World Academy of Science, Engineering and Technology
International Journal of Biomedical and Biological Engineering
Vol:7, No:1, 2013

A Study of Dose Distribution and Image Quality under an Automatic Tube Current Modulation (ATCM) System for a Toshiba Aquilion 64 CT Scanner Using a New Design of Phantom

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International Science Index, Biomedical and Biological Engineering Vol:7, No:1, 2013 waset.org/Publication/1695

***Abstract*—**Automatic tube current modulation (ATCM) systems are available for all CT manufacturers and are used for the majority of patients. Understanding how the systems work and their influence on patient dose and image quality is important for CT users, in order to gain the most effective use of the systems. In the present study, a new phantom was used for evaluating dose distribution and image quality under the ATCM operation for the Toshiba Aquilion 64 CT scanner using different ATCM options and a fixed mAs technique. A routine chest, abdomen and pelvis (CAP) protocol was selected for study and Gafchromic film was used to measure entrance surface dose (ESD), peripheral dose and central axis dose in the phantom. The results show the dose reductions achievable with various ATCM options, in relation with the target noise. The doses and image noise distribution were more uniform when the ATCM system was implemented compared with the fixed mAs technique. The lower limit set for the tube current will affect the modulations especially for the lower dose option. This limit prevented the tube current being reduced further and therefore the lower dose ATCM setting resembled a fixed mAs technique. Selection of a lower tube current limit is likely to reduce doses for smaller patients in scans of chest and neck regions.

***Keywords*—**Computed Tomography (CT), Automatic Tube Current Modulation (ATCM), Automatic Exposure Control (AEC).

I. INTRODUCTION

IN an effort to address concerns about high patient doses from computed tomography (CT) scans, manufacturers have introduced the capability to modulate the tube current to reduce the radiation exposure for regions of lower attenuation [1]-[3]. The automatic tube current modulation (ATCM) systems adjust the tube current to take into account the X-ray attenuation of the section of the patient being scanned. The purpose is reduce patient dose whilst maintain a consistent image quality or quantum noise level. Furthermore, by lowering tube current, X-ray tube heating is reduced allowing extended scans to be performed [4]. ATCM systems may vary the tube current in both x-y and z axes or only z-axis directions. Several investigators have published data relating to the efficiency of ATCM systems in reducing dose for patient examinations [3], [5]-[9]. Previous studies have shown that there is little difference in diagnostic quality between images obtained from ATCM systems and those from the fixed tube current technique [7-9]. However, there is little published information explaining how the systems modulate the tube current for different patient sizes, how this is related to the distribution of dose within a patient or phantom, and how the image quality varies.

One of the challenges facing CT users is to determine how modifications to scan protocols using ATCM will affect image quality and patient dose. In order to gain a better understanding of the dependence of CT dose distribution on body shape, a phantom has been developed to test CT ATCM systems. The phantom is elliptical in cross section with sections of different size each of which have a ratio of the lateral and AP diameter equal to 1.5. This is approximately the ratio of the antero posterior (AP) and lateral diameters of the human chest and abdomen as determined by the authors from actual patient images. Therefore the performance of the ATCM can be determined under conditions akin to those used in clinical practice. The purpose of this study is to investigate the variation in dose across the surface and image quality in term of noise produced by different ATCM settings within the phantom.

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II. MATERIAL AND METHOD

A. Phantom

The phantom used in this study comprises of three elliptical segments of differing dimensions, resembling a tiered wedding cake and constructed from high density polyethylene (Fig. 1). It has holes at the centre and periphery of the ellipse axes to allow for dosimetric measurement. Each section of the phantom was 120 mm in length and the diameters of the major and minor axes respectively for the three sections were: 1) 270 mm × 400 mm, 2) 260 mm × 385 mm, 3) 220 mm × 330 mm. The sections are subsequently referred to a ‘large’, ‘medium’ and ‘small’ throughout this paper. Ratios of the lateral and AP diameter are close to 1.5 for all sections. The sections were held together by two polyethylene rods each 10 mm in diameter running the length of the phantom. The phantom was laid on the couch as to represent a patient lying supine with the central axis horizontal. Consequently the upper and lower peripheries will be referred to as anterior and posterior.

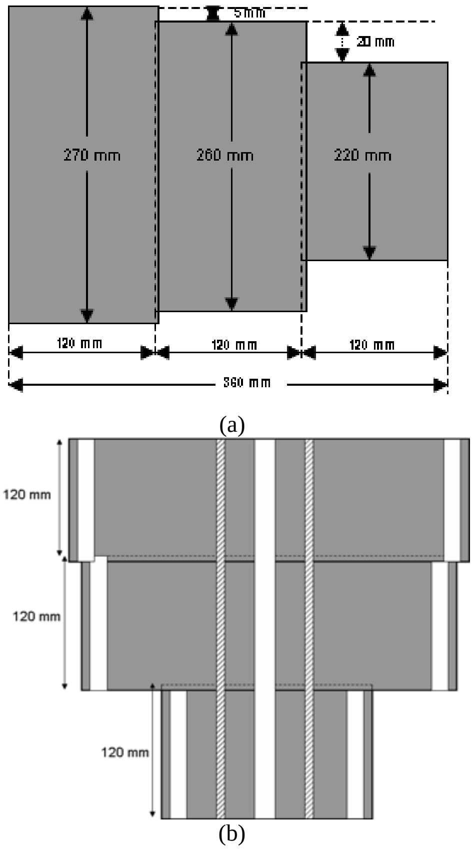


Fig. 1 ATCM 3 tiered wedding cake phantom (a) the side view and (b) the top view of phantom

B. Dose Measurements

Dose distributions were recorded using strips of Gafchromic XR-QA film 8 mm wide, equal in length to the section of phantom being studied. The film was calibrated using a Gulmay superficial therapy unit at 110 kV as described by Martin et al [10]. Absorbed doses inside the phantom were measured at four peripheral positions of each section (Anterior, Posterior, Left and Right) and centre axis doses were measured along the length of the phantom. Entrance surface doses (ESD) were measured at three positions on the surface of the phantom (Top, Left, Right surface). Polyethylene rods were inserted into each hole of the phantom before measuring ESDs in order to replicate normal back scatter radiation conditions. Fig. 2 shows the positions of dose measurement for each section of the phantom.

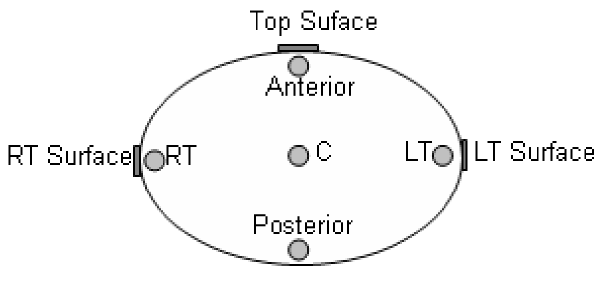


Fig. 2 Positions of dose measurement

C. Testing Approach

The study was performed in a Toshiba Aquilion 64 scanner using a routine Chest Abdomen and Pelvis (CAP) protocol because the CAP examination is one of the most frequent CT examinations performed. The exposure parameter settings were 120 kVp, 0.5 second rotation time, 32x0.5 mm collimation, 0.828 pitch, FC 11 reconstruction kernel, Quantum denoising software (QDS) filter and 5 mm image thickness. Dual scanograms of 300 mm length which excluded the edges of the phantom and a helical scan of the same length were performed. The exclusion of the edges from the scanogram is to avoid the rapid change in attenuation at the edge of the phantom which leads to spurious tube current calculations for the Toshiba ATCM system.

The ATCM system of the Toshiba scanner called SureExposure, it allows users to set a target standard deviation (SD) of pixel value (in Hounsfield units) and to define a minimum and maximum tube current that can be used. SureExposure uses data obtained from dual scanograms to determine the tube current modulation [7]. It determines the relative attenuation of a patient by convert this into water equivalent diameter along the z direction of the patient. The tube current is calculated to achieve the selected target noise and modulated to maintain the image noise throughout the examination, as the patient diameter varies. The tube current decreases for less attenuating regions [11].

Five different standard ATCM modes are available on Aquilion scanners that correspond to the selection of different pre-selected image noise levels which are given in brackets; a) high quality (SD=7.5 HU), b) quality (SD=10 HU), c) standard (SD=12.5 HU), d) low dose (SD =15 HU), and e) low dose plus (SD=20.0 HU). Four modes of operation were assessed in this study 1) the ATCM inactivated and a 200 mAs fixed technique 2) the high quality (HQ) option, 3) the standard (STD) option and 4) the low dose plus (LD+) option. Gafchromic film measurements were made in all positions previously identified for each scan.

D. Analysis

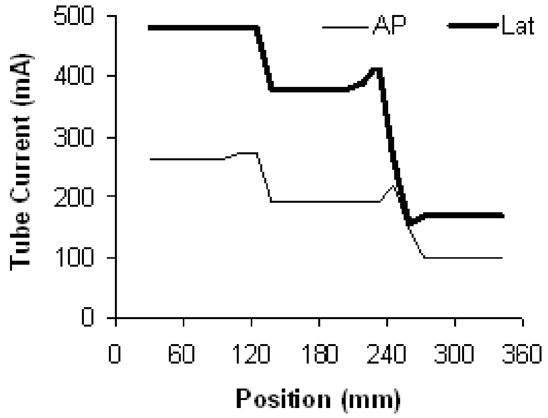
The variation in tube currents (mA) for the AP and lateral directions of the phantom is displayed on the screen after the dual scanograms and was recorded photographically. ImageJ which is a public domain Java image processing program was used in this study [12]. The information on the average mA/slice and mAs/slice was contained in the DICOM header and read out by using an ImageJ macro written specifically for this purpose. The image quality was evaluated from measuring the mean standard deviation of CT number for each image from 500 mm^2 regions of interest (ROIs) positioned close to the centre of the phantom and four positions of 3 cm from the edge of the phantom (anterior, posterior, right and left lateral).

III. Results

A. Evaluation of Automatic Tube Current Modulation

The mA curves for the HQ, STD and LD+ settings generated from the AP and lateral view are shown in Fig. 3. The tube current remained constant during each section. The

AP tube currents at the small section of the phantom were constant at 100 mA for all ATCM options due to the minimum tube current for the CAP protocol being set to 100 mA. For the HQ and STD options, tube current increased for larger sections of the phantom. The lateral tube current for the largest section of the phantom was at 480 mA and this is again because the maximum tube current setting for the protocol is 480 mA. The lateral tube current was double the AP tube current. For the STD and LD+ settings, the AP tube current remained constant at 100 mA and the lateral tube current increased up to 200 mA for the STD option. There were small peaks in the tube current between each section corresponding to the edges of different phantom sections. These peaks are a consequence of changing attenuation between the sections. Fig. 4 shows comparisons of the average mA/slice values from three different ATCM options.



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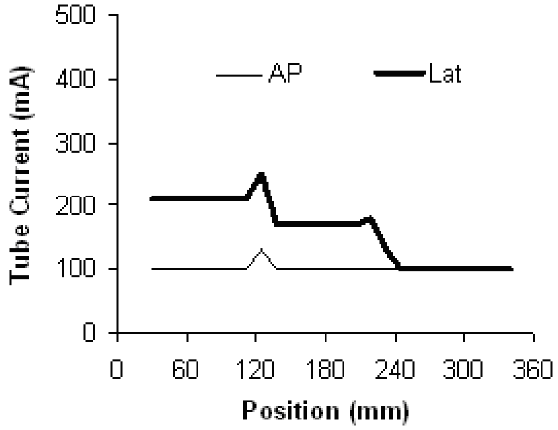

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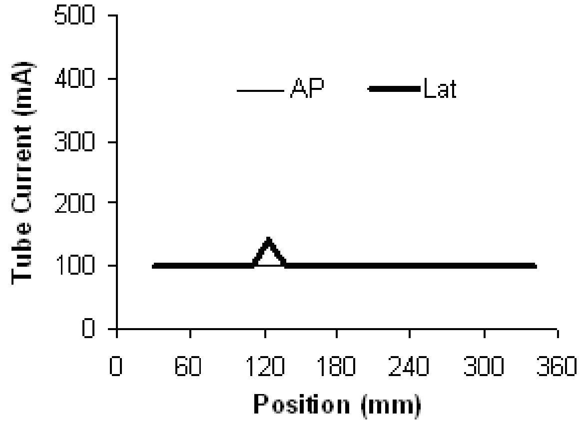


(c)

Fig. 3 The AP and lateral tube currents along the length of phantom (a) HQ (b) STD and (c) LD+ options

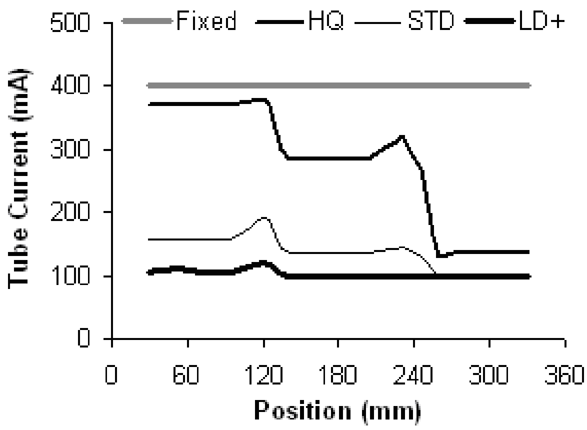


Fig. 4 Comparisons of the average mA/slice for different ATCM options and the fixed tube current technique

B. Measurement of ESDs, Periphery and Central Axis Dose in the Wedding Cake Phantom

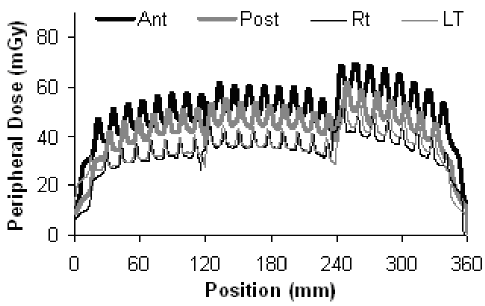
The peripheral dose profiles recorded with the phantom with the scanner operating under different ATCM options and the fixed mAs technique measured at different peripheral positions are shown in Fig. 5.

The peripheral dose levels were closely related to the diameter of the phantom with the fixed tube current. The largest dimension has the lowest peripheral dose and the smallest section of the phantom has greatest dose. The peripheral doses at the anterior periphery of the phantom were the highest for all sections with the fixed tube current. Differences of doses between peripheral positions were much smaller while the HQ and STD ATCM options were on operation. The peripheral doses of the HQ option measured at the anterior were 38, 33 and 25 mGy for the large, medium and small sections and the doses at other positions were about 15% lower than that at the anterior. The periphery dose profiles obtained from the LD+ option were similar in pattern compared to that of the fixed technique but the absolute doses were about four times less.

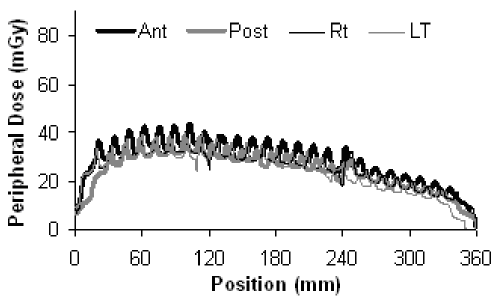
Comparison of doses between the fixed mAs technique and different ATCM options (Fig. 6) showed that the periphery dose measured from the fixed mAs technique at the anterior for all sections was around 50-60 mGy. This dose at the anterior was constantly higher than that at the lateral position. The ratios of the anterior and lateral periphery doses were 1.4-1.5 for different sections. The anterior peripheral dose was 1.2 times higher than that at the posterior. The smallest section received the highest dose while the largest section received the lowest dose in all positions.

For the HQ option, the doses from all positions were lower than the fixed mAs technique. The anterior ESDs, anterior and posterior peripheral doses and central dose dropped by 20%, 40% and 60% for the large, medium and small sections respectively compared with those from the fixed mAs technique. The lateral doses dropped by 10% and 50% for the medium and small sections while there was no change in the dose for the large section as it was operating at the maximum mA.

The doses at the centre of the phantom were similar to the ESDs at the anterior of the phantom. The ESDs increased from the large section to the small section for the fixed mAs technique and the LD+ ATCM option, but they decreased from the large section to the small section for the HQ ATCM option. For the STD option, the peripheral doses at the anterior and lateral were similar in the large and medium sections of the phantom while in the smallest section the anterior dose was 1.3 times higher than that at the lateral positions. The doses for all positions were around 60-70% lower and around 70-75% lower for the STD and LD+ options compared with the fixed mAs technique.



(a)



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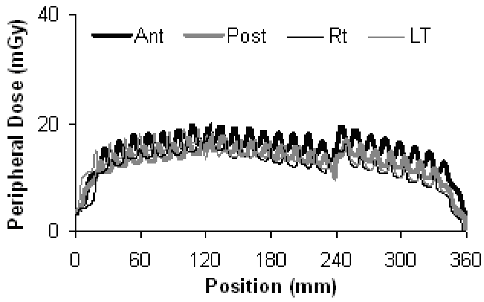

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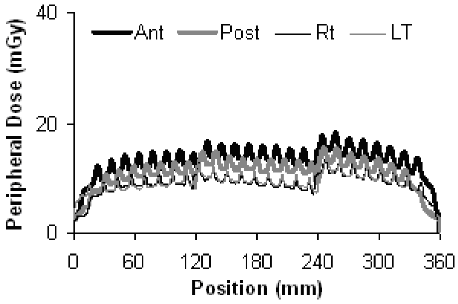


(d)

Fig. 5 Peripheral dose profiles at different positions, measured from (a) the fixed mAs technique, (b) HQ ATCM, (c) STD ATCM and (d) LD+ ATCM options

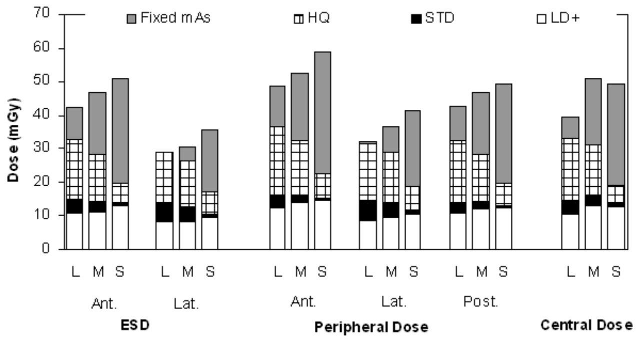


Fig. 6 Average ESD, peripheral dose and central dose across each section of the phantom; large (L), medium (M) and small (S) sections, measured from fixed mAs technique and ATCM modes; HQ, STD and LD+

C. Image Noise

The image noise level with different ATCM settings are shown in Fig. 7. The average noise remained constant over each section of the phantom. Overall, the image noise increased as the setting was changed from the HQ to LD+ as expected. The image noise from the fixed technique and the HQ ATCM option were similar in the large section and those from the LD+ and STD options were similar in the small section because the tube currents employed were similar.

The average noise measured from different sections and positions of measurement are shown in table I and II. There was less variation in noise for the HQ option while the noise measured from the fixed mAs technique and STD and LD+ options increased substantially in accordance with the diameter of the phantom. Fig. 8 shows comparisons of the image noise measured from four different positions of each image; anterior, posterior, average of left and right lateral and the centre, measured from the fixed mAs technique and the HQ ATCM option. The image noise values in the small section were about 40% lower than for other sections with the fixed mAs, but were similar when the HQ option was implemented.

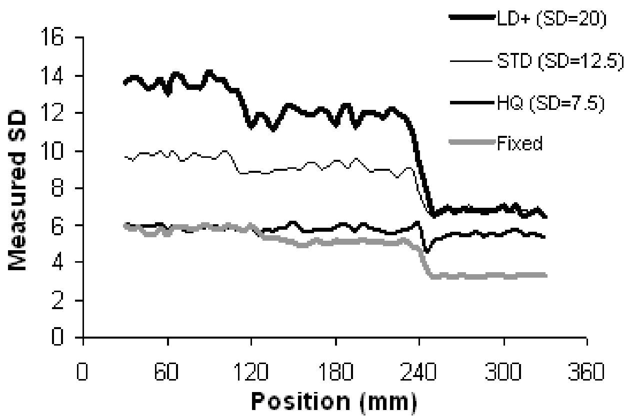
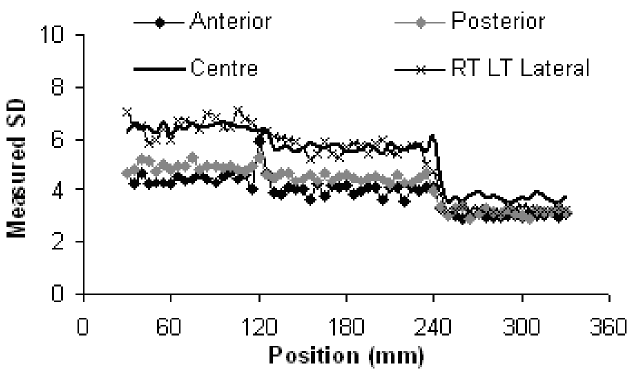
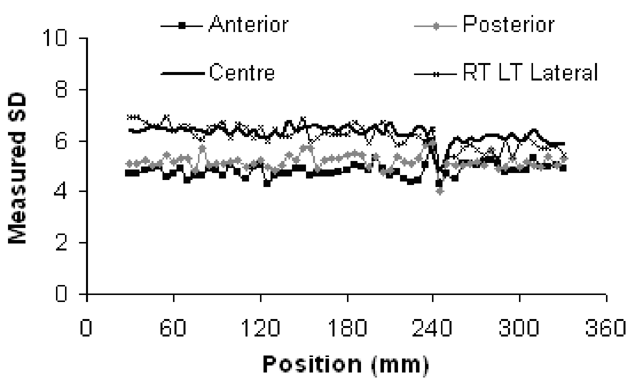


Fig. 7 Comparisons of noise level for the fixed mAs technique and different ATCM options



(a)



(b)

Fig. 8 Image noise from different positions in the phantom; Anterior, posterior, right and left lateral and the centre measured from (a) the fixed mAs technique and (b) the HQ option

TABLE I
AVERAGE IMAGE NOISE MEASURED AT EACH SECTION OF THE PHANTOM

ATCM option	Mean noise (Hounsfield Unit:HU)			
	Section L	Section M	Section S	All sections
Fixed 200 mAs	5.8±0.2	5.1±0.1	3.5±0.5	4.8±1
HQ (SD=7.5)	5.8±0.1	5.8±0.2	5.5±0.3	5.7±0.3
STD (SD=12.5)	9.5±0.4	9.1±0.2	6.9±0.6	8.5±1.2
LD+ (SD=20)	13.2±0.8	11.9±0.4	7.1±1.1	10.8±2.7

TABLE II
AVERAGE IMAGE NOISE, STANDARD DEVIATION AND COEFFICIENT OF VARIATION FROM ALL SECTIONS OF THE PHANTOM

		Fixed mAs	HQ	STD	LD+
Mean Noise	Mean±SD (range)	4.8±1.0 (2.9-7.6)	5.7±0.3 (4-7.8)	8.5±1.2 (5.2-12.8)	10.8±2.7 (5.3-19.2)
	%CV	21.4	4.5	14.6	25.4
Noise value from different positions of measurement					
Centre	Mean±SD	5.4±1.1	6.3±0.3	9.4±1.4	11.9±3.0
Ant.	Mean±SD	3.9±0.7	4.8±0.3	6.9±0.9	8.1±1.6
Post.	Mean±SD	4.2±0.8	5.2±0.3	7.7±1.1	9.1±1.9
Lateral	Mean±SD	5.2±1.4	6.2±0.5	9.3±1.6	12.5±3.7

IV. DISCUSSION

A. Tube Current Modulation

The SureExposure 3D ATCM system for the Toshiba Aquilion calculates the tube current value from the dual scanograms recorded prior to the scan. Overall, the tube current remained constant over each section of the phantom as expected. When selecting the HQ mode, the tube current was reduced by about 20% at the medium section compared with the large section and reduced by a further 50% at the small section. For the STD and LD+ modes there were substantial reductions in the dose. However, because of the minimum setting of 100 mA for this protocol there were no differences in the tube current between sections when the LD+ option was selected and also at the small section of the phantom when the STD option was used. Selection of a lower tube current limit is likely to reduce doses for smaller patients. Users should be aware of the maximum and minimum tube current that set for each protocol and ensure that these are appropriate for all the patient scanned.

There were small sharp peaks in the mAs/slice at the junction between the sections of the phantom (Fig. 3). This may be because of the rapid change in attenuation at the edges of the phantom and the beam overlapping with more than one section of the phantom for a significant proportion of time. The cause of these peaks needs to be investigated further.

B. Dose Distribution within the Phantom

The ESDs and peripheral doses for the anterior and posterior positions were found to be higher than those at the lateral position in the fixed mAs technique. This is because the anterior and posterior of the ellipse were close to the isocentre and so the X-ray beam from the tube to these positions passes through a region closer to the centre of the bow-tie filter. In addition the phantom is of narrower AP dimension therefore is of lower attenuation in the AP direction. The smallest section received the highest dose for the same reason.

However, because the minimum tube current setting of the protocol is 100 mA the AP and lateral tube currents used for the LD+ option remained constant at this level and could not decrease further. Therefore the LD+ ATCM option resembles a fixed 100 mA technique and this produces similar profiles to those with the fixed mAs technique. For the STD option, the AP and lateral doses in all positions were similar in the large and medium sections while the small section showed higher doses in the AP direction than those at the lateral. This, again, relates to the tube current modulation pattern (Fig. 3(b)). The tube current did not modulate to the true required mA and remained constant at 100 mA for both AP and lateral directions for the small section and this reflects the similar pattern found with the fixed tube current technique.

The calculated percentage variations in the doses compared to a fixed mA technique was based on an arbitrary tube current-exposure time product (mAs) of 200. However, these dose variations will critically depend on the fixed mA chosen and whether this is representative of the mAs that would be chosen for the CAP examination of a standard sized patient. For routine scanning techniques with manually selected tube load, mAs values will be varied depending on patient sizes.

C. Image Quality

The noise levels are linked to the changes in tube current (Fig. 4 and Fig. 7). As explained at the beginning of this paper, the Toshiba ATCM system functions by calculating the tube current required achieving the target noise. However, the measured noise from the LD+ option which was 10.8 HU is much lower than the target noise value which is 20.0. This is due to the minimum tube current of 100 mA which was set for the LD+ option being too high for the modulation to take effect. As the tube current is limited to a minimum of 100 mA this prevents the tube current being reduced further. The variation in the noise between the different sections of the phantom was higher for the LD+ option because of the tube current was effectively fixed due to the lower limit. In this case, the required target noise of 20.0 was not achieved and the image is better quality than expected but consequently patient dose is higher.

STD option results can be explained as a combination between ATCM and the fixed mAs technique. The image noise at the small section was lower than that at the large and medium section because the tube current used for the small section was still too high and leads to the image noise which was lower than that targeted.

The variation in image noise or percentage coefficient of variation (%CV) values for the HQ and also STD options were lower than that for the fixed mAs technique confirming that the image from ATCM setting is more uniform compared with the fixed mAs technique. It would be expected that the noise levels are similar for all positions of measurement since the ATCM system was designed to increase the uniformity of the image quality between different regions of the patient body. However while the noise levels at the two lateral positions of the same setting were similar, while the image noise levels at the posterior was slightly lower than that at the anterior. This may due to the attenuation by the couch.

V. Conclusion

Dose distributions and image quality under the ATCM system for the Toshiba Aquilion 64 scanner have been measured in a custom built phantom. These showed that the ATCM system reduced the tube current for the AP projection, so that the dose distribution within periphery of phantom was more uniform. The subsequent dose reduction was found for the HQ, STD and LD+ settings. The image noise was more constant across the different phantom sections in the ATCM compared with the fixed tube current technique. The minimum and maximum setting of the tube current in the CAP protocol effects the ATCM system, the tube current remained constant for the LD+ option and some parts of the STD setting and this leads to a similar pattern of dose distribution and image noise to the fixed tube current technique. When the ATCM is operated without limitation on the current, the patient dose will be reduced, but the required level of image quality will be maintained.

Acknowledgment

The authors wish to acknowledge the assistance of Mr. M J Carter in analyzing the Gafchromic film calibrations, Mr. D Robertson and Dr. G Singh in the operation of CT scanner.

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