi.org/10.1118/1.4826160>
6. Moro L, Panizza D, D'Ambrosio D, Carne I. Considerations on an automatic computed tomography tube current modulation system. *Radiat Prot Dosimetry* 2013; **156**: 525–30. doi: <https://doi.org/10.1093/rpd/nct095>
7. Kanal KM, Stewart BK, Kolokythas O, Shuman WP. Impact of operator-selected image noise index and reconstruction slice thickness on patient radiation dose in 64-MDCT. *AJR Am J Roentgenol* 2007; **189**: 219–25. doi: <https://doi.org/10.2214/AJR.06.1524>
8. Muramatsu Y, Ikeda S, Osawa K, Sekine R, Niwa N, Terada M, et al. Performance evaluation for CT-AEC(CT automatic exposure control)systems. [In Japanese.] *Nihon Hoshasen Gijutsu Gakkai Zasshi* 2007; **63**: 534–45. doi: <https://doi.org/10.6009/jjrt.63.534>
9. Brisse HJ, Madec L, Gaboriaud G, Lemoine T, Savignoni A, Neuenschwander S, et al. Automatic exposure control in multichannel CT with tube current modulation to achieve a constant level of image noise: experimental assessment on pediatric phantoms. *Med Phys* 2007; **34**: 3018–33. doi: <https://doi.org/10.1118/1.2746492>
10. Goo HW, Suh DS. The influences of tube voltage and scan direction on combined tube current modulation: a phantom study. *Pediatr Radiol* 2006; **36**: 833–40. doi: <https://doi.org/10.1007/s00247-006-0177-3>
11. Papadakis AE, Perisinakis K, Damilakis J. Automatic exposure control in pediatric and adult multidetector CT examinations: a phantom study on dose reduction and image quality. *Med Phys* 2008; **35**: 4567–76. doi: <https://doi.org/10.1118/1.2977535>
12. Agency MaHP. CT scanner automatic exposure control systems. MHRA Report 05016; 2005.
13. Lee CH, Goo JM, Ye HJ, Ye SJ, Park CM, Chun EJ, et al. Radiation dose modulation techniques in the multidetector CT era: from basics to practice. *Radiographics* 2008; **28**: 1451–9. doi: <https://doi.org/10.1148/rg.285075075>
14. Harri PA, Moreno CC, Nelson RC, Fani N, Small WC, Duong PA, et al. Variability of MDCT dose due to technologist performance: impact of posteroanterior versus anteroposterior localizer image and table height with use of automated tube current modulation. *AJR Am J Roentgenol* 2014; **203**: 377–86. doi: <https://doi.org/10.2214/AJR.13.11608>
15. Revolution CT Technical Reference Manual. GE Healthcare, 2014 5443887–1EN, Revision 1.
16. Patient-centered CT imaging: new methods for patient-specific optimization of image quality and radiation dose. Philips Healthcare; 2012.
17. SOMATOM Force System Owner Manual. Siemens Healthcare, 2013 Print No. C2–058.640.03.02.02.
18. Sookpeng S, Martin CJ, Gentle DJ. Comparison of different phantom designs for CT scanner automatic tube current modulation system tests. *J Radiol Prot* 2013; **33**: 735–61. doi: <https://doi.org/10.1088/0952-4746/33/4/735>
19. Wilson JM, Christianson OI, Richard S, Samei E. A methodology for image quality evaluation of advanced CT systems. *Med Phys* 2013; **40**: 031908. doi: <https://doi.org/10.1118/1.4791645>
20. Costello D, Maguire S. Characterising CT automatic exposure control systems using a CeLT phantom. IAPM 3rd Annual Scientific Meeting; 2012.
21. IEC 61223-3-5 evaluation and routine testing in medical imaging departments—part 3-5: acceptance tests—imaging performance of computed tomography X-ray equipment; 2004.