



Effects of convolution filter with beam hardening correction on computed tomography image quality

Jeferson Barbosa Marques^{a,*}, Simone Kodlulovich Renha^b, Hécio Mendonça Pereira^{c,d},
Thiago Viana Miranda Lima^{e,f}, Rafael Figueiredo Pohlmann Simões^a

^a Department of Medical Physics, Brazilian National Cancer Institute, Rio de Janeiro, Brazil

^b Institute of Radioprotection and Dosimetry, National Nuclear Energy Commission, Rio de Janeiro, Brazil

^c Department of Medical Imaging, Brazilian National Institute of Orthopedics and Traumatology, Rio de Janeiro, Brazil

^d Department of Medical Imaging, Brazilian National Cancer Institute, Rio de Janeiro, Brazil

^e Radiology and Nuclear Medicine, Luzerner Kantonsspital, Lucern, Switzerland

^f Department of Health Science and Medicine, University of Lucerne, Lucerne, Switzerland

ARTICLE INFO

Keywords:

Computed tomography
Image quality
Convolution filter
Phantom

ABSTRACT

Purpose: To quantify the effects of convolution filters (FC) with beam hardening correction (BHC) compared to FC without BHC on the computed tomography (CT) image quality.

Methods: This study was conducted on a Canon® Aquilion Lightning scanner. The exposure protocol includes acquisitions at 120 and 100 kVp. Sixteen FCs (8 with and 8 without BHC) were investigated using a Catphan®504 phantom. Uniformity, slice thickness, spatial resolution, Hounsfield unit and noise were analysed using the SPICE-CT ImageJ plugin and the noise power spectrum was analysed using the Imquest software.

Results: It was observed that the BHC did not significantly influence the uniformity, slice thickness, noise and noise power spectrum. Comparisons of 10% MTF between FC01 and FC11 showed relative differences of −29% and −5% at 120 and 100 kVp, respectively, while those between FC09 and FC19 were −55% and −25%. The Hounsfield unit of the Catphan's region of highest electron density was reduced by −7.29% at 120 kVp for FC with BHC. In both cases (FC with and without BHC), the noise values agreed with CT operating manual. At 120 kVp, FC11 and FC09 presented the maximum and minimum noise values, respectively.

Conclusion: In CT procedures that quantitatively evaluate the bone or calcium Hounsfield unit, FC with BHC should be avoided due to its effects on Hounsfield units, in special at higher voltage, such as 120 kVp.

1. Introduction

The use of computed tomography (CT) has increased since its introduction in the 1970 s, mainly for diagnostic purposes [1–4]. However, it should be considered that CT exposures contribute approximately 50% to the collective dose [5]. Many technical improvements have been made to optimise CT procedures, notably the iterative reconstruction (IR) and the development of protocol-specific convolution filters (FC) [6–8].

The Toshiba® Medical Systems Corporation, currently Canon® Inc., developed the Adaptive Iterative Dose Reduction 3D (AIDR3D®). Within AIDR3D®, FCs with or without beam hardening correction (BHC) are defined within the image reconstruction kernel used [9]. Therefore, choosing the more indicated FC for different clinical purposes

can be difficult.

Some studies have been conducted to evaluate the effects of the FCs on image quality. Davis et al. assessed the variation in a Toshiba CT scanner performance used for radiotherapy planning and reported that the FC selection affects the image quality metrics [10]. Andersen et al. compared several FCs to identify which one provides the best detectability of liver lesions [9]. The study conducted by Wan et al. indicated that the FC with BHC could underestimate the coronary calcium score [11]. Additionally, Ivanov et al. verified significant differences in Hounsfield units (HU) when FC with BHC was used for bone mineral density assessment [12].

However, as far as we can see, none of the studies aimed to characterise the effects of BHC on image quality. Thus, this study aims to quantify the BHC impact on the uniformity, slice thickness, spatial

* Corresponding author at: Department of Medical Physics, Brazilian National Cancer Institute, Rio de Janeiro, RJ 20230130, Brazil.

E-mail address: jeferson.marques@edu.inca.gov.br (J.B. Marques).

<https://doi.org/10.1016/j.ejmp.2023.102599>

Received 23 November 2022; Received in revised form 28 March 2023; Accepted 30 April 2023

Available online 9 May 2023

1120-1797/© 2023 Associazione Italiana di Fisica Medica e Sanitaria. Published by Elsevier Ltd. All rights reserved.

resolution, Hounsfield unit, noise and noise power spectrum in CT acquisition on the chosen FC with BHC compared to without.

2. Methodology

All images were acquired on a Canon® Aquilion Lightning CT scanner on the same day, after performing tube conditioning and air calibration. The acquisition parameters were as follows: 32 cm displayed field of view, 2 mm reconstruction slice thickness, 0.938 pitch, 0.75 s rotation time, 60 mAs, 16×1 mm total collimation and 512×512 matrix size. Exposures were taken at 120 and 100 kVp to verify how BHC influence changes with the X-ray spectrum. All images were reconstructed using AIDR3D®.

Some CT manufacturers clearly display when the chosen convolution filter has the BHC applied, but this is not true for the Canon software available in the device used in this work; this information is only available in the operation manual. There are different options for FCs with and without BHC for body, head, bone and lung acquisitions. In this study, acquisitions were made for all FCs available to the body (8 with and 8 without BHC). Fig. 1 presents the FCs under study and shows the correlation between smooth and sharp images depending on the FC selection.

According to Fig. 1, the smoothest image is obtained for FC01 (with BHC) and FC11 (without BHC). It gets sharper from FC01/11 to FC05/15 and then from FC07/17 to FC09/19. According to the operation manual, contours (delineation) are much more enhanced in FC07-09 and FC17-19 than in FC01-05 and FC11-15.

Image quality was assessed using the CTP404, CTP486 and CTP528 modules of the Catphan®504 phantom (The Phantom Laboratory, Salem, USA). The CTP404 module consists of eight electron density regions to assess Hounsfield unit and slice thickness accuracy and linearity. Table 1 shows the materials inserted in the phantom and the respective HU range provided by the manufacturer's manual. Each material's standard Hounsfield unit was defined as the midpoint of its range, except the air. The CTP486 module consists of a 150 mm diameter water equivalent region for noise and uniformity assessment, while the CTP528 module has a 0.28 mm diameter bead point source for evaluating spatial resolution through modular transfer function (MTF) measurements.

Image quality analysis was performed using the SPICE-CT ImageJ plugin version 1.8.8 that provides a Catphan® semi-automated image analysis where the user has only to select the slice and the Imquest open-source software [13–17]. The following parameters were analysed: uniformity, slice thickness, spatial resolution, Hounsfield unit, noise and noise power spectrum (NPS). Only NPS assessment was performed using the Imquest software. Uniformity was measured as the difference

Table 1

HU range for the materials inserted in the phantom and for some structures in the human body.

Material	HU range	Standard HU
Air	–1046:–986	–1000
PMP	–220:–172	–196
LDPE	–121:–87	–104
Polyethylene	–65:–29	–47
Water	–7:7	0
Acrylic	92:137	114
Delrin®	344:387	366
Teflon®	941:1060	1000
Lung	–600:–400	–
Fat	–100:–60	–
Soft Tissue	40:80	–
Bone	400:1000	–

between the HU of an ROI placed in the centre and the average HU of four ROIs placed in the periphery (top, right, bottom and left) and the noise was measured as the average standard deviation of the same five ROIs used to calculate uniformity. The slice thickness was measured for each ramp of the CTP404 module and the average value was analysed. NPS evaluation was performed in 20 consecutive slices with 4 square ROIs (64×64) each, in a total of 80 [15]. The final NPS parameter – average frequency (f_{av}) – was determined as the mean of all 80 ROIs for each protocol. Fig. 2 shows the ROI positioning on the Catphan® modules to perform each analysis. A two-tailed *t*-test was used for statistical analysis of the FCs with and without BHC ($n = 8$) and a *p*-value ≤ 0.05 was considered statistically significant.

3. Results

Uniformity measurements varied from -1.21 to 0.71 HU (average of -0.17 HU) for all FCs, being within the tolerance interval of ± 4 HU [18]. The maximum difference between the 2 mm reconstruction slice thickness and the measured value was $+0.17$ mm and the average difference was approximately $+0.08$ mm. No dependence of the BHC on uniformity (smallest $p = 0.3329$) and slice thickness (smallest $p = 0.1740$) was observed.

	With BHC	Without BHC
Smooth	FC01	FC11
	FC02	FC12
	FC03	FC13
	FC04	FC14
Sharp	FC05	FC15
Smooth	FC07	FC17
	FC08	FC18
Sharp	FC09	FC19

Fig. 1. The description of the convolution Kernels under study.

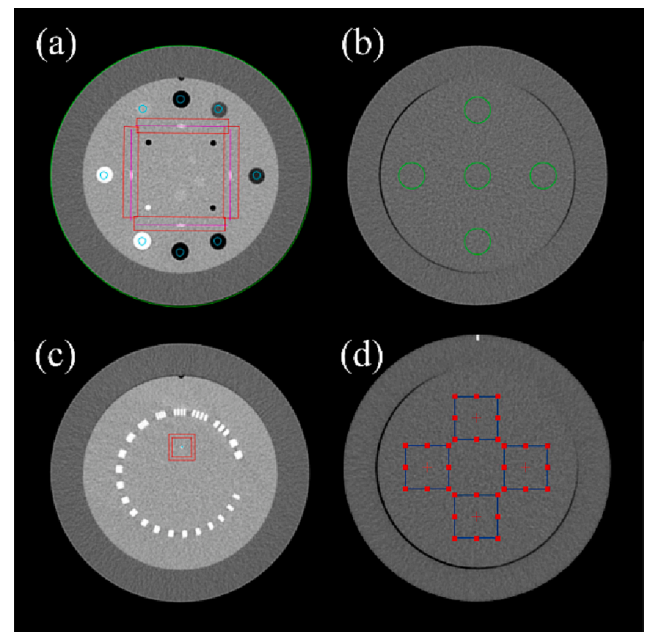


Fig. 2. ROI positioning to analyse (a) Hounsfield unit and slice thickness, (b) uniformity and noise, (c) MTF and (d) NPS.

3.1. Spatial resolution

The MTF curves only for FC01/11 and FC09/19 are shown in Fig. 3 for clarity. Large differences were observed between the MTF values for FC01/11 and FC09/19. Using the values of 10% MTF of the smoothest FC as reference values, comparisons between FC01 and FC09 showed differences of 46% and 43% at 120 and 100 kVp, respectively, while those between FC11 and FC19 were 130% and 80%. To perceive the effect of BHC influence on the MTF curves, we made direct comparisons between FC with and without BHC. Comparisons of 10% MTF between FC01 and FC11 showed relative differences of -29% and -5% at 120 and 100 kVp, respectively, while those between FC09 and FC19 were -55% and -25%. As shown in the subplots of Fig. 3c and d, although in some cases BHC increases MTF, it was observed that BHC processing generally decreases MTF values, where more negative values were observed.

3.2. Hounsfield units

Fig. 4 shows the differences in HU (Δ HU) between the measured and standard Hounsfield units obtained for the same material at 120 kVp and 100 kVp. The Hounsfield units of PMP, LDPE, polyethylene and acrylic are within the tolerance presented in the Catphan® manual. For the air, only Hounsfield units at 120 kVp with FC08 and FC18 were slightly outside the upper limit. All the Hounsfield units of Delrin® are below the lower limit. This happened for Teflon® only for FC with BHC at 120 kVp. The BHC processing did not affect the Hounsfield units of air, PMP, LDPE, polyethylene and acrylic ($p \geq 0.1441$). However, significant differences were observed for Hounsfield units of Delrin® and Teflon® due to the BHC influence on materials with high electron density – in 10^{23} e/cm^3 – ($p < 0.0002$). On average, at 120 kVp, Hounsfield units of Delrin® and Teflon® decreased from 339 HU to 316 HU ($\Delta = -23 \text{ HU}$,

-6.93%) and from 953 HU to 883 HU ($\Delta = -70 \text{ HU}$, -7.29%), respectively. At 100 kVp, its influence was more subtle as Hounsfield units of Delrin® and Teflon® decreased from 336 HU to 329 HU ($\Delta = -7 \text{ HU}$, -2.04%) and from 975 HU to 964 HU ($\Delta = -11 \text{ HU}$, -1.12%), respectively.

3.3. Spectrum influence

Fig. 5 shows the Δ HU between 120 and 100 kVp separated by the BHC processing. Although the spectrum significantly changed the Hounsfield units of all materials (p value less than 0.007) for FC with and without BHC, its influence was stronger on Teflon® than on the other materials. On average, when the tube potential decreased from 120 to 100 kVp, the Hounsfield unit of Teflon® increased from 883 HU to 964 HU ($\Delta = 81 \text{ HU}$, 9.17%) and from 953 HU to 975 HU ($\Delta = 22 \text{ HU}$, 2.31%) for FC with and without BHC, respectively.

3.4. Image noise and noise power spectrum

Fig. 6 shows quantitatively how the noise is affected by the FCs at 120 and 100 kVp. It is known that noise is not limited to stochastic quantum noise, but also includes structured noise which can originate from several factors including scatter, dark currents, nonuniform detector gain, beam hardening, shading, and other unknown sources [19–21]. The changes agree with the operation manual which provides only qualitative information (Fig. 1). Concerning FC selection, the noise increases from FC01 to FC05 and from FC07 to FC09, and these behaviours also occur for FCs without BHC. Moreover, it was not observed any influence of the BHC on the noise. On average, noise values for the same FC increased by 1.58 HU ($17.3\% \pm 0.34 \text{ HU}$ (2.2%)) as the kVp decreased, highlighting the spectrum influence on image noise, as discussed by Lira et al. [22]. From Fig. 6, the minimum and maximum

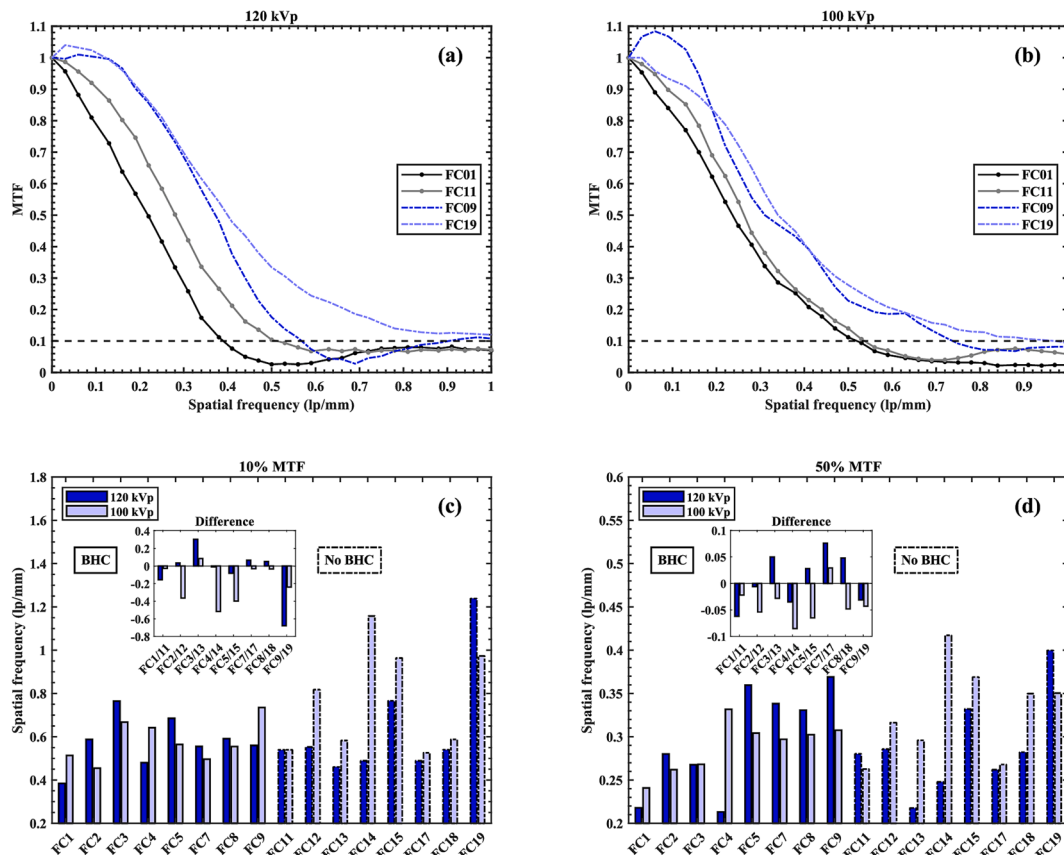


Fig. 3. Modular transfer function (MTF) curves for FC01, FC09, FC11 and FC19 obtained at (a) 120 and (b) 100 kVp and the values of (c) 10% MTF and (d) 50% MTF.

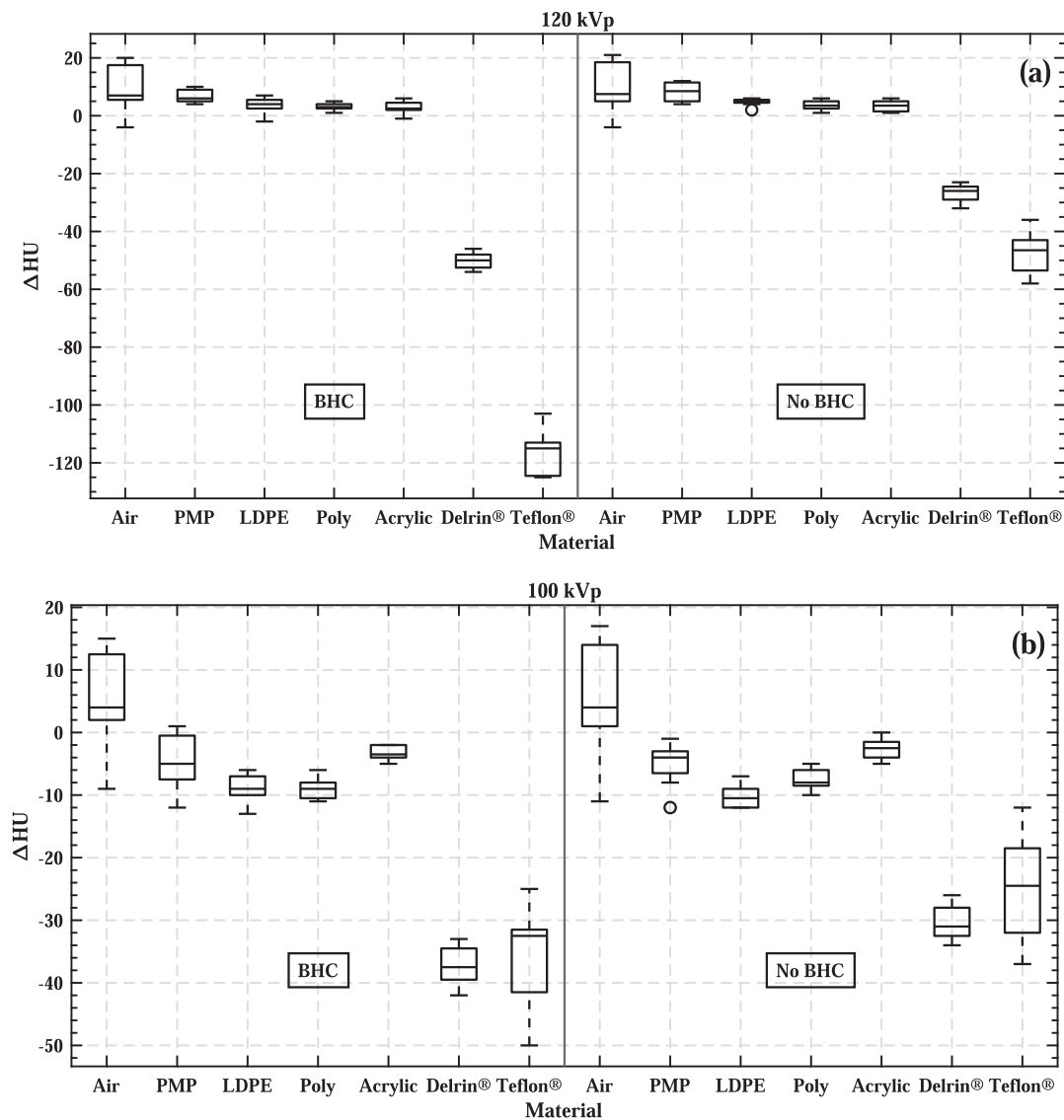


Fig. 4. ΔHU between measured and standard Hounsfield units for FC with and without BHC obtained at (a) 120 kVp and (b) 100 kVp.

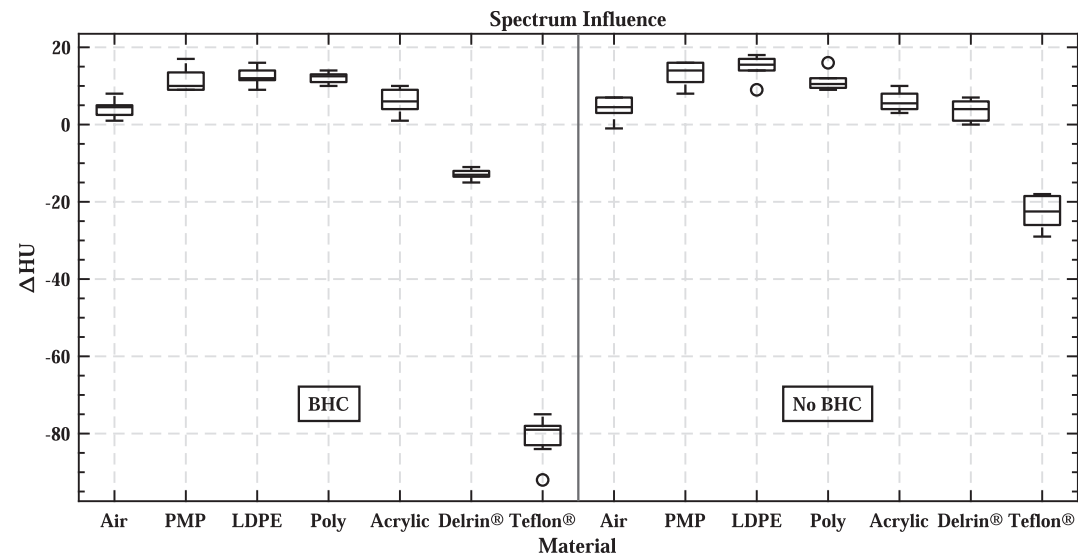


Fig. 5. ΔHU between images obtained at 120 and 100 kVp, separated by the BHC processing.

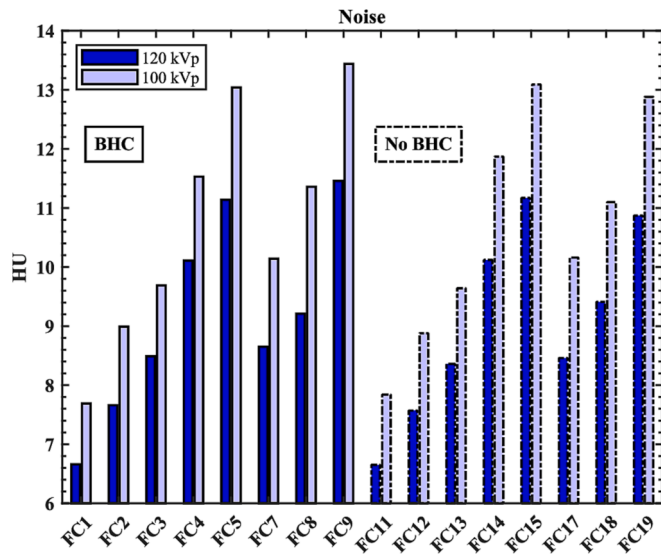


Fig. 6. Noise measurements at 120 and 100 kVp for all FCs.

increases observed were 14.0% for FC04 and 23.3% for FC08, respectively. The most significant differences were observed between FC11 and FC09 at 120 kVp and FC01 and FC09 at 100 kVp, with noise increases of 4.80 HU (72.2%) and 5.75 HU (74.8%), respectively.

The NPS curves for FC01/11, FC05/15, FC07/17 and FC09/19 are shown in Fig. 7. As well as in noise, BHC processing did not influence the NPS curves. The average frequency (f_{av}) of the NPS curves increases with the filter sharpness (Fig. 7) [20], following the same trend observed for noise in relation to FC selection. In contrast to the noise, NPS parameter was less sensitive to the spectrum energy variation. On average, the f_{av} values for the same FC decreased by $-1.23\% \pm 0.02\%$ as the kVp decreased.

4. Discussion

In this study, we assessed the effects of FC with BHC compared to FC without BHC on the image quality of a Canon® Aquilion Lightning scanner. Of the five image quality metrics analysed, no influence of BHC on uniformity, slice thickness, noise and NPS was observed. However, concerning the other parameters - spatial resolution and Hounsfield Units -, BHC changed them.

Changes in spatial resolution were observed due to the FC selection, in agreement with that of Davis et al. [10]. The increase in the values of 10% and 50% MTF between FC01/11 and FC09/19 was expected since they are the smoothest and sharpest kernel in this study, respectively.

The BHC increases the MTF values in some cases, but at 100 kV, BHC generally decreases it, while at 120 kV no clear trend was observed. It was difficult to observe a general trend, probably due to the different exposures taken for each FC and the intrinsic high variation in MTF. It would be necessary to perform more than one exposure for each FC or reconstruct the same acquisition with different FCs to observe it.

The results indicate that BHC can reduce the Hounsfield units of materials with higher electron densities, as observed by Davis et al. for FCs different from those in this work [10]. They studied FCs for the body (only five without BHC) and head (12 with and 4 without BHC). Clinical outcomes of that have been seen in applications such as CAC quantification and bone density assessments. Wan et al. reported underestimation of CAC quantification when FC02 and FC08 (both with BHC) were used compared with the standard FC12 (without BHC) and Ivanov et al. reported underestimation of bone mineral density when FC03 (with BHC) was used in contrast with FC17 (without BHC) [11,12]. If there is no clinical need for HU quantification, the BHC is a crucial tool in image quality - removing beam hardening artifacts [23,24]. However, BHC may lead to the degradation of the diagnosis that depends on the Hounsfield unit of higher electronic density materials. Many authors have evaluated the relationship between the Hounsfield unit and extracorporeal shockwave lithotripsy (ESWL) success [25–28]. The lowest limit to achieve ESWL success from these studies was 815 HU, but there is a high probability of misconception if BHC is used. Specific research should be performed for FC with BHC to estimate a more reasonable limit.

Different decreases in the CT number for FCs with and without BHC should be considered when training neural networks for diagnostic applications or radiomics. If it is trained only for FC with or without BHC, it can be led astray by this difference. Therefore, specific cases must be studied individually, considering the use of BHC.

Concerning the spectrum energy, the Teflon® Hounsfield unit increases as the tube voltage decreases, as shown in Fig. 5. This behaviour was also observed by Bucher et al. in the quantitative evaluation of beam-hardening artefact in dual-energy CT myocardial imaging, where the average HU changed from 72 to 102 HU as the tube potential decreased from 140 to 100 kVp for the kernel with BHC [29]. However, in contrast to our work, similar differences were observed between kernels with and without BHC. Nevertheless, their study was conducted on Siemens® equipment (Siemens Healthineers, Munich, Germany), therefore most likely, the mathematics of the BHC used is different from that of Canon®. Our study indicates that the BHC influence from Canon® has a dependence on the spectrum, but further studies should be conducted on it.

Comparisons between FC with BHC and its analogue without BHC at the same kVp (FC01/11, FC02/12 and so on) did not present any trend on noise analysis and showed a mean relative difference of 0.71% for noise and 0.87% for f_{av} . Although the BHC processing does not directly

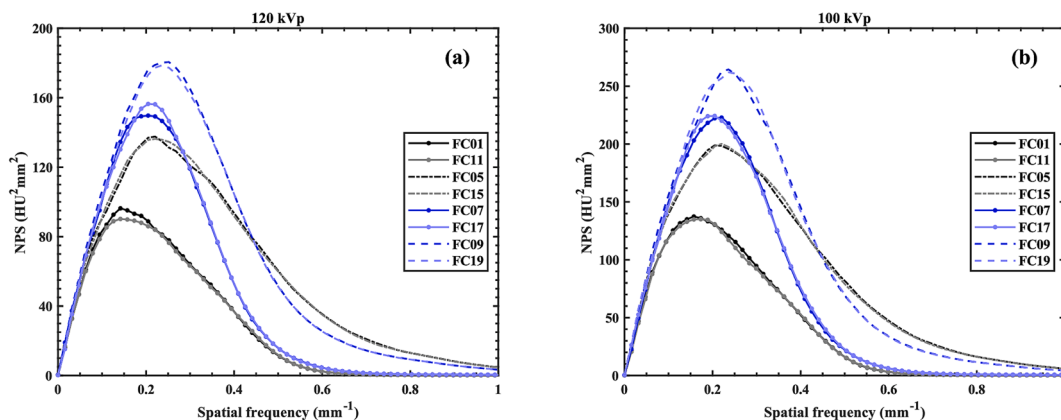


Fig. 7. Noise power spectrum (NPS) curves for FC01/11, FC05/15, FC07/17 and FC09/19 obtained at (a) 120 and (b) 100 kVp.

affect the noise, the FC selection does this and therefore, can be used in protocol optimisation, mainly for dose reduction without quality image degrading, as presented by Alshamari et al. [30]. They studied different imaging parameters, including convolution filter, to obtain a radiation dose in the CT procedure similar to that of conventional radiography for the examination of the lumbar spine on Siemens® equipment. The FC can be a helpful tool to achieve optimised protocols due to its influence on image noise.

Several studies have evaluated how the convolution kernels or convolution filters can influence the radiotherapy dose calculation when considering radiation treatment planning [31–35]. Davis et al. reported that when HU change was within ± 20 HU for soft tissue and ± 50 HU for bone and air, the change in the planning target volume (PTV) and organs at risk (OAR) doses was below 1% [33]. Our results showed larger differences due to the BHC (-70 HU for Teflon® at 120 kVp), considering that the HU for bone varies from 400 to 1000 (Table 1). We believe that the BHC alone would not be able to change the PTV and OAR doses by more than 1%. Vergalasova et al. [31] did not report significant differences for HU-ED calibration curves but observed large differences in monitor units and isodose volumes were found for higher energy electrons between multiple convolution kernels from Siemens® equipment (Siemens Healthineers, Munich, Germany). Therefore, we recommend studying the effects of FC with BHC before its use in CT simulation scanning, especially in scanners that do not have specific studies.

5. Conclusion

The BHC did not affect the uniformity, slice thickness, noise and NPS. However, it affected the spatial resolution and the Hounsfield unit of materials with higher electron density (in 10^{23} e/cm³) as Teflon®. Although the noise is BHC independent (mean relative difference of 0.71% in analogue FCs), the maximum noise increases at 120 kVp were observed between FC11 and FC09, while at 100 kVp were observed between FC01 and FC09, with values equal to 72.1% and 74.8%, respectively. Large differences were observed for Delrin® and Teflon® regarding the Hounsfield unit at 120 kVp due to BHC processing. Although the BHC is a crucial tool in image quality, these differences can potentially cause misdiagnoses for clinical purposes that directly evaluate the Hounsfield unit of materials with higher electron density. At 100 kV, BHC generally decreases the 10% and 50% MTF, while at 120 kV no clear trend was observed. Finally, using FC with BHC for routine examinations should be avoided when no knowledge of its influence on clinical outcomes is available.

Declarations

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Liguori C, Frauenfelder G, Massaroni C, Saccomandi P, Giurazza F, Pitocco F, et al. Emerging clinical applications of computed tomography. *Med Dev* 2015;8:265–78. <https://doi.org/10.2147/MDER.S70630>.
- [2] Das A, Acharya UR, Panda SS, Sabut S. Deep learning based liver cancer detection using watershed transform and Gaussian mixture model techniques. *Cogn Syst Res* 2019;54:165–75. <https://doi.org/10.1016/j.cogsys.2018.12.009>.
- [3] Hoshino N, Sakamoto T, Hida K, Sakai Y. Diagnostic accuracy of computed tomography colonography for tumor depth in colorectal cancer: A systematic review and meta-analysis. *Surg Oncol* 2019;30:126–30. <https://doi.org/10.1016/j.suronc.2019.08.003>.
- [4] Gierada DS, Black WC, Chiles C, Pinsky PF, Yankelevitz DF. Low-dose ct screening for lung cancer: Evidence from 2 decades of study. *Radiol Imaging. Cancer* 2020;2(2):e190058. <https://doi.org/10.1148/rycan.2020190058>.
- [5] Schauer DA, Linton OW. NCRP Report no. 160, Ionizing radiation exposure of the population of the united states, medical exposure — Are we doing less with more, and is there a role for health physicists? *Health Phys* 2009;97:1–5. <https://doi.org/10.1097/01.hp.0000356672.44380.b7>.
- [6] Kalender WA, Seissler W, Klotz E, Vock P. Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation. *Radiology* 1990;176:181–3. <https://doi.org/10.1148/radiology.176.1.2353088>.
- [7] Hsieh J, Flohr T. Computed tomography recent history and future perspectives. *J Med Imaging* 2021;8:1–24. <https://doi.org/10.1117/1.jmi.8.5.052109>.
- [8] Moro L, Calderoni F, Eshja E, Poggi P. CT kernel for calcium quantification with arbitrary tube voltage: a phantom evaluation based on radiomic features. *Phys Med* 2021;92:S222. [https://doi.org/10.1016/S1120-1797\(22\)00478-1](https://doi.org/10.1016/S1120-1797(22)00478-1).
- [9] Andersen HK, Jensen K, Berstad AE, Aaløkken TM, Kristiansen J, von Gohren Edwin B, et al. Choosing the best reconstruction technique in abdominal computed tomography: A systematic approach. *J Comput Assist Tomogr* 2014;38(6):853–8. <https://doi.org/10.1097/RCT.0000000000000139>.
- [10] Davis AT, Palmer AL, Pani S, Nisbet A. Assessment of the variation in CT scanner performance (image quality and Hounsfield units) with scan parameters, for image optimisation in radiotherapy treatment planning. *Phys Med* 2018;45:59–64. <https://doi.org/10.1016/j.ejmp.2017.11.036>.
- [11] Wan Y-L, Tsay P-K, Wu PW, Juan Y-H, Tsai H-Y, Lin C-Y, et al. Impact of filter convolution and displayed field of view on estimation of coronary Agatston scores in low-dose lung computed tomography. *Int J Cardiol* 2017;236:451–7. <https://doi.org/10.1016/j.ijcard.2017.02.124>.
- [12] Ivanov DV, Kirillova IV, Kossovich LY, Bessonov LV, Petraikin AV, Dol AV, et al. Influence of convolution kernel and beam-hardening effect on the assessment of trabecular bone mineral density using quantitative computed tomography. *Izv Saratov Univ Math Mech Inform* 2020;20(2):205–19. <https://doi.org/10.18500/1816-9791-2020-20-2-205-219>.
- [13] Loveland J. SPICE-CT Package for Computed Tomography QC 2011.
- [14] Gawel J, Kındón J. Assessment of the CT image quality parameters on the edges of the field of view. *Phys Med* 2018;52:113–4. <https://doi.org/10.1016/j.ejmp.2018.06.374>.
- [15] Lubis LE, Basith RA, Hariyati I, Ryangga D, Mart T, Bosmans H, et al. Novel phantom for performance evaluation of contrast-enhanced 3D rotational angiography. *Phys Med* 2021;90:91–8. <https://doi.org/10.1016/j.ejmp.2021.09.002>.
- [16] Papadakis AE, Damilakis J. Technical Note: Quality assessment of virtual monochromatic spectral images on a dual energy CT scanner. *Phys Med* 2021;82:114–21. <https://doi.org/10.1016/j.ejmp.2021.01.079>.
- [17] Solomon J, Zhang Y, Wilson JSE. An automated software tool for task-based image quality assessment and matching in clinical CT using the TG-233 Framework. *Med Phys* 2018;45:E134.
- [18] Gulliksrud K, Stokke C, Trægde Martinsen AC. How to measure CT image quality: Variations in CT-numbers, uniformity and low contrast resolution for a CT quality assurance phantom. *Phys Med* 2014;30:521–6. <https://doi.org/10.1016/j.ejmp.2014.01.006>.
- [19] Wagner RF, Brown DG, Pastel MS. Application of information theory to the assessment of computed tomography. *Med Phys* 1979;6:83–94. <https://doi.org/10.1118/1.594559>.
- [20] Boedeker KL, Cooper VN, McNitt-Gray MF. Application of the noise power spectrum in modern diagnostic MDCT: Part I. Measurement of noise power spectra and noise equivalent quanta. *Phys Med Biol* 2007;52:4027–46. <https://doi.org/10.1088/0031-9155/52/14/002>.
- [21] Won Kim C, Kim JH. Realistic simulation of reduced-dose CT with noise modeling and sinogram synthesis using DICOM CT images. *Med Phys* 2014;41(1):011901. <https://doi.org/10.1118/1.4830431>.
- [22] Lira D, Padole A, Kalra MK, Singh S. Tube potential and CT radiation dose optimization. *AJR Am J Roentgenol* 2015;204:W4–. <https://doi.org/10.2214/AJR.14.13281>.
- [23] Kyriakou Y, Meyer E, Prell D, Kachelrieß M. Empirical beam hardening correction (EBHC) for CT. *Med Phys* 2010;37:5179–87. <https://doi.org/10.1118/1.3477088>.
- [24] Rüeggsegger P, Hangartner Th, Keller HU, Hinderling Th. Standardization of computed tomography images by means of a material-selective beam hardening correction. *J Comput Assist Tomogr* 1978;2:184–8. <https://doi.org/10.1097/00004728-197804000-00012>.
- [25] Il PY, Yu JH, Sung LH, Noh CH, Chung JY. Evaluation of possible predictive variables for the outcome of shock wave lithotripsy of renal stones. *Korean J Urol* 2010;51:713–8. <https://doi.org/10.4111/kju.2010.51.10.713>.
- [26] Ouzaid I, Al-qahatani S, Dominique S, Hupertan V, Fernandez P, Hermieu J-F, et al. A 970 Hounsfield units (HU) threshold of kidney stone density on non-contrast computed tomography (NCCT) improves patients' selection for extracorporeal shockwave lithotripsy (ESWL): Evidence from a prospective study. *BJU Int* 2012;110(11b):E438–42. <https://doi.org/10.1111/j.1464-410X.2012.10964.x>.
- [27] Nakasato T, Morita J, Ogawa Y. Evaluation of Hounsfield Units as a predictive factor for the outcome of extracorporeal shock wave lithotripsy and stone composition. *Urolithiasis* 2015;43:69–75. <https://doi.org/10.1007/s00240-014-0712-x>.
- [28] Oktay C, Coraplı M, Tutus A. The usefulness of the Hounsfield unit and stone heterogeneity variation in predicting the shockwave lithotripsy outcome. *Diagn Interv Radiol* 2022;28(3):187–92. <https://doi.org/10.5152/dir.2022.20945>.
- [29] Bucher AM, Wichmann JL, Schoepf UJ, Wolla CD, Canstein C, McQuiston AD, et al. Quantitative evaluation of beam-hardening artefact correction in dual-energy CT

- myocardial perfusion imaging. *Eur Radiol* 2016;26(9):3215–22. <https://doi.org/10.1007/s00330-015-4137-x>.
- [30] Alshamari M, Geijer M, Norrman E, Geijer H. Low-dose computed tomography of the lumbar spine: A phantom study on imaging parameters and image quality. *Acta Radiol* 2014;55:824–32. <https://doi.org/10.1177/0284185113509615>.
- [31] Vergalasova I, McKenna M, Yue NJ, Reyhan M. Impact of computed tomography (CT) reconstruction kernels on radiotherapy dose calculation. *J Appl Clin Med Phys* 2020;21:178–86. <https://doi.org/10.1002/acm2.12994>.
- [32] Davis AT, Palmer AL, Nisbet A. Can CT scan protocols used for radiotherapy treatment planning be adjusted to optimize image quality and patient dose? A systematic review. *Br J of Radiol* 2017;90:20160406. <https://doi.org/10.1259/bjr.20160406>.
- [33] Davis AT, Muscat S, Palmer AL, Buckle D, Earley J, Williams MGJ, et al. Radiation dosimetry changes in radiotherapy treatment plans for adult patients arising from the selection of the CT image reconstruction kernel. *BJR|Open* 2019;1(1): 20190023. <https://doi.org/10.1259/bjro.20190023>.
- [34] Zurl B, Tiefling R, Winkler P, Kindl P, Kapp KS. Hounsfield units variations: Impact on CT-density based conversion tables and their effects on dose distribution. *Schwankungen der Hounsfield-Einheiten: Auswirkung von CT-dichtebasierten Konversionstabellen und ihr Einfluss auf Dosisverteilungen. Strahlenther Onkol* 2014;190(1):88–93. <https://doi.org/10.1007/s00066-013-0464-5>.
- [35] Nhila O, Talbi M, El Mansouri M, El Katib M, Chakir EM. Evaluation of CT acquisition protocols effect on hounsfield units and optimization of CT-RED calibration curve selection in radiotherapy treatment planning systems. *Mosc Univ Phys Bull* 2022;77:661–71. <https://doi.org/10.3103/S0027134922040105>.