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The effect of out-of-plane patient shielding on CT radiation exposure and tube current modulations, a phantom study across three vendors

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Running title:

Out-of-field shields disrupt TCM in CT

The effect of out-of-plane patient shielding on CT radiation exposure and tube current modulations, a phantom study across three vendors

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ABSTRACT

Objective

The aim of this study was to evaluate how out-of-plane patient shielding affects radiation exposure parameters and tube current modulation on different vendors' computed tomography (CT) scanners.

Methods

Helical CT scans were performed using two homogenous phantoms to mimic patient attenuation. Four CT scanners from three vendors were investigated by varying the distance of the patient shield from the border of the imaging volume. Scans were performed with a shield placed before and after the localizer. Changes in volume Computed Tomography dose index ($CTDI_{vol}$), Dose-length product (DLP), and tube current-time products were studied.

Results

Out-of-field lead shield increased the $CTDI_{vol}$ and DLP values for each scanner at least for one scan setting when the shield was present in the localizer. The most notable changes were recorded with >1.3 pitch values when the shield was closest to the scanned volume (2.5 cm), and the scan direction was towards the shield.

Conclusion

The usage of patient shields in the localizer CT scans can disturb TCM even when placed 7.5 cm away from the edge of the scan.

INTRODUCTION

The use of in- and out-of-plane patient shielding in computed tomography (CT) has been under critical discussion during recent years, and different organizations have implemented their recommendations. The recommendations for using patient shielding are based on the practices introduced several decades ago and are justified by risks due to ionizing radiation [1]. A recent publication by the British Institute of Radiology recommends that "the use of patient shielding in CT is not generally advised" [2]. Similarly, the American Association of Physicists in Medicine advocates that no additional fetal, gonadal, or bismuth shields should be used in diagnostic X-ray imaging due to potential risks of degrading image quality and increase in the patient radiation dose [3,4]. As the recommendations for the usage of shields vary, it is not uncommon that the practices of using the patient shields also vary [5,6]. However, there have been significant developments in X-ray imaging technology, which provide alternative means for reducing the patient radiation dose [1].

Adaptive or dynamic collimation is a standard technique in modern wide-array CT scanners to reduce the radiation dose due to the overscanning effect in spiral or helical CT imaging [7–9]. Helical scanning is favored especially in body imaging as scanning times are shorter and lesser motion artifacts are introduced in comparison to axial CT scans [10]. Dose savings by dynamic collimation increase with higher pitch factors and smaller scan ranges [7,8].

Out-of-plane patient shielding with lead aprons is another technique to further reduce the exposure of the tissue outside the imaging volume. A pulmonary embolism CT scan of a pregnant patient is a plausible scenario where lead aprons may be considered to reduce the exposure to the fetus[6,11]. In a previous Monte-Carlo study, significant uterus dose savings of 20 to 56% were reported when a lead apron was placed around a patient's abdomen[12]. Furthermore, patient shields have been shown to reduce the radiation doses outside the scan range from 19.1 to 4.3% in pediatric chest CT, depending on how close to the scan range the shield has been positioned[13]. Breast shielding has also been recommended during head CT with over 80 to 90% organ dose reduction to the dose-sensitive breast tissue[14–16]. In addition, breast shielding has also been recommended during abdominal and neck CT[17]. Yet, for the adult chest CT, the reduction in the effective dose has been shown to be only 4% when lead shields have been placed on the abdomen in a phantom study [18].

However, the shield must not be placed inside the scanned field of view (FOV) due to a potential increase in primary beam exposure owing to an increase in the tube current as a result of automatic exposure control systems (AEC)[1]. Another study of fetal doses during pulmonary embolism CT scans reported no increase of dose to the fetus due to the presence of lead[19]. Nevertheless, there is a potential risk for tube current increase despite proper shield placement outside the primary scanning range. In a previous phantom study, an increase of fetal dose was demonstrated when the patient shield was applied before the localizer images close to the planned scan region and a lower dose was reported without shielding[20].

If shields are used in clinical work, the practice may require positioning of the shields before the acquisition of the localizer images to ensure that the lead apron is not in the scan region or to avoid repositioning of the patient, thus affecting TCM[13, 21, 22]. The aim of this study was to evaluate how additional out-of-plane patient shielding affects radiation exposure parameters and tube current modulation inside the imaged volume. $CTDI_{vol}$, DLP and tube current-time product values on different vendor's CT scanners were determined, depending on the proximity of the shield, scan direction, selected pitch, and by placing the shield before and after the localizer using an abdomen-based protocol.

MATERIALS AND METHODS

Phantoms

Two (33.5 x 22.5 x 16.3 cm (length x width x height)) phantoms filled with nickel chloride solution (TL Unified Phantom, GE Healthcare, Milwaukee, USA) were positioned lengthwise and adjacent to each other on the CT scanner bed (Figure 1 a)). The phantoms were positioned in the isocenter with the aid of alignment lasers. The phantoms were chosen so that the attenuation of the object would be constant longitudinally and that the lead-free shield apron (Model 60x70 cm NL, ScanFlex, Medical AB) with 0.5 Pb equivalency at 100 kVp would lie on top of the phantoms without becoming wrinkled. The phantoms' water-equivalent diameter was approximately 22 cm which would correspond to a 15-year-old tissue-equivalent abdomen phantom[23]. Phantoms were marked with 2.5 cm intervals so that the apron could be positioned accurately.

CT scans

Four CT scanners from three vendors were investigated by varying the distance of the apron from the scan range, the scan direction, and the pitch values. Shield placement was investigated separately by positioning the lead apron before and after the localizer, and comparing the tube exposure in each slice obtained with these strategies. The investigated CTs were Revolution CT and Discovery 690 (GE Healthcare, Milwaukee, USA), Somatom Definition Flash (Siemens Healthcare, Erlangen, Germany) and Aquilion One Vision Edition (Toshiba Medical Systems, Otawara, Japan). For the Revolution CT scanner, two different collimations, 40 and 80 mm, were also investigated. For the Toshiba and GE Discovery scanner 40 mm collimation, and for the Siemens scanner 38.4 mm collimation was used. Helical CT scans were performed with angular-longitudinal tube current modulation: SmartmA for GEs, CareDose4D for Siemens and SureExposure3D for Toshiba.

Reference image quality or noise level, depending on the vendor, were set so that a reference scan with 0.6 pitch, 0.5 s rotation time, and 100 kVp peak tube voltage without the lead apron would yield a $CTDI_{vol}$ (32 cm) of 1.5 mGy. For the Siemens scanner with 2.0 and 3.2 pitch scans, a 0.28 s rotation time was used. The specific scan and image reconstruction parameters for each CT device are listed in Table 1. The scan range was set to 10 cm, with start and end positions being constant for each scan. Radiation exposure ($CTDI_{vol}$ and DLP) evaluations were performed with varying apron to edge of the scan range distances (2.5, 5, 7.5, and 10 cm) (Figure 1 b). In addition, to test the effect of scan direction on exposure, scans were performed towards and away from the apron (Figure 1b). For each apron distance, separate anterior-posterior and lateral scouts were obtained.

Subsequently, the $CTDI_{vol}$ and DLP values were obtained from the dose reports provided by the CT scanners. Tube current-time products (mAs) were acquired from the reconstructed thin slice images using Matlab (v. 9.4, The MathWorks Inc., Natick, MA, 2018) by multiplying the tube current and the exposure time for each slice. The relative change in $CTDI_{vol}$ and DLP was calculated in comparison to the reference scans obtained without aprons being present in either the localizer or the helical CT scan for each pitch value.

RESULTS

The most notable changes in the $CTDI_{vol}$ and DLP values were generally recorded with larger pitch values when the patient shield was in the localizer and closest to the scanned area (2.5 cm), and the scan direction was towards the shield (Tables 2-4). In contrast, when the shield was positioned after the localizer, changes in CTDIvol and DLP were within 3% compared to the reference scans for each lead apron position (Tables S1-S10).

With the Toshiba scanner, the largest change in $CTDI_{vol}$ value was +46.7%, whereas when the shield was 5 cm or further away, the changes in $CTDI_{vol}$ were less than 10%. Smaller pitch values did not seem to have a substantial effect on the results.

The Siemens scanner produced notable differences in the radiation output. Only when the apron was positioned 10 cm from the edge of the scan, the differences in $CTDI_{vol}$ and DLP were less than 4% compared with the reference scan without the shield (Table 3). When the apron was at 7.5 cm, the DLP was still increased by 28.6% with 1.4 pitch and scan direction towards the apron.

When the GE Revolution scanner was used with 40 mm collimation, the differences in $CTDI_{vol}$ and DLP values were less than 5% when the apron was positioned 5 cm or further away from the edge of the scan (Table 4). The largest differences (+37.7%) occurred with the largest pitch (1.375) when the apron was at 2.5 cm from the scanned volume and when the scan direction was towards the shield. When the collimation was increased to 80mm, the differences to the reference scan were more noticeable than with the 40 mm collimation. With the 80 mm collimation, the apron had to be positioned at a 10 cm location in order to get less than a 5% increase in DLP for every pitch and scan direction set-up compared to the reference scan. With the Discovery scanner, the $CTDI_{vol}$ was 246.7% larger compared to the reference scan at the highest pitch setting and scan direction towards the shield when the shield was at 2.5 cm place. When the shield was at 2.5 cm, every scan showed over a 126% increase in $CTDI_{vol}$ and DLP when compared to the reference scan.

Tube current time-product curves (Figure 2) show how the increase of mAs values can occur several centimeters before the end of the scan in our set-up. The increase was relatively constant throughout the scan region for the Toshiba scanner with 40 mm collimation, while for Discovery with 40 mm collimation and Revolution with 80 mm collimation, the increase in tube current-time product occurs over 5 cm before the scan ends. Flash and Revolution with 40 mm collimation started to raise the mAs at the latest position at about 2 to 3 cm before the end of the scan.

DISCUSSION

In the present work, the effect of out-of-plane patient shielding on radiation exposure and tube current modulation was evaluated on different modern CT scanners. A uniform phantom was scanned using an abdomen-based protocol, and the distance of the lead shield from the imaging plane and the imaging direction was varied. The effect of different helical pitch values and collimation settings were also investigated. Previous studies have mainly focused on dose reduction in the out-of-plane organs, and the information on the exposure changes in the imaging plane is limited when lead aprons are applied. In this study, all CT scanners showed an increase in tube current when the lead apron was placed before the localizer at the closest position at a 2.5 cm distance from the scanned volume. The effect was pronounced especially at high pitch values (> 1.3). Moreover, when the distance between the shield and the scan area was increased to over 5 cm, the changes in the exposure values generally decreased, depending on the scanner type, pitch, collimation, and scan direction. When the apron was placed after the localizers, no such tube current increase was observed with any of the CT scanners.

Previously, a higher dose to the patient has been reported in a phantom study investigating fetal doses with Siemens SOMATOM Definition Flash CT when patient shielding was placed next to the scan area compared to scan without shielding[(20)]. The increase in the effective dose, $CTDI_{vol}$, and DLP was approximately 50% when using patient shielding, pitch factor of 1.5, and tube current modulation. With a comparable pitch factor of 1.4 and with the shield at a 2.5-cm distance, an 80-90% increase in $CTDI_{vol}$ and DLP were observed in this study. In addition, the most notable changes in the tube current occurred in the scan region closest to the shielding and when the scan direction was towards the shield. The results of this study are consistent with the previous findings[(20)]. Siemens CARE Dose 4D uses localizer images and real-time pre-projection data for the determination of tube current modulation, which most likely increases the dose next to lead aprons if they are included in the localizers, and the scan direction is towards the shield[21]. Similar results have been shown where CARE Dose 4D increases mAs values upfront when approaching a region of higher attenuation [(24)]. A comparable increase in mAs values was observed with the other scanners when the direction was towards the shield, which may be caused by a similar tube current modulation strategy to CARE Dose 4D. However, each vendor has different characteristics in the behavior of AEC[(25)]. The difference between exposure values using 1.4 and 3.2 pitch factors is most likely explained by the differential efficacy of the dynamic collimator at high pitch settings[8].

Similar to Siemens Flash, the GE Revolution CT scanner showed the greatest increases in mAs at 2.5 – 5 cm shield distance and scan direction towards the shield, especially at 80 mm collimation and high pitch. Larger beam collimation and higher pitch are known to be associated with increased exposure[(26)]. A narrower beam covers a shorter longitudinal distance per rotation and thus enables faster changes in TCM[21]. Furthermore, the changes in the tube current were emphasized in the volume close to the lead apron. The difference in the results between Siemens and GE's Revolution and Discovery may be explained by the manufacturer-specific behavior of AEC, and the potential differences in the dynamic collimation mechanism may influence the results[9]. It should be noted that the GE scanners have different X-ray tubes, which might also have a significant role in the different results between Revolution 40 mm and Discovery at 40 mm collimation.

The Toshiba scanner showed the smallest differences between the scans. The greatest change in TCM and increase of the tube current near the edge of the lead apron was observed at 2.5 cm shield distance, scanning direction towards the apron and pitch of approximately 1.4, similarly as with Siemens and GE scanner.

The aim of out-of-plane shields is to reduce the overall patient dose. As the shields are not included in the scanned region, their function is to reduce the amount of external scatter to the patient, which has been questioned as the majority of radiation burden to the out-of-field organs is from internal scatter[(2,6)]. In this work, for the 10 cm distance between the edge of the scan range and the lead shield, there was practically no effect on the scan $CTDI_{vol}$ or DLP compared to the reference scans in all scanners when the shield was placed before the localizer. With the lead apron at a 10 cm distance, the dose savings to tissues outside scanning volume has been shown to be minimal, about 4% and only 0.2% compared to the total scan dose[13]. Moreover, there is usually a safety margin of 5-10 cm required to ensure that the lead apron is not accidentally placed in the primary X-ray beam, thus questioning the need for the usage of patient shielding[13]. So far, patient shielding has been applied to subjects at most risk to the radiation, *i.e.,* pediatric and younger patients and pregnant women. However, it has been shown that the dose to the fetus might increase when performing a standard pulmonary embolism CT scan if the shield is in the localizer[20]. Instead, focusing on the selection of the scan parameters or shortening of the scan length could be more effective strategies to optimize the radiation exposure than the usage of the lead aprons[12,20]. In addition, alternative approaches for overall dose reduction other than shielding, such as breast displacement during coronary CT and organ exposure modulation, have been shown to be effective[(27–29)]. Despite the risks associated with the out-of-plane shields, several legislative documents or recommendations still recommend or suggest that the shield should be considered for use, even within 5 cm from the edge of the scan[(6)].

In helical CT scan mode, the amount of overscanning and thus the extra radiation dose compared to axial mode increases if a larger pitch factor and width of collimation is selected[(6,7)]. However, helical scans have a few benefits over axial scans. Helical scanning of volumes larger than 160 mm, which is the current upper width limit for wide-array detectors, is faster and less susceptible to motion artifacts than axial mode[(10)]. In addition, dynamic collimation reduces the amount of out-of-plane radiation exposure to tissues [(7)]. Nevertheless, with shorter scan lengths, it is possible to reduce the overradiation and the effective dose with the axial scanning mode[(26,30)]. Yet, most efforts in dose optimization should be focused on patient positioning and centering, selection of tube current and voltage, collimation, pitch, and scan range[(31–34)].

Prior research has demonstrated radiation dose savings if aprons are positioned after the localizer images have been scanned[(34)]. It is true that dose savings might be possible and that exposure values are not affected by the shields but there are other factors that should be taken into account before decision on lead apron placement is made. In practice, shields may be positioned before obtaining the localizer images to confirm proper placement and distance of the apron or to avoid patient movement between the scout and the actual CT scan[(13,22)]. Some radiographers find lead aprons heavy to handle and that they do not fit optimally to the patient shape, which may result in improper placement or sliding of the shield from the covered region[35], and possibly compromising image quality if exposed to the primary beam. It has been reported that multiple localizers are sometimes used when fine-tuning the apron position, which results in additional radiation burden due to unnecessary localizer scan and a possible increase in exposure of the actual scan as in our results[13]. Nevertheless, the aforementioned risk factors and relatively minor gains and dose benefits with patient shielding should be considered when deciding whether to use shielding.

This study was limited by the lack of actual patient data; however, the effect of lead apron on TCM has been observed in the past on diagnostic images from our institution in the scanners included in this study (data not shown). In addition, the phantom was selected owing to its homogeneity so that the changes in TCM on different scans would be due to lead apron and not due to possible uncertainties in apron positioning or the scan volume. A low tube output of 1.5 mGy $CTDI_{vol}$ was selected to avoid TCM to reach tube current limit. Different body size phantoms and image quality, and exposure levels were not examined, which might provide further information on the TCM properties when scans are performed with aprons. Additionally, the image quality and effect of different dynamic collimators were not investigated.

In conclusion, based on the results of this study, patient shielding can cause severe disturbance in the tube current modulation of a CT even when shield is placed 7.5 cm away from the edge of the scan. As the lead aprons may increase the radiation exposure of the CT scan compared to relatively minimal achievable dose savings, the discontinuation of this shielding practice should be considered.

References

1. Marsh, R. M. and Silosky, M. *Patient Shielding in Diagnostic Imaging: Discontinuing a Legacy Practice*, American Journal of Roentgenology **212**(4), 755–757 (2019).

2. Hiles, P., Benson, E., Helen Hughes, Rob Loader, Dan Shaw, Sue Edyvean, Yvonne Sullivan, Guy Hickson, Phil Cosson, Lynda Johnson and David Dommett. Guidance on using shielding on patients for diagnostic radiology applications (2020).

3. AAPM Position Statement on the Use of Bismuth Shielding for the Purpose of Dose Reduction in CT scanning. .

4. AAPM. AAPM Position Statement on the Use of Patient Gonadal and Fetal Shielding PP 32-A (2019).

5. Safiullah, S., Patel, R., Uribe, B., Spradling, K., Lall, C., Zhang, L., Okhunov, Z., Clayman, R. V. and Landman, J. *Prevalence of Protective Shielding Utilization for Radiation Dose Reduction in Adult Patients Undergoing Body Scanning Using Computed Tomography*, Journal of Endourology **31**(10), 985–991 (2017).

6. Candela-Juan, C., Ciraj-Bjelac, O., Sans Merce, M., Dabin, J., Faj, D., Gallagher, A., de las Heras Gala, H., Knežević, Ž., Malchair, F., De Monte, F., Simantirakis, G. and Theodorakou, C. *Use of out-of-field contact shielding on patients in medical imaging: A review of current guidelines, recommendations and legislative documents*, Physica Medica **86**(January), 44–56 (2021).

7. Deak, P. D., Langner, O., Lell, M. and Kalender, W. A. *Effects of adaptive section collimation on patient radiation dose in multisection spiral CT*, Radiology **252**(1), 140–147 (2009).

8. Booij, R., Dijkshoorn, M. L. and van Straten, M. *Efficacy of a dynamic collimator for overranging dose reduction in a second- and third-generation dual source CT scanner*, European Radiology **27**(9), 3618–3624 (2017).

9. Yang, K., Li, Z., Li, X. and Liu, B. *Characterization of dynamic collimation mechanisms for helical CT scans with direct measurements*, Physics in Medicine and Biology **64**(21) (2019).

10. Lambert, J. W., Phillips, E. D., Villanueva-Meyer, J. E., Nardo, L., Facchetti, L. and Gould, R. G. *Axial or Helical? Considerations for wide collimation CT scanners capable of volumetric imaging in both modes*, Medical Physics **44**(11), 5718–5725 (2017).

11. Kelaranta, A., Mäkelä, T., Kaasalainen, T. and Kortesniemi, M. *Fetal radiation dose in three common CT examinations during pregnancy – Monte Carlo study*, Physica Medica **43**, 199–206 (2017).

12. Ryckx, N., Sans-Merce, M., Schmidt, S., Poletti, P. A. and Verdun, F. R. *The use of out-of-plane high Z patient shielding for fetal dose reduction in computed tomography: Literature review and comparison with Monte-Carlo calculations of an alternative optimisation technique*, Physica Medica **48**, 156–161 (2018).

13. Yu, L., Bruesewitz, M. R., Vrieze, T. J. and McCollough, C. H. *Lead Shielding in Pediatric Chest CT: Effect of Apron Placement Outside the Scan Volume on Radiation Dose Reduction*, American Journal of Roentgenology **212**(1), 151–156 (2019).

14. Brnić, Z., Vekić, B., Hebrang, A. and Anić, P. *Efficacy of breast shielding during CT of the head*, European Radiology **13**(11), 2436–2440 (2003).

15. Trožić, Š., Mekiš, N. and Zalokar, N. *The efficiency of lead and non-lead shielding on breast dose in head CT*, Journal of Radiological Protection **40**(3), 816–826 (2020).

16. Zalokar, N. and Mekiš, N. *A PHANTOM STUDY SHOWING THE IMPORTANCE OF BREAST SHIELDING DURING HEAD CT*, Radiation Protection Dosimetry **188**(4), 464–469 (2020).

17. Chung, J. J., Cho, E. S., Kang, S. M., Yu, J. S., Kim, D. J. and Kim, J. H. *Usefulness of a lead shielding device for reducing the radiation dose to tissues outside the primary beams during CT*, Radiologia Medica **119**(12), 951–957 (2014).

18. Iball, G. R. and Brettle, D. S. *Organ and effective dose reduction in adult chest CT using abdominal lead shielding*, The British Journal of Radiology **84**(1007), 1020–1026 (2011).

19. Chatterson, L. C., Leswick, D. A., Fladeland, D. A., Hunt, M. M. and Webster, S. T. *Lead versus Bismuth-Antimony Shield for Fetal Dose Reduction at Different Gestational Ages at CT Pulmonary Angiography*, Radiology **260**(2), 560–567 (2011).

20. Begano, D., Söderberg, M. and Bolejko, A. *TO USE OR NOT USE PATIENT SHIELDING ON PREGNANT WOMEN UNDERGOING CT PULMONARY ANGIOGRAPHY: A PHANTOM STUDY*, Radiation protection dosimetry **189**(4), 458–465 (2020).

21. Söderberg, M. *Overview, practicaltips and potential pitfalls of using automatic exposure control in CT: Siemens CARE Dose 4D*, Radiation Protection Dosimetry **169**(1), 84–91 (2016).

22. Strahlenschutzkommission. Use of patient radiation protection equipment in the diagnostic application of X-rays on humans (2018).

23. Wang, J., Christner, J. A., Duan, X., Leng, S., Yu, L. and McCollough, C. H. *Attenuation-based estimation of patient size for the purpose of size specific dose estimation in CT. Part II. Implementation on abdomen and thorax phantoms using cross sectional CT images and scanned projection radiograph images*, Medical Physics **39**(11), 6764 (2012).

24. Merzan, D., Nowik, P., Poludniowski, G. and Bujila, R. *Evaluating the impact of scan settings on automatic tube current modulation in CT using a novel phantom*, British Journal of Radiology **90**(1069) (2017).

25. Martin Weber Kusk, R. T. *Incorrectly placed gonad shields: Effect on CT automatic exposure correction from four different scanners*, Radiography **20**(3), 241–245 (2014).

26. Tzedakis, A., Damilakis, J., Perisinakis, K., Stratakis, J. and Gourtsoyiannis, N. *The effect of z overscanning on patient effective dose from multidetector helical computed tomography examinations*, Medical Physics **32**(6), 1621–1629, John Wiley and Sons Ltd (2005).

27. Foley, S. J., McEntee, M. F., Achenbach, S., Brennan, P. C., Rainford, L. S. and Dodd, J. D. *Breast Surface Radiation Dose During Coronary CT Angiography: Reduction by Breast Displacement and Lead Shielding*, American Journal of Roentgenology **197**(2), 367–373 (2011).

28. Lambert, J. W. and Gould, R. G. *Evaluation of a Net Dose-Reducing Organ-Based Tube Current Modulation Technique: Comparison With Standard Dose and Bismuth-Shielded Acquisitions*, American Journal of Roentgenology **206**(6), 1233–1240 (2016).

29. Wang, J., Duan, X., Christner, J. A., Leng, S., Yu, L. and McCollough, C. H. *Radiation dose reduction to the breast in thoracic CT: Comparison of bismuth shielding, organ-based tube current modulation, and use of a globally decreased tube current*, Medical Physics **38**(11), 6084–6092 (2011).

30. Tzedakis, A., Damilakis, J., Perisinakis, K., Karantanas, A., Karabekios, S. and Gourtsoyiannis, N. *Influence of z overscanning on normalized effective doses calculated for pediatric patients undergoing multidetector CT examinations*, Medical Physics **34**(4), 1163–1175 (2007).

31. Kaasalainen, T., Mäkelä, T. and Kortesniemi, M. *The effect of vertical centering and scout direction on automatic tube voltage selection in chest CT: a preliminary phantom study on*

two different CT equipments, European Journal of Radiology Open **6**(December 2018), 24–32 (2019).

32. McCollough, C. H., Chen, G. H., Kalender, W., Leng, S., Samei, E., Taguchi, K., Wang, G., Yu, L. and Pettigrew, R. I. *Achieving Routine Submillisievert CT Scanning: Report from the Summit on Management of Radiation Dose in CT*, Radiology **264**(2), 567–580 (2012).

33. Abadi, E., Segars, W. P., Harrawood, B., Sharma, S., Kapadia, A. and Samei, E. *Virtual clinical trial for quantifying the effects of beam collimation and pitch on image quality in computed tomography*, Journal of Medical Imaging **7**(04), 1 (2020).

34. Coursey, C., Frush, D. P., Yoshizumi, T., Toncheva, G., Nguyen, G. and Greenberg, S. B. *Pediatric Chest MDCT Using Tube Current Modulation: Effect on Radiation Dose with Breast Shielding*, American Journal of Roentgenology **190**(1), W54–W61 (2008).

35. Iball, G. R. and Brettle, D. S. *Use of lead shielding on pregnant patients undergoing CT scans: Results of an international survey*, Radiography **17**(2), 102–108 (2011).

Figure legends

Figure 1. a) Placement of lead apron on phantoms. b) Scout image illustrating the scan range, scan directions (away and towards), water-equivalent diameter (WED) of 21.9 cm, and the tube current-time products ranging from 41.5 mAs to 94.5 mAs for this particular case. The dashed lines indicate the lead apron positions (2.5, 5, 7.5 and 10 cm from the edge of the scanned region).

Figure 2. Tube current-time product values with lead apron at scan position 2.5 cm from Toshiba Aquilion One (a), GE Discovery (b), Siemen Flash (c, also including scan position at 5 cm) and GE Revolution (d) with 40 mm and 80 mm collimation demonstrate scanned region with the largest variation in DLP compared with the reference scans at 1.4 pitch. The legend shows the distance of the lead apron from the scanned region and the corresponding DLP change compared to the reference in brackets. The location of the lead apron is on the side of the slice location at 100 mm.

Table 1. Scan parameters for the tube current modulation evaluation

Vendor and model	Beam collimation (mm)	Pitch	Slice thickness (mm)/interval (mm)	Image quality paramenters
GE Revolution (Performix HDw tube)	40/80 (64/128x0.625 mm)	0.516/0.984/1.375 (40 mm) 0.508/0.992/1.375 (80 mm)	0.625/0.625	NI 27, (with following parameters: 100 kV, SmartmA 35-700), STND kernel, Asir 40 %)
Siemens Somatom Definition Flash	38.4 (128x0,6 mm and 2x128x0.6mm with 2.0 and 3.2 pitch)	0.6/1/1.4/3.2	0.6/0.6	Quality Ref. mAs 168 at 100 kV. CARE Dose 4D average strength. I30f/3 SAFIRE
Toshiba Aquilion ONE Vision	40 (80x0.5 mm)	0.64/0.95/1.388	0.6/0.6	SD 16.00 (with following SureExposure parameters: Recon FC 18, Image Thickness 5.0, Dose Reduction AIDR3D STD, XY 3D)
GE Discovery 690	40 (64x0.625mm)	0.516 /0.984/1.375	0.625/0.625	NI 46, (with following parameters: 100 kV, SmartmA 30-700, Recon mode Full, Plus IQ Enhance, STND kernel, Asir 40%)

Table 2. CTDI$_{vol}$ (mGy) and DLP (mGy*cm) values and their relative change in scans obtained placing the patient shield to the localizer images at distances of 2.5, 5, 7.5 and 10 cm from the edge of the scanned region, compared with reference scans taken without patient shields compared with reference scans from Toshiba scanner (40 mm collimation).

Shield position	scan direction	pitch	CTDI$_{vol}$ (% change)	DLP (% change)
2.5 cm	towards	0.638	1.5 (0)	21.9 (-1.8)
	towards	0.95	1.2 (0)	18 (0)
	towards	1.388	22 (46.7)	35 (46.4)
	away	0.638	1.5 (-6.3)	22.3 (-2.2)
	away	0.95	1.3 (8.3)	18.8 (4.4)
	away	1.388	1.6 (6.7)	25.8 (7.9)
5 cm	towards	0.638	1.5 (0)	21.9 (-1.8)
	towards	0.95	1.2 (0)	18 (0)
	towards	1.388	1.5 (0)	23.9 (0)
	away	0.638	1.5 (-6.3)	22.3 (-2.2)
	away	0.95	1.3 (8.3)	18.8 (4.4)
	away	1.388	1,5 (0)	24.8 (3.8)
7.5 cm	towards	0.638	1.5 (0)	21.9 (-1.8)
	towards	0.95	1.2 (0)	18 (0)
	towards	1.388	1.5 (0)	23.9 (0)
	away	0.638	1.5 (-6.3)	22.3 (-2.2)
	away	0.95	1.2 (0)	18 (0)
	away	1.388	1.5 (0)	24.8 (3.8)
10 cm	towards	0.638	1.5 (0)	21.9 (-1.8)
	towards	0.95	1.2 (0)	18 (0)
	towards	1.388	1.5 (0)	23.9 (0)
	away	0.638	1.5 (-6.3)	22.3 (-2.2)
	away	0.95	1.2 (0)	18 (0)
	away	1.388	1.5 (0)	23.9 (0)

CTDI$_{vol}$ = Volume Computed Tomography Dose Index, DLP = Dose Length Product

Table 3. CTDI$_{vol}$ (mGy) and DLP (mGy*cm) values and their relative change in scans obtained placing the patient shield to the localizer images at distances of 2.5, 5, 7.5 and 10 cm from the edge of the scanned region, compared with reference scans taken without patient shields from Siemens scanner (38.4 mm collimation).

Shield position	scan direction	pitch	CTDI$_{vol}$ (% change)	DLP (% change)
2.5 cm	towards	0.6	2 (32.4)	22.5 (32.4)
	towards	1.0	2.9 (97.3)	36.5 (97.3)
	towards	1.4	2.9 (95.9)	36.5 (86.2)
	towards	2.0 (DS*)	2.6 (55.5)	38.4 (55.5)
	towards	3.2 (DS)	2.3 (41.1)	37.9 (41.4)
	away	0.6	1.5 (0)	17 (0)
	away	1.0	1.5 (6.9)	19.5 (3.7)
	away	1.4	1.5 (5.5)	21.5 (10.8)
	away	2.0 (DS)	2.6 (57.9)	39 (57.9)
	away	3.2 (DS)	2.4 (47.9)	39.8 (48.5)
5 cm	towards	0.6	1.5 (0)	17 (0)
	towards	1.0	2 (37.7)	25.5 (37.8)
	towards	1.4	2.7 (81)	3.5 (80.6)
	towards	2.0 (DS)	1.7 (4.9)	26 (5.3)
	towards	3.2 (DS)	1.8 (11.7)	30 (11.9)
	away	0.6	1.5 (0)	17 (0)
	away	1.0	1.5 (2.8)	18.8 (0)
	away	1.4	1.5 (2.7)	20 (3.1)
	away	2.0 (DS)	1.8 (6.7)	26.4 (6.9)
	away	3.2 (DS)	1.9 (16.6)	31.4 (17.2)
7.5 cm	towards	0.6	1.5 (0)	17 (0)
	towards	1.0	1.5 (0)	18.5 (0)
	towards	1.4	1.9 (29.3)	25.2 (28.6)
	towards	2.0 (DS)	1.7 (1.8)	25 (1.2)
	towards	3.2 (DS)	1.7 (2.5)	27.4 (2.2)
	away	0.6	1.5 (0)	17 (0)
	away	1.0	1.5 (4.2)	19 (1.1)
	away	1.4	1.5 (2.7)	20 (3.1)
	away	2.0 (DS)	1.7 (1.8)	25 (1.2)
	away	3.2 (DS)	1.7 (2.5)	27.4 (2.2)
10 cm	towards	0.6	1.5 (0)	17 (0)
	towards	1.0	1.5 (0)	18.3 (-1.1)
	towards	1.4	1.5 (0)	19.6 (0)
	towards	2.0 (DS)	1.7 (1.8)	25 (1.2)
	towards	3.2 (DS)	1.7 (2.5)	27.4 (2.2)
	away	0.6	1.5 (0)	17 (0)
	away	1.0	1.5 (2.8)	18.8 (0)
	away	1.4	1.5 (2.7)	20 (3.1)

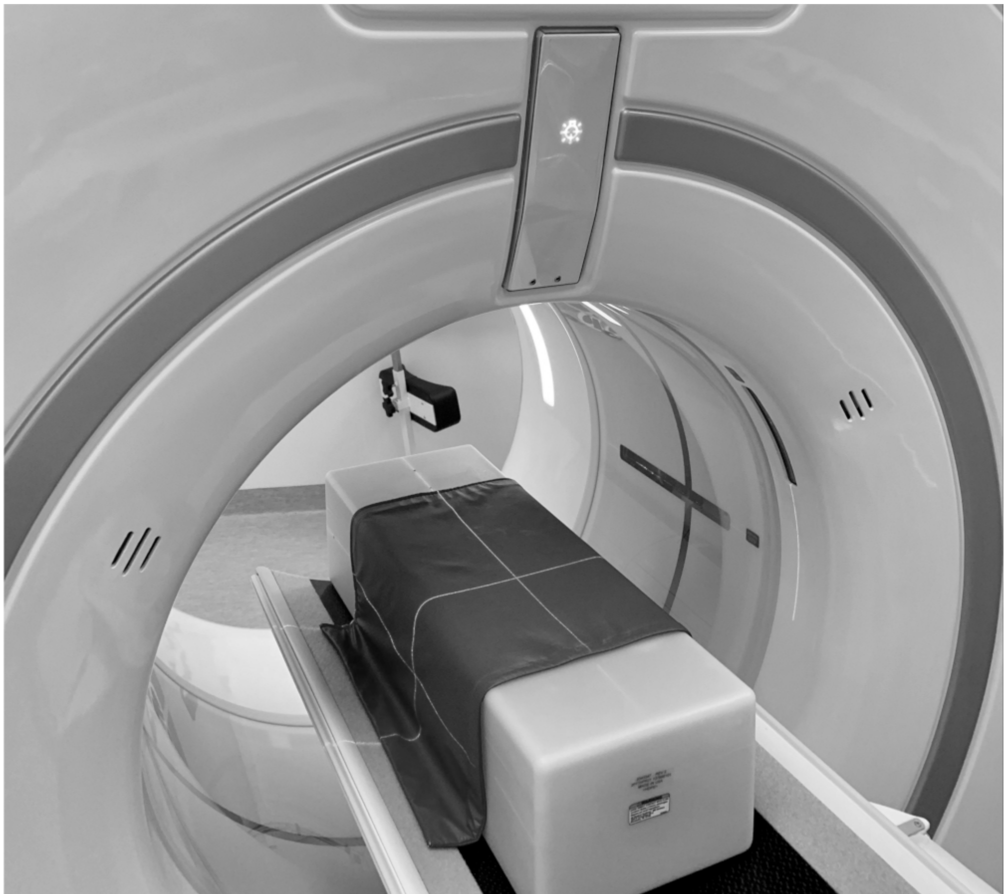
	away	2.0 (DS)	1.7 (1.8)	25 (1.2)
	away	3.2 (DS)	1.7 (2.5)	27.3 (1.9)

$CTDI_{vol}$ = Volume Computed Tomography Dose Index

Table 4. $CTDI_{vol}$ (mGy) and DLP (mGy*cm) values and their relative change in scans obtained placing the patient shield to the localizer images at distances of 2.5, 5, 7.5 and 10 cm from the edge of the scanned region, compared with reference scans taken without patient shields from GE scanners.

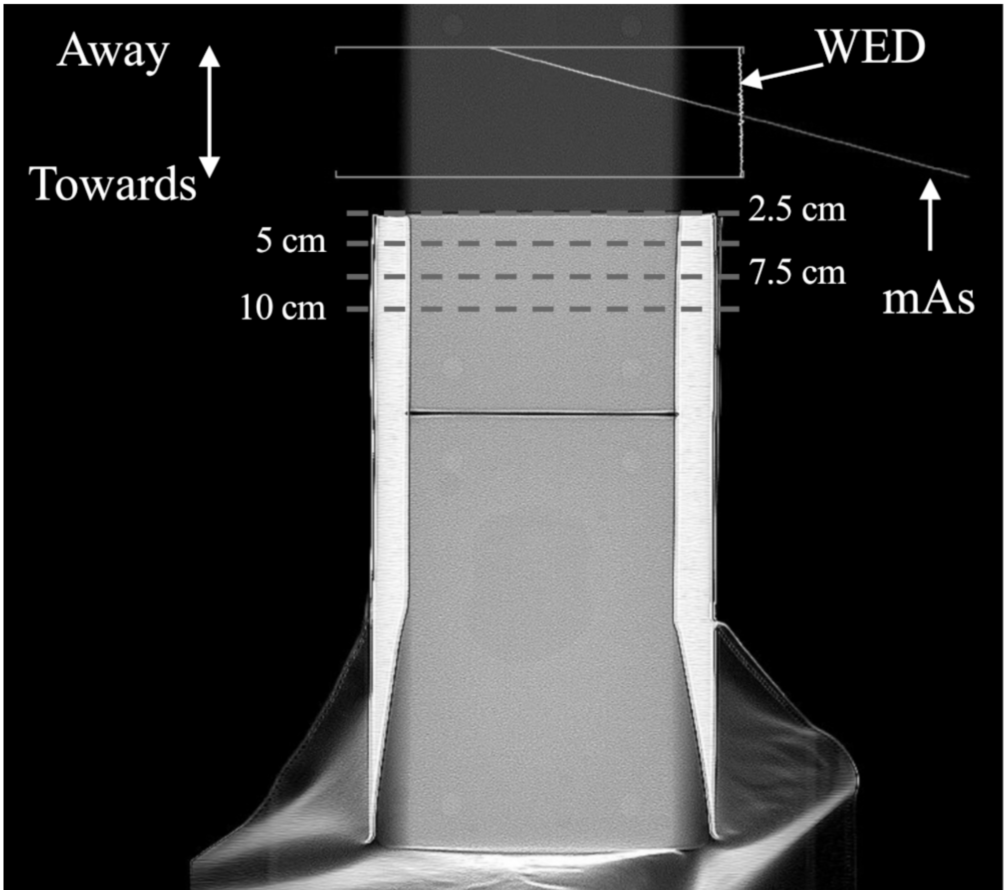
			Revolution, 40 mm collimation		Revolution, 80 mm collimation		Discovery, 40 mm collimation	
Shield position	scan direction	pitch	$CTDI_{vol}$ (% change)	DLP (% change)	$CTDI_{vol}$ (% change)	DLP (% change)	$CTDI_{vol}$ (% change)	DLP (% change)
2.5 cm	towards	0.5	1.7 (20.3)	24.2 (19.7)	2.1 (42.4)	34.4 (42.4)	3.4 (126.4)	47.3 (126.1)
	towards	1.0	1.4 (0)	18.5 (-0.1)	2.6 (65)	42.7 (64.7)	2.9 (120.3)	42.8 (119.7)
	towards	1.375	2.2 (37.7)	32.1 (37.7)	3.1 (88.4)	57.8 (87.8)	4.2 (246.7)	69.6 (245.5)
	away	0.5	1.7 (16.8)	23.5 (16.5)	2 (41.7)	34.1 (41.2)	3.5 (137.2)	49.6 (137.1)
	away	1.0	1.6 (8.4)	20.1 (8.1)	2.6 (60.6)	41.6 (60.8)	3.7 (181.2)	54.8 (181.3)
	away	1.375	2 (23.5)	28.7 (23.3)	2.9 (78)	54.6 (77.6)	4 (228.7)	66 (228.6)
5 cm	towards	0.5	1.4 (-2.1)	19.7 (-2.4)	1.7 (18.8)	28.6 (18.3)	1.5 (0)	20.9 (-0.3)
	towards	1.0	1.5 (5.6)	19.7 (5.9)	2.2 (35)	35 (34.8)	1.6 (17.3)	22.9 (17.3)
	towards	1.375	1.5 (-7.4)	21.5 (-7.7)	2.7 (62.2)	49.7 (61.6)	1.5 (23)	24.8 (23)
	away	0.5	1.4 (-2.1)	19.7 (-2.4)	1.7 (15.3)	27.8 (14.9)	1.5 (0)	20.9 (-0.3)
	away	1.0	1.5 (6.3)	19.7 (5.9)	2.2 (35.6)	35.1 (35.5)	1.4 (5.3)	20.6 (5.6)
	away	1.375	1.5 (-7.4)	21.5 (-7.5)	2.1 (26.8)	38.9 (26.5)	1.5 (22.1)	24.6 (22.3)
7.5 cm	towards	0.5	1.4 (-0.7)	19.9 (-1.3)	1.4 (0)	24.2 (0)	1.5 (0)	20.9 (-0.3)
	towards	1.0	1.4 (-1.4)	18.2 (-1.8)	1.6 (-1.9)	25.4 (-2.1)	1.3 (0)	19.5 (0)
	towards	1.375	1.6 (-2.5)	22.7 (-2.6)	1.8 (8.5)	33.3 (8.2)	1.3 (3.3)	20.8 (3.4)
	away	0.5	1.4 (-0.7)	19.9 (-1.3)	1.4 (0)	24.2 (0)	1.5 (0)	20.9 (-0.3)
	away	1.0	1.4 (-1.4)	18.3 (-1.5)	1.6 (-1.9)	25.5 (-1.5)	1.4 (3)	20(2.9)
	away	1.375	1.6 (-2.5)	22.7 (-2.3)	1.7 (3)	31.6 (2.8)	1.3 (2.5)	20.6 (2.4)
10 cm	towards	0.5	1.6 (9.8)	24.2 (19.6)	1.4 (0)	24.2 (0)	1.5 (0)	20.9 (-0.3)
	towards	1.0	1.5 (3.5)	19.2 (3.4)	1.6 (-2.5)	25.3 (-2.6)	1.3 (0)	19.5 (0)
	towards	1.375	1.6 (-2.5)	22.7 (-2.4)	1.6 (-3.7)	29.7 (-3.6)	1.3 (4.1)	20.9 (3.9)
	away	0.5	1.6 (9.8)	22.2 (9.8)	1.4 (0)	24.2 (0)	1.5 (0)	20.9 (-0.3)
	away	1.0	1.5 (4.2)	19.2 (3.4)	1.6 (-1.9)	25.4 (-2)	1.4 (2.3)	19.8 (2)
	away	1.375	1.6 (-1.9)	22.8 (-2)	1.6 (-3)	29.8 (-3.2)	1.3 (4.9)	21.1 (4.8)

$CTDI_{vol}$ = Volume Computed Tomography Dose Index, DLP = Dose Length Product



a)

Figure 1. a) Placement of lead apron on phantoms. b) Scout image illustrating the scan range, scan directions (away and towards), water-equivalent diameter (WED) of 21.9 cm, and the tube current-time products ranging from 41.5 mAs to 94.5 mAs for this particular case. The dashed lines indicate the lead apron positions (2.5, 5, 7.5 and 10 cm from the edge of the scanned region).



b)

Figure 1. a) Placement of lead apron on phantoms. b) Scout image illustrating the scan range, scan directions (away and towards), water-equivalent diameter (WED) of 21.9 cm, and the tube current-time products ranging from 41.5 mAs to 94.5 mAs for this particular case. The dashed lines indicate the lead apron positions (2.5, 5, 7.5 and 10 cm from the edge of the scanned region).

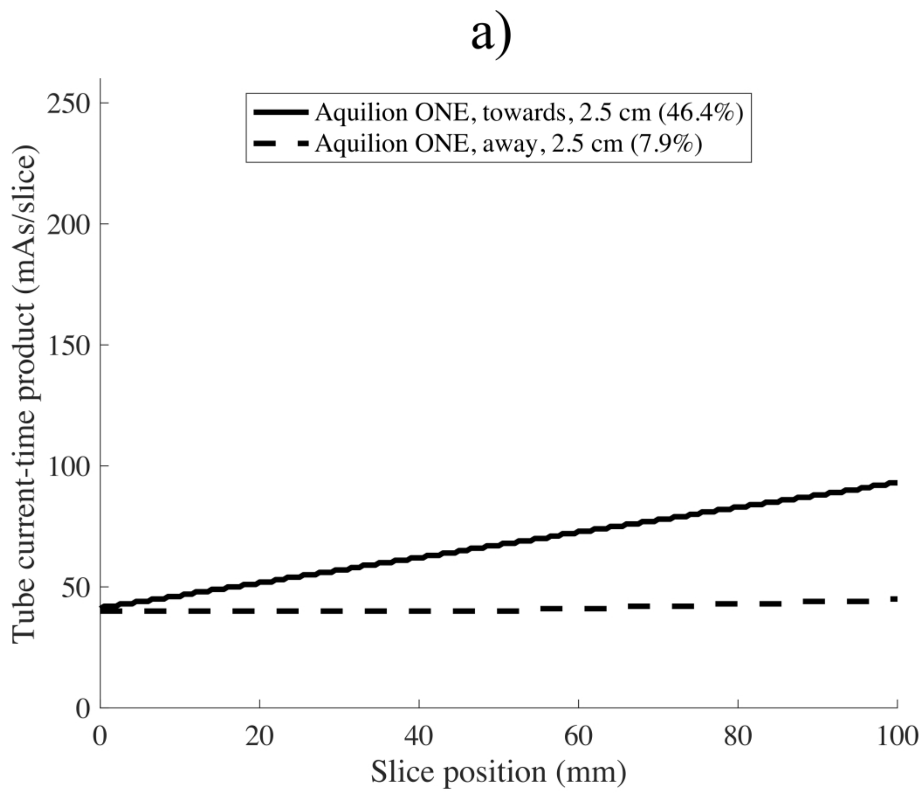


Figure 2. Tube current-time product values with lead apron at scan position 2.5 cm from Toshiba Aquilion One (a), GE Discovery (b), Siemen Flash (c, also including scan position at 5 cm) and GE Revolution (d) with 40 mm and 80 mm collimation demonstrate scanned region with the largest variation in DLP compared with the reference scans at 1.4 pitch. The legend shows the distance of the lead apron from the scanned region and the corresponding DLP change compared to the reference in brackets. The location of the lead apron is on the side of the slice location at 100 mm

1113x884mm (96 x 96 DPI)

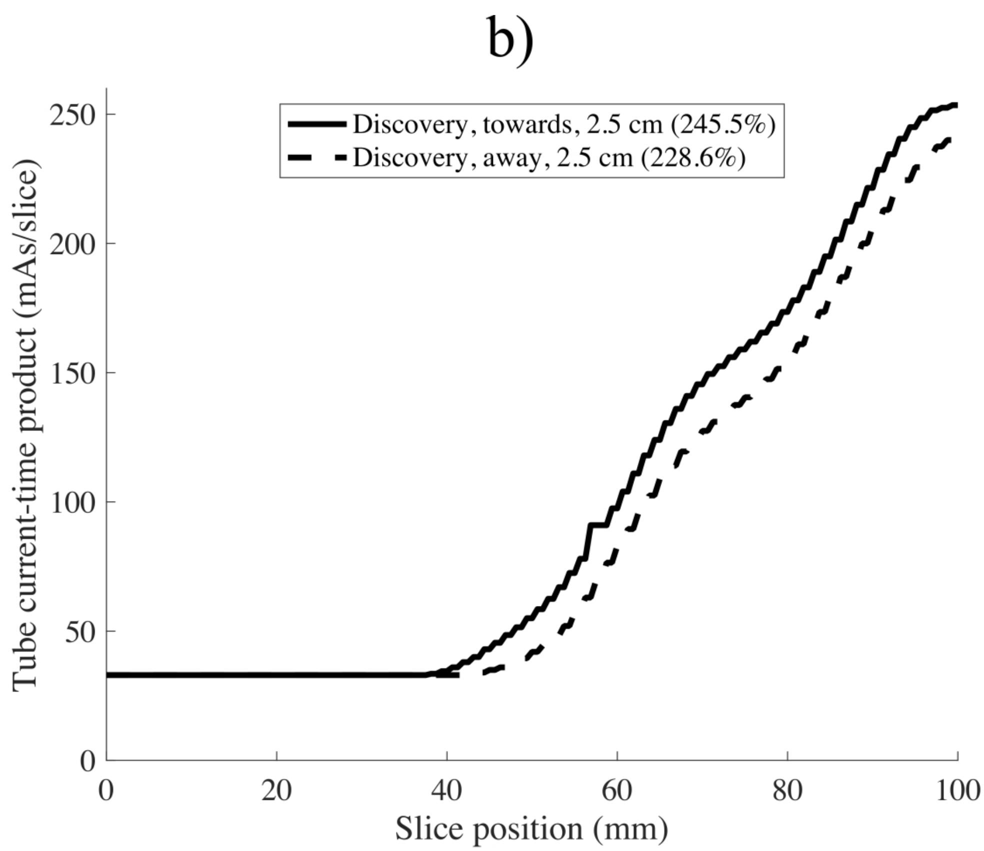


Figure 2. Tube current-time product values with lead apron at scan position 2.5 cm from Toshiba Aquilion One (a), GE Discovery (b), Siemen Flash (c, also including scan position at 5 cm) and GE Revolution (d) with 40 mm and 80 mm collimation demonstrate scanned region with the largest variation in DLP compared with the reference scans at 1.4 pitch. The legend shows the distance of the lead apron from the scanned region and the corresponding DLP change compared to the reference in brackets. The location of the lead apron is on the side of the slice location at 100 mm

1042x880mm (96 x 96 DPI)

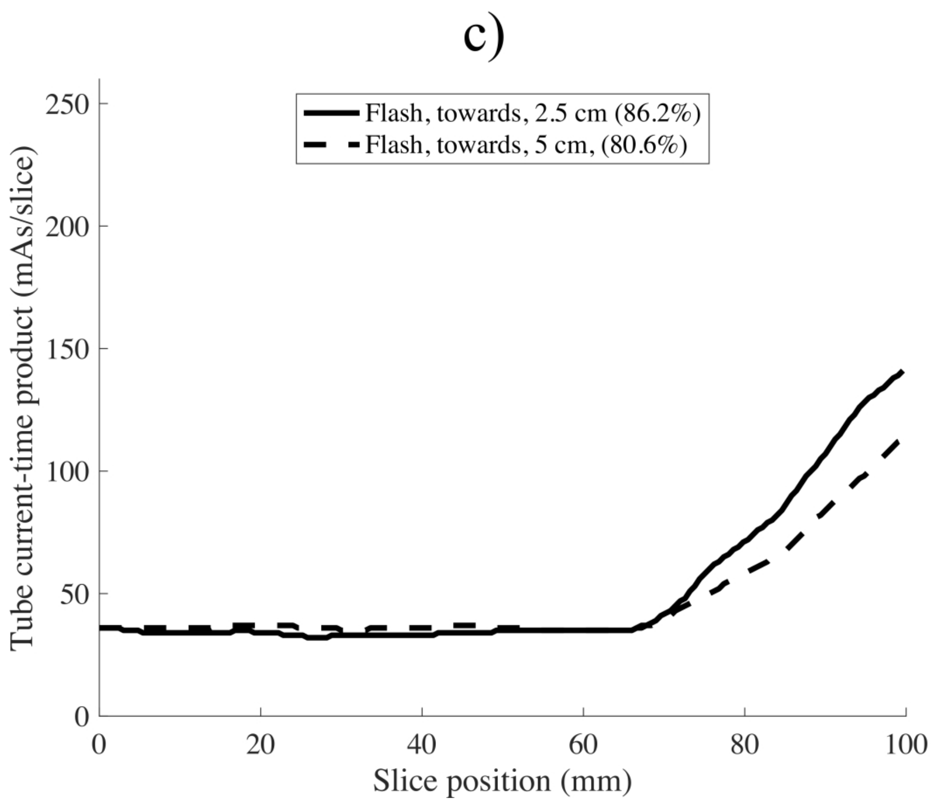


Figure 2. Tube current-time product values with lead apron at scan position 2.5 cm from Toshiba Aquilion One (a), GE Discovery (b), Siemen Flash (c, also including scan position at 5 cm) and GE Revolution (d) with 40 mm and 80 mm collimation demonstrate scanned region with the largest variation in DLP compared with the reference scans at 1.4 pitch. The legend shows the distance of the lead apron from the scanned region and the corresponding DLP change compared to the reference in brackets. The location of the lead apron is on the side of the slice location at 100 mm

1100x882mm (96 x 96 DPI)

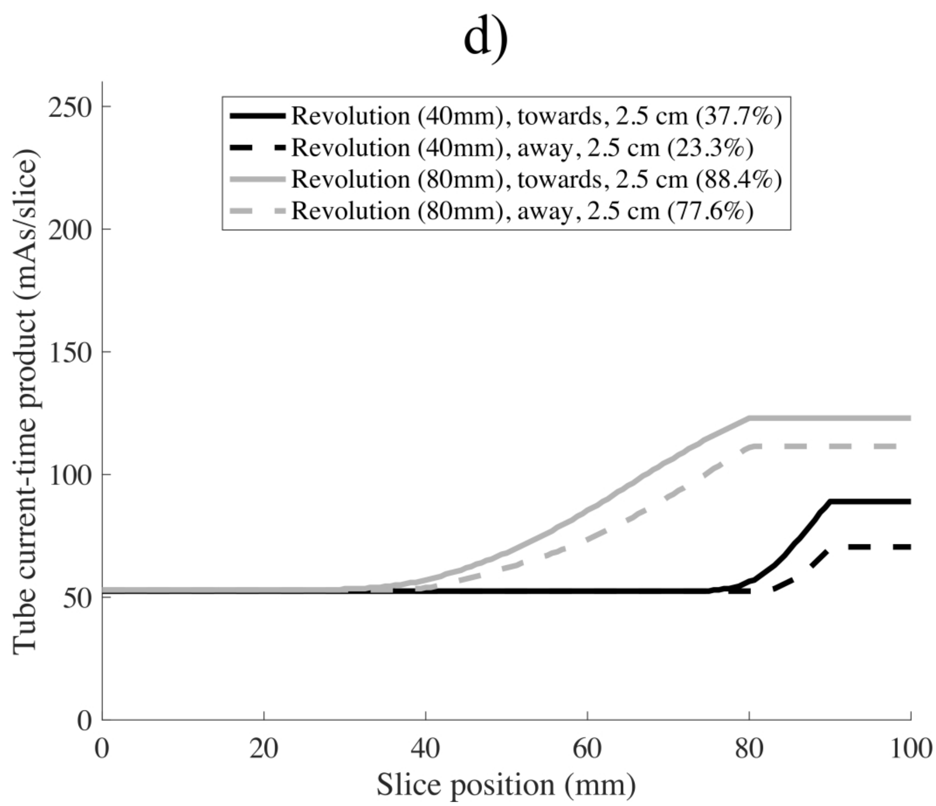


Figure 2. Tube current-time product values with lead apron at scan position 2.5 cm from Toshiba Aquilion One (a), GE Discovery (b), Siemen Flash (c, also including scan position at 5 cm) and GE Revolution (d) with 40 mm and 80 mm collimation demonstrate scanned region with the largest variation in DLP compared with the reference scans at 1.4 pitch. The legend shows the distance of the lead apron from the scanned region and the corresponding DLP change compared to the reference in brackets. The location of the lead apron is on the side of the slice location at 100 mm.

1098x890mm (96 x 96 DPI)