

Title	Determination of a suitable low-dose abdominopelvic CT protocol using model-based iterative reconstruction through cadaveric study.
Authors	Moloney, Fiachra;Twomey, Maria;Fama, Daniel;Balta, Joy Y.;James, Karl;Kavanagh, Richard G.;Moore, Niamh;Murphy, Mary J.;O'Mahony, Siobhan M.;Maher, Michael M.;Cryan, John F.;O'Connor, Owen J.
Publication date	2018-04-15
Original Citation	Moloney, F., Twomey, M., Fama, D., Balta, J. Y., James, K., Kavanagh, R. G., Moore, N., Murphy, M. J., O'Mahony, S. M., Maher, M. M., Cryan, J. F. and O'Connor, O. J. 'Determination of a suitable low-dose abdominopelvic CT protocol using model-based iterative reconstruction through cadaveric study', Journal of Medical Imaging and Radiation Oncology, In Press. doi: 10.1111/1754-9485.12733
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://onlinelibrary.wiley.com/doi/abs/10.1111/1754-9485.12733 - 10.1111/1754-9485.12733
Rights	© 2018 The Royal Australian and New Zealand College of Radiologists. This is the peer reviewed version of the following article: Moloney, F. et al (2018), Determination of a suitable low#dose abdominopelvic CT protocol using model#based iterative reconstruction through cadaveric study. J Med Imaging Radiat Oncol., which has been published in final form at https://doi.org/10.1111/1754-9485.12733 . This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.
Download date	2026-08-24 16:05:59
Item downloaded from	https://hdl.handle.net/10468/6616



University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

**Determination of a suitable low dose abdominopelvic CT protocol using model
based iterative reconstruction through cadaveric study**

25 Abstract

26 *Objective*

27 Cadaveric studies provide a means of safely assessing new technologies and optimising
28 scanning prior to clinical validation~~use~~. Reducing radiation exposure in a clinical setting
29 ~~usually requires~~can entail ~~small~~ incremental dose reductions to avoid missing important
30 clinical findings. The use of cadavers allows assessment of the impact of more
31 substantial dose reductions on image quality. Our aim was to identify a suitable low
32 dose abdominopelvic CT protocol for subsequent clinical ~~use~~validation.

34 *Methods*

35 Five human cadavers were scanned at one conventional dose and three low dose
36 settings. All scans were reconstructed using three different reconstruction algorithms:
37 filtered back projection (FBP), hybrid iterative reconstruction (60% FBP and 40%
38 adaptive statistical iterative reconstruction (ASIR40)), and model-based iterative
39 reconstruction (MBIR). Two readers rated the image quality both quantitatively and
40 qualitatively.

42 *Results*

43 MBIR reconstructions had significantly better objective image noise and higher
44 qualitative scores compared with both FBP and ASIR40 reconstructions at all dose
45 levels. The greatest absolute noise reduction, between MBIR and FBP, of 34.3 HU
46 (equating to a 68.1% reduction) was at the lowest dose level. MBIR reduced image
47 noise and improved image quality even in CT images acquired with a mean radiation
48 dose reduction of 62.2% compared with conventional dose studies reconstructed with

ASIR40, with lower levels of objective image noise, superior diagnostic acceptability and contrast resolution, and comparable subjective image noise and streak artifact scores.

Conclusion

This cadaveric study demonstrates that MBIR reduces image noise and improves image quality in abdominopelvic CT images acquired with dose reductions of up to 62%.

Keywords

Abdominopelvic; Tomography, X-ray Computed; Cadaver; Iterative reconstruction; Radiation exposure

Introduction

There has been an exponential increase in the use of computed tomography (CT) in recent years with CT currently imparting more than 50% of all radiation exposure from diagnostic imaging¹. The relationship of radiation exposure from diagnostic imaging to a quantifiable risk of cancer induction remains a controversial topic. However, protracted exposure to low-level ionising radiation is widely believed to be associated with an increased risk of malignancy²⁻⁴ and dose optimisation without loss of diagnostic performance is essential to good practice when performing CT. Abdominopelvic CT accounts for 50% of total CT collective dose⁵ in many patient cohorts, and dose reduction strategies in this area will therefore have a significant impact on the overall population dose from diagnostic imaging.

Potential dose reduction techniques that may be employed when performing abdominopelvic CT include automatic exposure control⁶, low tube voltage techniques⁷, scan range control⁸, and adaptive collimation⁹. ~~Some of these~~ Some of these strategies are limited by a resultant increase in image noise and ~~resulting~~ reduced image quality especially with traditional analytical reconstruction algorithms such as filtered back projection (FBP). Advanced iterative reconstruction (IR) algorithms that reduce image noise facilitating the generation of diagnostic quality images at reduced radiation doses have received much attention in the literature recently¹⁰⁻¹². IR techniques create a set of synthesized projections by accurately modelling the data collection process in CT. The model incorporates statistical information of the CT system including photon statistics and electronic acquisition noise to reduce image noise¹³.

Hybrid iterative reconstruction techniques such as adaptive statistical iterative reconstruction (ASIR) (GE Healthcare, GE Medical Systems, Milwaukee, USA) is one

such method that may be blended with FBP to reduce noise while preserving image quality and the familiar appearance of traditional FBP-reconstructed images. ASIR is ~~the most-a commonly~~ studied iterative algorithm in abdominopelvic CT ~~to-date~~ with studies reporting dose reductions ~~in the order of from~~ 25% to 74% with preserved image quality and diagnostic value¹⁴⁻¹⁷.

~~More +~~Recently, more computationally intense pure IR algorithms such as model-based iterative reconstruction (MBIR) (Veo) (GE Healthcare, GE Medical Systems, Milwaukee, USA) have become commercially available. In addition to incorporating modelling of photon and noise statistics, pure IR algorithms such as MBIR use a more complex system of prediction models including modelling of optic factors such as tube and detector response, and the exact geometric features of the focal spot, CT cone beam and absorbing voxels¹⁸. It is ~~necessary~~ preferable, however, to evaluate the diagnostic quality of images reconstructed with MBIR before availing of the potential dose reductions it is purported to provide. These data would also be informative for the development of low dose scanning protocols in the clinical setting, which would likely assist in the granting of ethical approval. ~~introduction of the technique into widespread clinical practice.~~

Several strategies may be used to compare the efficacy of reconstruction techniques in noise reduction including technical and anthropomorphic phantoms^{19, 20} the split-dose technique or the artificial addition of image noise to conventional dose images to simulate low dose images²¹. Technical and anthropomorphic phantoms provide a safe, objective and reproducible method of assessing the image quality of different reconstruction algorithms over a range of radiation dose levels. Preliminary phantom

experiments with MBIR report a significant reduction in image noise and streak artifact, with significant improvements in image quality compared to FBP and ASIR^{22, 23}.

Many phantom models do not accurately reflect the complex relationship that exists

Commented [OO1]: reference

between anatomical variability and image quality, and results of phantom studies may not be entirely applicable to the clinical setting. However, patient studies to assess the performance of reconstruction algorithms at different dose levels can often be

problematic to implement, as imaging large numbers of patients at different dose settings introduces confounding factors in addition to ethical challenges. To date,

clinical studies assessing the use of MBIR in abdominopelvic CT are limited^{22, 24}.

The use of radiological images acquired from cadavers for research²³, teaching²⁵, and training²⁶ purposes has been well described in the literature. Cadavers also provide an

excellent model with which to compare reconstruction algorithms by facilitating the

repeated scanning of one subject over a range of radiation dose settings without

movement artefact or dose concerns. This method has been used in thoracic CT imaging

to demonstrate maintenance of acceptable image quality despite 82% dose reduction

using MBIR²⁷. To the best of our knowledge, this is the first study to assess the image

quality of cadaveric abdominopelvic CT scans reconstructed with MBIR.

The aim of this study was to use cadaveric imaging to determine ~~the dose range at~~

~~which MBIR~~ if MBIR improved image quality compared with ASIR and FBP, to

quantify the extent of this improvement and to assess if there was a benefit to MBIR

over conventional methods for low dose image reconstruction. ~~had the greatest efficacy~~

~~for noise reduction while maintaining acceptable image quality. These data will provide~~

~~essential information that will help guide the~~ development of safe protocols which are

~~more likely to be granted ethical approval for validation trials performance of reduced dose CT using MBIR.~~

Methods

Subjects

The study was conducted under the auspices of a 'License to Practice Anatomy' granted to the Chair of the Department of Anatomy and Neuroscience of our institution under the Anatomy Act 1832. Donors premorbidly signed written consent for the use of their bodies for the purposes of education and research. Five human cadavers (4 male, 1 female) were included in the study. The median time from death to CT scanning was 38 days (range, 8 to 180). The cadavers were fresh frozen at -4°C and thawed for the purpose of the study as per standard practice. Cadaver body-mass index (BMI) was not measured directly but was estimated from effective diameter measurements taken from the CT images and the regression equation in the Boos et al 2016 study²⁸; mean cadaver BMI was estimated to be 30kg/m².

CT technique

All subjects were scanned with a 64-slice GE Discovery 750HD CT scanner (General Electric Healthcare, Waukesha, WI, USA). Each cadaver was scanned without intravenous or oral contrast in the supine position enclosed in a body bag without any metallic fasteners. Scans were performed with the arms by the side to minimise cadaver manipulation due to the affects of rigor mortis.

The protocol was employed with varying tube voltage (kV) and current (mA) settings of 80kV/225mA, 120kV/100mA, 100kV/225mA, and 120kV/200mA; the resultant CTDI_{vol}, resulting in mean, mean dose length products (DLP) and mean size specific dose estimates (SSDE) of $238.7 \pm 12.41 \text{ mGy.cm}$, $5.364 \pm 0.62 \text{ mGy}$, $315.56 \pm 16.4 \text{ mGy.cm}$, $7.091 \pm 0.82 \text{ mGy}$, $447.2 \pm 23.35 \text{ mGy.cm}$, $10.04 \pm 1.162 \text{ mGy}$ and $630.91 \pm 332.7 \text{ mGy.cm}$, $14.172 \pm 1.64 \text{ mGy}$ respectively. can be seen in Table 1. The radiation exposure resultant from the CT localizer radiographs was excluded from the dose calculations.

The 120kV/200mA protocol was used as a reference conventional dose (CD) protocol following a review of the radiation dose of 100 standard abdominopelvic CT studies performed at our institution (mean DLP of $640.4 \pm 272.83 \text{ mGy.cm}$). The 80kV/225mA, 120kV/100mA, and 100kV/225mA low dose protocols were given the names low dose 1 (LD1), low dose 2 (LD2), and low dose 3 (LD3), respectively. The gantry rotation time (0.8 seconds), collimation (40 x 0.62mm), pitch factor (0.98), and slice thickness (0.625 mm) were kept constant for all acquisitions.

CT image reconstruction

All images were reconstructed from the raw-data acquisitions. Each cadaver was scanned at four different dose levels as detailed above and each of these data sets was reconstructed using three different reconstruction techniques: filtered back projection; our standard departmental reconstruction technique, hybrid iterative reconstruction (60% FBP and 40% ASIR), labelled ASIR40; and pure iterative reconstruction (MBIR),

resulting in a total of 12 series per cadaver. Images were reconstructed from an acquisition thickness of 0.625mm to a final slice thickness of 1.25mm for all series.

Quantitative analysis of image noise

Objective image quality analysis was performed independently on a dedicated workstation (Advantage Workstation VolumeShare 2, Version 4.4, GE Medical Systems, Milwaukee, WI) by two operators (FM, 5 years experience and DF, 1 year experience). Attenuation values in Hounsfield units (HU) were measured at five levels using circular regions of interest (ROIs) ~~histograms~~ of equal size (diameter 10mm). The ~~regions of interest (ROIs)~~ were placed in the following anatomical structures: most superior portion of liver parenchyma just inferior to liver parenchyma at the level of the right hemi-diaphragm; liver parenchyma at the level of the porta hepatis; erector spinae at the right renal hilum; psoas muscle at the iliac crest; and gluteus maximus muscle at the roof of the acetabulum. The ROIs were placed in as homogenous an area as possible, taking care to avoid fat planes and blood vessels. The standard deviation of the mean attenuation in the ROI served as an objective measure of image noise²⁹. The signal-to-noise ratio (SNR) of each ROI was calculated by dividing the mean HU by its standard deviation³⁰. Each operator took measurements independently and the mean measurement was used for analysis. The operators were blinded to the scanning protocol and reconstruction technique used and the order of the series was randomized.

Qualitative analysis

214 Subjective image quality assessment was performed independently on the Advantage
215 Workstation by two readers (FM, 5 years experience and MT, 6 years experience).
216 Subjective image noise, diagnostic acceptability, and contrast resolution were graded on
217 a 10-point scale at 5 anatomical levels: right hemi-diaphragm, porta hepatis, right renal
218 hilum, iliac crest, and roof of the acetabulum. Image noise was graded as acceptable
219 (score of 5) if average graininess was seen with satisfactory depiction of small
220 anatomical structures such as blood vessels and tissue interfaces, unacceptable (score of
221 1) if graininess interfered with structure depiction, and excellent (score of 10) if there
222 was no appreciable mottle. Diagnostic acceptability was graded as acceptable (score of
223 5), unacceptable (score of 1), or excellent (score of 10) if depiction of solid organs,
224 large bowel, small bowel, peri-colonic fat, and peri-enteric fat for diagnostic
225 interpretation and degree of image degradation by beam hardening artifacts was
226 satisfactory, unsatisfactory or considerably superior, respectively. Contrast resolution
227 was also graded at the liver, spleen and buttock musculature using a 10-point scale in
228 which a score of 10 represented superior contrast between different abdominal soft
229 tissues, a score of 1 indicated the poorest contrast, and a score of 5 indicated acceptable
230 contrast. Streak artifact was also graded at each level using a 3-point scale: 0, no streak
231 artifact present; 1, streak artifact present but not interfering with image interpretation;
232 and 2, streak artifact present and interfering with image interpretation.

233 The parameters of image quality were selected on the basis of previous studies and the
234 *European Guidelines on Quality criteria for Computed Tomography*^{31, 32}. The authors
235 had used these methods previously and trained the other readers before analysis with a
236 set of 5 practice scans³³. The order of the data sets was randomized and the readers were
237 blinded to the scanning protocol and reconstruction technique. The readers used a

combination of axial and coronal reformats for interpretation and altered the CT level and window width at their discretion.

Statistical analysis

Data was exported from Microsoft Office Excel 2010 (Microsoft Corporation, CA, USA) into GraphPad Prism version 6.0 (GraphPad Software Incorporated, San Diego, USA) and Statistical Package for the Social Sciences (SPSS) version 22 (IBM, Chicago, Illinois, USA) for further analysis. Distribution of variables was assessed using D'Agostino-Pearson omnibus normality test. Inter-observer concordance was assessed with Cohen's κ test.

Two-way analysis of variance was used to compare three or more groups of parametric indices. Tukey's multiple comparisons test was used to assess differences between reconstruction techniques at each dose level for quantitative and qualitative parameters. Mean differences between reconstruction algorithms and their 95% confidence intervals were calculated at each dose level. Percentage noise and dose reduction compared with FBP and ASIR40 was determined for the MBIR data sets. Dunnett's test was used to compare the quantitative and qualitative parameters of the low dose MBIR series with CD ASIR40 series. P values less than 0.05 were considered to be statistically significant.

Results

Quantitative analysis of image noise

Objective image noise was significantly different at each dose level ($p < 0.0001$) and between each reconstruction algorithm at every dose level ($p < 0.0001$ for all comparisons) with the greatest levels of image noise at LD1 (Figure 1a). MBIR reconstructions had significantly lower measures of objective image noise compared with both FBP and ASIR40 reconstructions at all dose levels ($p < 0.0001$ for all comparisons) with the greatest mean difference observed for both at the LD1 level; mean differences of 34.263HU (CI, 30.492 to 38.354) and 20.56HU (CI, 16.475 to 24.64) compared with FBP and ASIR40, respectively. MBIR facilitated percentage noise reductions of 68.1%, 69.2%, 61.02%, and 65% compared with FBP and 56.2%, 57.9%, 52.6%, and 56.6% compared with ASIR40 at the LD1, LD2, LD3, and CD levels, respectively. SNR for MBIR data sets was significantly higher than both FBP and ASIR40 data sets at each dose level ($p < 0.0001$) with the greatest mean difference compared with FBP at LD2 (2.62 (CI, 1.67 to 3.56)) and compared with ASIR40 at CD (2.263 (CI, 1.3 to 3.2)) (Figure 1b). No significant difference was observed in SNR between FBP and ASIR40 data sets at all dose levels.

Qualitative analysis

There was excellent agreement between the two raters for the assessment of diagnostic acceptability and presence of streak artifact (k , 0.824 and 0.868, $p < 0.001$) with moderate agreement for the assessment of subjective image noise and contrast resolution (k , 0.795 and 0.623, $p < 0.001$). Using mean scores for further analysis it was

shown that subjective image noise, diagnostic acceptability, and contrast resolution scores were significantly different between each reconstruction algorithm at each dose level ($p < 0.0001$ for all comparisons).

MBIR reconstructions had significantly higher qualitative scores compared with both FBP and ASIR40 reconstructions at all dose levels ($p < 0.0001$ for all comparisons) with the greatest mean differences observed for all qualitative measures at the LD1 level (Figures 2, 3 and 4). Figure 5 is an example of the images obtained following reconstruction with FBP, ASIR and MBIR at the LD1 dose level (80kV, 225mA).

MBIR reconstructions had significantly lower levels of streak artifact compared with FBP ($p < 0.001$) and ASIR40 ($p < 0.01$) at the lowest dose level only (LD1). All other comparisons were non-significant (Figure 6).

No statistically significant difference in image noise or SNR was seen between the MBIR reconstructed images at the various dose levels (Figures 1 and 2). An example of the MBIR reconstructed images at the four dose levels can be seen in Figure 7.

Comparison of low dose MBIR with conventional dose ASIR40

Our standard practice currently is to use conventional dose ASIR40 in the clinical setting. LD MBIR series were acquired with a mean dose reduction compared with CD ASIR40 of 62.17%, 50%, and 29.12% for LD1 MBIR, LD2 MBIR, and LD3 MBIR series, respectively. All LD MBIR reconstructions had significantly lower levels of objective image noise compared with the CD ASIR40 protocol ($p < 0.0001$ for all comparisons).

All low dose MBIR series and conventional dose ASIR40 series had above average to excellent subjective image noise, diagnostic acceptability, and contrast resolution scores.

Diagnostic acceptability and contrast resolution scores were superior for all LD MBIR series compared with CD ASIR40 ($p < 0.0001$ for all comparisons). LD2 MBIR and LD3 MBIR had superior subjective image noise scores compared with CD ASIR40 ($p < 0.0001$ for both comparisons) with no significant difference in subjective image noise between LD1 MBIR and CD ASIR40 reconstructions (Figure 2). Streak artifact was similar between all of the LD MBIR and the CD ASIR40 reconstructions (Figure 6) with no statistically significant difference observed.

Discussion

Iterative reconstruction algorithms serve to improve image quality by noise reduction and improved spatial resolution over filtered back projection. Blending ASIR with FBP is less computationally intense than MBIR, modelling only photon and electronic noise statistics in order to reduce computational time. MBIR incorporates modelling of certain parameters previously omitted from blended or hybrid iterative reconstruction algorithms. These include a system model that addresses the nonlinear, polychromatic nature of x-ray tubes by modelling the photons in the data set, a statistical noise model that considers the focal spot and detector size, and a prior model that corrects unrealistic situations in the reconstruction process to decrease the computational time³⁴. The incorporation of system optic information enables reductions in image noise and

artifacts with improvements in spatial resolution. The major limitation of these additional data processing steps is the prolonged reconstruction time required (45 minutes in one series³⁵), compared with FBP and ASIR, and although this may preclude its use in the emergency setting, it is unlikely to be a significant issue for most routine abdominopelvic CT examinations. Reconstruction times were many hours for such examinations only a few years ago. With improved computational efficiency reconstruction times will likely continue to improve and allow MBIR to be used in all clinical settings. Anecdotally it was been noted that greater dose reductions required longer reconstruction times, although this may preclude its use in the emergency setting, it is unlikely to be a significant issue for most routine abdominopelvic CT examinations. With improved computational efficiency, this time will likely reduce significantly and allow MBIR to be used in all clinical settings.

MBIR has been shown to reduce image noise and improve image quality at conventional dose levels compared ~~with~~ both FBP and ASIR^{13, 18}. The utility of MBIR at preserving image quality at lower radiation dose levels has also been investigated. ~~Many studies have demonstrated~~ Successful use of MBIR in chest CT has been demonstrated with reporting dose reductions of up to 79% ~~with~~ and preserved image quality³⁶. However, few studies have investigated the utility of MBIR in abdominopelvic CT^{22, 24} or the dose range at which MBIR has the greatest efficacy for noise reduction.

In ~~the present paper~~ our study, MBIR datasets had significantly lower levels of objective image noise compared with both FBP and ASIR⁴⁰ at both conventional and low dose levels with the greatest absolute noise reduction observed at the lowest radiation dose level. A similar finding was observed for the qualitative indices with the greatest

improvement in image quality also observed at the lowest dose level. In addition, MBIR significantly reduced streak artifact at the lowest dose level only.

Compared with ~~our current the standard~~ conventional dose CT protocol reconstructed with ASIR40, MBIR facilitated the acquisition of images with lower levels of image noise, higher diagnostic quality and contrast resolution scores, and comparable subjective image noise and streak artifact scores, while enabling a 62% dose reduction. Findings suggest that the greatest utility of MBIR in abdominopelvic CT is reduced image noise which helps maintain image quality in spite of low radiation dose acquisition, thus enabling the creation of diagnostic quality studies at substantially reduced radiation doses.

Cadaveric study has been used in the past to assess CT dose optimization in chest^{27, 37, 38} and orthopaedic CT^{39, 40}, however this is the first multi-specimen cadaveric study in the literature to assess radiation dose optimization in abdominal CT. A cadaver more closely simulates actual body composition than a phantom and ethical concerns over live human radiation dose experiments are not present with cadaveric study. A further advantage of cadaveric study is the ability to utilize cadavers of different body habitus; with a phantom study this would involve acquiring multiple (often very expensive) CT phantoms. Cadaveric study allows experimentation with a near perfect simulation for live human tissue and allows the use of multiple different radiation exposures to assess for differences in radiation dose and image quality. Decreasing radiation dose in clinical studies ~~in live humans~~ introduces a risk to patients regarding suboptimal images leading to impaired diagnostic confidence of the radiologist and therefore these studies often use small increments of radiation reduction to minimize this. With cadaveric study,

Commented [OOJ2]: ref

large reductions in radiation dose can be instituted and ~~the~~ images assessed for quality without ~~the same~~ concerns over missed diagnosis. This type of study also obviates additional radiation exposure to a patient, which may occur due to additional research scanning or from the requirement for repeat scanning due to *insufficient diagnostic confidence in the original images. Having confirmed the ability of MBIR to maintain image quality in a low-dose setting, the present results help support ethical applications to allow validation of these methods of radiation dose reduction in clinical practice.* ~~decreased diagnostic confidence from the original images. Having confirmed the ability of MBIR to maintain image quality in the low-dose setting, we can now confidently set up CT protocols with markedly reduced radiation dose to confirm the applicability of these findings to clinical practice.~~

MBIR-reconstructed images have an impasto appearance different to FBP- and lower percentages of blended ASIR/FBP-reconstructed images¹⁴. Initial studies of ASIR also reported a similar phenomenon⁴¹, but partial blending with FBP and further technological advancements in the algorithm have minimized this effect. Other studies have reported new artifacts in MBIR-reconstructed images such as a ‘staircase effect’ at bone interfaces and a ‘bordering blacked-out artifact’ on skin surfaces¹⁸. Although these artifacts were visible in all planes, predominantly on axial reformations, the overall effect on image quality was deemed to be minor. In the present paper, the readers were familiar with the altered appearance of MBIR-reconstructed images and believed this phenomenon did not interfere with diagnostic acceptability and was minimized in the coronal plane.

We recognize the limitations of this study are recognised our study. We studied the
 image quality characteristics of abdominopelvic CT scans reconstructed with three
 different reconstruction algorithms were studied. An assessment of the utilityability of
 MBIR-reconstructed images to detect for the detection and characterization of
 pathological findings was not made and further clinical studies are required to validate
 its diagnostic ability. Cadavers were scanned with the arms by their sides and this may
 have resulted in which had potential to decreased overall image quality compared
 with clinical image datasets; nonetheless, we feel that comparison between the different
 reconstruction algorithms on the same cadavers should remain remains
 valid.

Evaluation of the impact of MBIR on contrast resolution of liver and other solid organs
 following intravenous contrast administration was not possible. Furthermore, cadaveric
 imaging precludes the administration of intravenous and oral contrast media. Low dose
 clinical images reconstructed with MBIR have not been deemed adequate for the
 assessment of solid organ lesions but adequate for assessment of retroperitoneal
 adenopathy or acute complications of Crohn's disease. It is important therefore to
 emphasise that the use of cadaveric imaging should only be undertaken if it provides an
 appropriate substitute for clinical imaging. Quantitative analysis needs to be
 supplemented with a qualitative assessment of image acceptability in the anticipated
 application. Although cadaveric imaging may show promise, validation through careful
 conducted clinical studies remains essential.

Previous clinical studies using intravenous and oral contrast have reported a reduction
 in streak artifact with the use of MBIR^{13, 18}. In the present paper reduced streak artifact
 was only observed on MBIR images compared with alternative reconstruction

Commented [OOJ3]: see either testicular cancer mbir by
 kevin o regan or Siobhan mbir paper

techniques at the lowest dose level only. This suggests that the improved performance of MBIR for streak artefact removal occurs mainly in the low dose setting. This will require further assessment. This is particularly relevant to the assessment of streak artifact. Also, evaluation of the impact of pure IR on contrast resolution of liver and other solid organs post contrast was not possible; it is important to acknowledge this as this is a vital factor in abdominal imaging. Previous clinical studies using intravenous and oral contrast have reported a reduction in streak artifact with the use of MBIR^{13, 18}. However, in the present paper reduced streak artifact was only observed in MBIR-reconstructed images at the lowest dose level only, indicating a possible under evaluation of the ability of MBIR to reduce streak artifact in our study.

Furthermore, due to the inherent difference in the appearance of MBIR-reconstructed images described above, readers may have not been completely blinded to the reconstruction algorithm during subjective analysis. However, blinding to the imaging protocol was satisfactory. Finally, the results of our study may not be completely applicable to pure iterative reconstruction algorithms available from other vendors and independent validation of these techniques ~~would~~may also be required.

Conclusion

In conclusion, this cadaveric study demonstrates that MBIR can facilitate the acquisition of abdominopelvic CT scans with lower levels of image noise and greater image quality compared with conventional dose images reconstructed with FBP or ASIR40, while enabling ~~up to 62%~~significant radiation dose reduction. These data will provide essential information that will help guide the development of safe protocols which are more likely to be granted ethical approval for the purposes of clinical

~~validation. Further analysis of low dose imaging reconstructed with MBIR will focus on the clinical utility of MBIR at this dose range.~~

References

1. Wall BF. Ionising radiation exposure of the population of the United States: NCRP Report No. 160. Radiation Protection Dosimetry. 2009;136(2):136-8.
2. Preston DL, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, et al. Solid cancer incidence in atomic bomb survivors: 1958-1998. Radiat Res. 2007;168(1):1-64.
3. Nakashima M, Kondo H, Miura S, Soda M, Hayashi T, Matsuo T, et al. Incidence of multiple primary cancers in Nagasaki atomic bomb survivors: association with radiation exposure. Cancer Sci. 2008;99(1):87-92.
4. Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C, et al. Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. BMJ. 2005;331(7508):77.
5. Mettler FA, Jr., Thomadsen BR, Bhargavan M, Gilley DB, Gray JE, Lipoti JA, et al. Medical radiation exposure in the U.S. in 2006: preliminary results. Health Phys. 2008;95(5):502-7.
6. Allen BC, Baker ME, Einstein DM, Remer EM, Herts BR, Achkar JP, et al. Effect of altering automatic exposure control settings and quality reference mAs on radiation dose, image quality, and diagnostic efficacy in MDCT enterography of active inflammatory Crohn's disease. AJR American journal of roentgenology. 2010;195(1):89-100.
7. Ippolito D, Talei Franzesi C, Fior D, Bonaffini PA, Minutolo O, Sironi S. Low kV settings CT angiography (CTA) with low dose contrast medium volume protocol in the assessment of thoracic and abdominal aorta disease: a feasibility study. The British journal of radiology. 2015;88(1049):20140140.
8. Kalra MK, Maher MM, Toth TL, Kamath RS, Halpern EF, Saini S. Radiation from "extra" images acquired with abdominal and/or pelvic CT: effect of automatic tube current modulation. Radiology. 2004;232(2):409-14.
9. Kalra MK, Maher MM, Toth TL, Hamberg LM, Blake MA, Shepard JA, et al. Strategies for CT radiation dose optimization. Radiology. 2004;230(3):619-28.
10. Boos J, Aissa J, Lanzman RS, Heusch P, Schimmoller L, Schleich C, et al. CT angiography of the aorta using 80 kVp in combination with sinogram-affirmed iterative reconstruction and automated tube current modulation: Effects on image quality and radiation dose. Journal of medical imaging and radiation oncology. 2016;60(2):187-93.
11. Veldhoen S, Laqmani A, Derlin T, Karul M, Hammerle D, Buhk JH, et al. 256-MDCT for evaluation of urolithiasis: iterative reconstruction allows for a significant reduction of the applied radiation dose while maintaining high subjective and objective image quality. J Med Imaging Radiat Oncol. 2014;58(3):283-90.

- 493 12. Willemink MJ, Leiner T, de Jong PA, de Heer LM, Nievelstein RA, Schilham
494 AM, et al. Iterative reconstruction techniques for computed tomography part 2:
495 initial results in dose reduction and image quality. *Eur Radiol.* 2013;23(6):1632-
496 42.
- 497 13. Katsura M, Sato J, Akahane M, Matsuda I, Ishida M, Yasaka K, et al.
498 Comparison of pure and hybrid iterative reconstruction techniques with
499 conventional filtered back projection: image quality assessment in the
500 cervicothoracic region. *European journal of radiology.* 2013;82(2):356-60.
- 501 14. O'Neill SB, Mc Laughlin PD, Crush L, O'Connor OJ, Mc Williams SR, Craig O,
502 et al. A prospective feasibility study of sub-millisievert abdominopelvic CT using
503 iterative reconstruction in Crohn's disease. *European radiology.* 2013;23(9):2503-
504 12.
- 505 15. Desai GS, Thabet A, Elias AY, Sahani DV. Comparative assessment of three
506 image reconstruction techniques for image quality and radiation dose in patients
507 undergoing abdominopelvic multidetector CT examinations. *The British journal of*
508 *radiology.* 2013;86(1021):20120161.
- 509 16. Mitsumori LM, Shuman WP, Busey JM, Kolokythas O, Koprowicz KM.
510 Adaptive statistical iterative reconstruction versus filtered back projection in the
511 same patient: 64 channel liver CT image quality and patient radiation dose.
512 *European radiology.* 2012;22(1):138-43.
- 513 17. Mueck FG, Korner M, Scherr MK, Geyer LL, Deak Z, Linsenmaier U, et al.
514 Upgrade to iterative image reconstruction (IR) in abdominal MDCT imaging: a
515 clinical study for detailed parameter optimization beyond vendor
516 recommendations using the adaptive statistical iterative reconstruction
517 environment (ASIR). *RoFo : Fortschritte auf dem Gebiete der Rontgenstrahlen und*
518 *der Nuklearmedizin.* 2012;184(3):229-38.
- 519 18. Deak Z, Grimm JM, Treitl M, Geyer LL, Linsenmaier U, Korner M, et al.
520 Filtered back projection, adaptive statistical iterative reconstruction, and a model-
521 based iterative reconstruction in abdominal CT: an experimental clinical study.
522 *Radiology.* 2013;266(1):197-206.
- 523 19. Herin E, Gardavaud F, Chiaradia M, Beaussart P, Richard P, Cavet M, et al.
524 Use of Model-Based Iterative Reconstruction (MBIR) in reduced-dose CT for
525 routine follow-up of patients with malignant lymphoma: dose savings, image
526 quality and phantom study. *European radiology.* 2015;25(8):2362-70.
- 527 20. Patino M, Fuentes JM, Hayano K, Kambadakone AR, Uyeda JW, Sahani DV. A
528 quantitative comparison of noise reduction across five commercial (hybrid and
529 model-based) iterative reconstruction techniques: an anthropomorphic phantom
530 study. *AJR American journal of roentgenology.* 2015;204(2):W176-83.
- 531 21. Yamamura J, Tornquist K, Buchert R, Wildberger J, Nagel HD, Dichtl D, et al.
532 Simulated low-dose computed tomography in oncological patients: a feasibility
533 study. *Journal of computer assisted tomography.* 2010;34(2):302-8.
- 534 22. Murphy KP, Crush L, Twomey M, McLaughlin PD, Mildenerberger IC, Moore N,
535 et al. Model-Based Iterative Reconstruction in CT Enterography. *AJR American*
536 *journal of roentgenology.* 2015;205(6):1173-81.
- 537 23. De Crop A, Smeets P, Van Hoof T, Vergauwen M, Dewaele T, Van Borsel M, et
538 al. Correlation of clinical and physical-technical image quality in chest CT: a human
539 cadaver study applied on iterative reconstruction. *BMC Med Imaging.* 2015;15:32.

- 540 24. Singh S, Kalra MK, Do S, Thibault JB, Pien H, O'Connor OJ, et al. Comparison
541 of hybrid and pure iterative reconstruction techniques with conventional filtered
542 back projection: dose reduction potential in the abdomen. *Journal of computer*
543 *assisted tomography*. 2012;36(3):347-53.
- 544 25. Schramek GG, Stoevesandt D, Reising A, Kielstein JT, Hiss M, Kielstein H.
545 *Imaging in anatomy: a comparison of imaging techniques in embalmed human*
546 *cadavers*. *BMC Med Educ*. 2013;13:143.
- 547 26. Reed AB, Crafton C, Giglia JS, Hutto JD. Back to basics: use of fresh cadavers
548 in vascular surgery training. *Surgery*. 2009;146(4):757-62; discussion 62-3.
- 549 27. Mueck FG, Roesch S, Scherr M, Fischer F, Geyer L, Peschel O, et al. How low
550 can we go in contrast-enhanced CT imaging of the chest?: A dose-finding cadaver
551 study using the model-based iterative image reconstruction approach. *Acad Radiol*.
552 2015;22(3):345-56.
- 553 28. Boos J, Lanzman RS, Heusch P, Aissa J, Schleich C, Thomas C, et al. Does body
554 mass index outperform body weight as a surrogate parameter in the calculation of
555 size-specific dose estimates in adult body CT? *The British journal of radiology*.
556 2016;89(1059):20150734.
- 557 29. Marin D, Nelson RC, Schindera ST, Richard S, Youngblood RS, Yoshizumi TT,
558 et al. Low-tube-voltage, high-tube-current multidetector abdominal CT: improved
559 image quality and decreased radiation dose with adaptive statistical iterative
560 reconstruction algorithm--initial clinical experience. *Radiology*. 2010;254(1):145-
561 53.
- 562 30. O'Connor OJ, Vandeleur M, McGarrigle AM, Moore N, McWilliams SR,
563 McSweeney SE, et al. Development of low-dose protocols for thin-section CT
564 assessment of cystic fibrosis in pediatric patients. *Radiology*. 2010;257(3):820-9.
- 565 31. Bongartz G, Golding S, Jurik A, Leonardi M, Van Meerten EVP, Geleijns J, et
566 al. European guidelines on quality criteria for computed tomography.
567 *EUR(Luxembourg)*. 1999.
- 568 32. Bongartz G, Golding S, Jurik A, Leonardi M, van Meerten EvP RR, Schneider
569 K, et al. CT quality criteria, European Commission. 2004.
- 570 33. Kalra MK, Maher MM, Toth TL, Kamath RS, Halpern EF, Saini S. Comparison
571 of Z-axis automatic tube current modulation technique with fixed tube current CT
572 scanning of abdomen and pelvis. *Radiology*. 2004;232(2):347-53.
- 573 34. Yu Z, Thibault JB, Bouman CA, Sauer KD, Hsieh J. Fast model-based X-ray CT
574 reconstruction using spatially nonhomogeneous ICD optimization. *IEEE Trans*
575 *Image Process*. 2011;20(1):161-75.
- 576 35. Vardhanabhuti V, Loader RJ, Mitchell GR, Riordan RD, Roobottom CA. Image
577 quality assessment of standard- and low-dose chest CT using filtered back
578 projection, adaptive statistical iterative reconstruction, and novel model-based
579 iterative reconstruction algorithms. *AJR American journal of roentgenology*.
580 2013;200(3):545-52.
- 581 36. Katsura M, Matsuda I, Akahane M, Sato J, Akai H, Yasaka K, et al. Model-
582 based iterative reconstruction technique for radiation dose reduction in chest CT:
583 comparison with the adaptive statistical iterative reconstruction technique.
584 *European radiology*. 2012;22(8):1613-23.
- 585 37. Yanagawa M, Honda O, Yoshida S, Kikuyama A, Inoue A, Sumikawa H, et al.
586 Adaptive statistical iterative reconstruction technique for pulmonary CT: image

quality of the cadaveric lung on standard- and reduced-dose CT. Acad Radiol. 2010;17(10):1259-66.

38. Millon D, Vlassenbroek A, Van Maanen AG, Cambier SE, Coche EE. Low contrast detectability and spatial resolution with model-based Iterative reconstructions of MDCT images: a phantom and cadaveric study. European radiology. 2017;27(3):927-37.

39. Tozakidou M, Reisinger C, Harder D, Lieb J, Szucs-Farkas Z, Muller-Gerbl M, et al. Systematic Radiation Dose Reduction in Cervical Spine CT of Human Cadaveric Specimens: How Low Can We Go? AJNR Am J Neuroradiol. 2017.

40. Lombard C, Gervaise A, Villani N, Louis M, Raymond A, Blum A, et al. The Impact of Dose Reduction in Quantitative Kinematic CT of Ankle Joints Using a Full Model-Based Iterative Reconstruction Algorithm: A Cadaveric Study. AJR American journal of roentgenology. 2018;210(2):396-403.

41. Prakash P, Kalra MK, Digumarthy SR, Hsieh J, Pien H, Singh S, et al. Radiation dose reduction with chest computed tomography using adaptive statistical iterative reconstruction technique: initial experience. Journal of computer assisted tomography. 2010;34(1):40-5.

Table & Figure Legend

Table 1.

CTDI_{vol}, DLP and SSDE for each of the different CT protocols

Figure 1.

a) Variation in objective image noise and b) SNR with choice of reconstruction algorithm at each low dose (LD) and conventional dose (CD) protocol. Data are plotted as mean and standard deviation. FBP (filtered back projection); ASIR40 (40% adaptive statistical iterative reconstruction); MBIR (model based iterative reconstruction).

Figure 2.

Variation in subjective noise scores with choice of reconstruction algorithm at each low dose (LD) and conventional dose (CD) protocol. Data are plotted as mean and standard deviation. FBP (filtered back projection); ASIR40 (40% adaptive statistical iterative reconstruction); MBIR (model based iterative reconstruction).

Figure 3.

Variation in diagnostic acceptability scores with choice of reconstruction algorithm at each low dose (LD) and conventional dose (CD) protocol. Data are plotted as mean and standard deviation. FBP (filtered back projection); ASIR40 (40% adaptive statistical iterative reconstruction); MBIR (model based iterative reconstruction).

Figure 4.

Variation in contrast resolution scores with choice of reconstruction algorithm at each low dose (LD) and conventional dose (CD) protocol. Data are plotted as mean and standard deviation. FBP (filtered back projection); ASIR40 (40% adaptive statistical iterative reconstruction); MBIR (model based iterative reconstruction).

Figure 5.

An example of the images obtained through FBP, ASIR and MBIR reconstructions at the LD1 dose level (80kV, 225mA).

Figure 6.

643 Variation in streak with choice of reconstruction algorithm at each low dose (LD) and
644 conventional dose (CD) protocol. Data are plotted as mean and standard deviation. FBP
645 (filtered back projection); ASIR40 (40% adaptive statistical iterative reconstruction);
646 MBIR (model based iterative reconstruction).

647

648 **Figure 7.**

649 An example of the MBIR reconstructed images at the four dose levels CD, LD1, LD2
650 and LD3.

651