Title	Pure iterative reconstruction improves image quality in computed tomography of the abdomen and pelvis acquired at substantially reduced radiation doses in patients with active Crohn disease
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Abstract:

Objective:

We assessed diagnostic accuracy and image quality of modified protocol (MP) CT of abdomen and pelvis reconstructed using pure iterative reconstruction (IR) in patients with Crohn's disease (CD).

Methods:

Thirty-four consecutive patients with CD were referred with suspected extramural complications. Two contemporaneous CT datasets were acquired in all patients: standard protocol (SP) and modified protocol (MP). MP and SP protocols were designed to impart radiation exposures of 10-20% and 80-90% of routine abdominopelvic CT respectively. MP images were reconstructed with model-based iterative reconstruction (MBIR) and adaptive statistical iterative reconstruction (ASIR).

Results:

MP-CT and SP-CT DLP were 88±58mGy.cm (1.27±0.87mSv) and 303±204mGy.cm (4.8±2.99mSv) respectively ($p< 0.001$). Median diagnostic acceptability, spatial resolution and contrast resolution were significantly higher and subjective noise scores were significantly lower on SP-ASIR40 compared with all MP datasets. There was perfect clinical agreement between MP-MBIR and SP-ASIR40 images for detection of extramural complications.

Conclusion:

MP-CT using pure IR is feasible for assessment of active CD.

Keywords: Iterative reconstruction, computed tomography (CT), Crohn's disease, abscess, radiation dose.

Introduction:

At present there is considerable research and industry drive to reduce radiation exposure during CT imaging, while preserving image quality and diagnostic accuracy. Patients with Crohn's disease (CD) are exposed to high lifetime cumulative doses of ionizing radiation primarily due to the more widespread and repeated use of CT (1-5).

Hybrid iterative reconstruction (IR) algorithms have been used successfully in CD and have facilitated dose reductions in the order of 30-50% over traditional filtered back projection (6-8). Dose reductions of a similar magnitude have been achieved in other patient populations with good preservation of diagnostic accuracy (9-17). Hybrid IR has certain limitations, however, including reliance on an *ideal* statistical model of photon and electronic noise and the requirement for blending with comparatively noisy filtered back projection (FBP) images required to improve image acceptability among radiologists (18).

Pure iterative reconstruction algorithms differ significantly from their hybrid predecessors in that they operate using a model of the actual physical characteristics of the individual scanner including the focal spot, the x-ray fan beam, the 3-Dimensional interaction of the x-ray beam within the patient and the 2-Dimensional interaction of the x-ray beam within the detector (18). Early data suggest that abdominal CT reconstructed with pure IR is superior to hybrid IR and may facilitate dose reductions in the order of 75% over FBP (19).

The advantages of emerging dose optimization technology such as pure IR may have greatest benefit in patient cohorts, such as those with Crohn's disease, who often present at an early age and sometimes have decades of active disease requiring repeated CT imaging (1). Therefore, we designed a prospective intraindividual feasibility study involving the contemporaneous acquisition of modified protocol (MP) (~1mSv) and standard protocol (SP) (~5mSv) CT of the abdomen and pelvis in patients with active Crohn's disease with the following aims:

1) To demonstrate the feasibility of a modified dose CT protocol which would reduce the effective dose of a CT abdomen and pelvis to within the one-millisievert range using pure IR in patients with active Crohn's disease.
2) To compare objective noise and subjective image quality differences when MP images are reconstructed with model based iterative reconstruction (MBIR), 40% and 70% adaptive statistical iterative reconstruction (ASiR) and FBP.
3) To determine the diagnostic accuracy of MP CT using pure iterative reconstruction in the assessment of CD patients with suspected extramural complications compared with SP CT.

With regard to the first aim, i.e. assessment of whether a CT scan of abdomen and pelvis in the submillisievert range would allow acceptable image quality and diagnostic yield by making use of newly available pure iterative reconstruction, the following should be clarified. This study was not intended simply as an investigation of pure IR but rather a study of whether an optimally developed submillisievert protocol reconstructed with pure IR can deliver in terms of image quality and diagnostic yield. A multidisciplinary group of radiologists, CT technologists, medical physicists and CT applications specialists discussed the MP protocol and decided that reducing the kV to 100 kV was a good strategy to achieve the above aim as it would allow sufficient mA range for effective tube current modulation. As will be described later, the SP protocol, to which MP protocol was being compared, had a kV of 120 kV.

Materials and methods:

A prospective study design was employed following institutional review board approval and registration with the Clinical Trials registry (ClinicalTrials.gov Identifier NCT 01244386). Thirty-four patients with confirmed Crohn's disease (CD) were recruited from a tertiary referral outpatient inflammatory bowel disease clinic. Patients were scanned over an eight-month period. The indication for abdominopelvic CT was uniform; all patients had an exacerbation of CD and required imaging assessment of clinically suspected extramural complications of their disease such as abscess or perforation. Exclusion criteria included patients with CD who were less than sixteen years of age, those presenting acutely via the emergency department, and those without histological confirmation of CD. Written informed consent was obtained from all patients. Each patient had their weight and height measured using a digital device (Seca electronic measuring station Model 763, Seca Medical, Hamburg, Germany) and their Body Mass Index (BMI) was subsequently recorded.

CT acquisition:

All CT images were acquired using 64-slice multi-detector row CT (General Electric Lightspeed VCT-XTe, GE Healthcare, GE Medical Systems, Milwaukee, WI). All patients consented to have two contemporaneous intravenous contrastenhanced CT acquisitions of the abdomen and pelvis; both imaging identical anatomic areas from the lung bases to the symphysis pubis. 1.5 liters of positive oral contrast (2% Gastrograffin, Bracco Diagnostics Inc., Princeton, NJ) were ingested in all cases and a single 100mL bolus of intravenous contrast (Iohexol, Omnipaque 300, GE Healthcare, Mississauga, ON) delivered at a flow rate of 2.5mL/sec was administered in 33 patients as per local departmental practice (1 patient had an allergy to iodinated contrast material). The volume of injected intravenous contrast was not adjusted for patient size in order to standardize technique.

A modified protocol (MP) acquisition was performed initially; this was commenced on arrested inspiration 45 seconds after peak aortic enhancement. The second, standard protocol (SP) scan was commenced approximately 6 seconds afterward. The MP protocol was designed to impart a radiation exposure of 10-20% of that of a routine abdominal CT performed at our institution. The second protocol was designed to impart an effective dose of 80-90% that of a routine CT acquisition and labeled the standard protocol (SP) for study purposes. Using this strategy, the image quality and diagnostic yield of the MP CT could be compared with that of the SP CT and no patient would incur additional radiation exposure as a result of recruitment into the study. Single medio-lateral and antero-posterior scout views were obtained prior to the helical acquisitions.

The MP CT employed a tube voltage of 100kV, rotation time of 0.5s and also used z-axis automated tube current modulation with minimum and maximum tube current thresholds set at 20 and 350mA, respectively, with a noise index of 70. The SP CT used a tube voltage of 120kV, rotation time of 0.8s and z-axis automated tube current modulation with minimum and maximum tube current thresholds set at 50 and 350mA, respectively, with a noise index of 38. Fixed noise indices were selected, regardless of patient size/BMI, for each of the MP and SP to minimize the effect of a change in noise index as a confounder of image quality.

CT image reconstruction:

Images were acquired at 0.625mm and subsequently reconstructed to slices measuring 2mm thick. MP CT data were reconstructed using a pure iterative reconstruction algorithm (model based iterative reconstruction, MBIR, GE Healthcare, GE Medical Systems, Milwaukee, WI) (MP-MBIR) and for comparison purposes, also reconstructed with filtered back projection (MP-FBP) and increasing percentages of hybrid iterative reconstruction (adaptive statistical iterative reconstruction, ASIR, GE Healthcare, GE Medical Systems, Milwaukee, WI); 40% ASIR (MP-ASIR 40) and 70% ASIR (MP-ASIR 70). SP CT images were reconstructed per standard departmental protocol with 40% ASIR and 60% FBP consistent with the manufacturers recommendations (SP-ASIR 40).

CT Calibration and Dose Measurement:

Dose length product (DLP) and volume Computed Tomography dose index ($CTDI_{vol}$) values were recorded from each CT dose report for MP and SP images. $CTDI_{vol}$ and DLP tolerances were verified using a standard 32cm perspex phantom, a 10cm ionization chamber with a Victoreen NERO mAx unit (Fluke Biomedical, OH, USA). The 32cm phantom was imaged at tube currents of 40mA and 50mA with a 32cm FoV. Radiation measurements were taken with the pencil chamber inserted at central and peripheral locations. Three measurements at each location were averaged and used to calculate corresponding CTDI values which were subsequently converted to a weighted CTDI. The displayed CTDI and DLP values of the CT console were recorded and percentage error calculated using ionisation chamber measures. Calibration of the CT unit was performed once per week in accordance with the manufacturer's instructions.

Size specific dose estimates (SSDE) were calculated by calculating the effective patient diameter and multiplying $CTDI_{vol}$ by multiplication factors as per American Association of Physicists in Medicine (AAPM) (21,22). The Imaging performance and assessment in CT patient dosimetry calculator (ImPACT version 0.99x, London, England) was used to calculate effective dose (ED). The radiation exposure resultant from the CT topograms was excluded from analysis.

Quantitative Analysis of Image Noise:

Spherical regions of interest (ROIs) (diameter, 10mm; volume, 519mm^3) were placed in the following 4 anatomic structures by a single reader (AF, 1 years experience): liver at diaphragm, liver at porta hepatis, erector spinae at level of the renal hilum and psoas muscle at the iliac crest. In each structure, efforts were made to place the ROI in as homogenous an area as possible, away from blood vessels, fat planes etc. Mean attenuation in HU and standard deviation of the mean attenuation in the ROI were recorded for all datasets. The standard deviation of the mean attenuation in the ROI served as an objective measure of noise (20). The magnitude of noise reduction was subsequently derived by subtracting the objective noise on the MP-ASIR 40, MP-ASIR 70 and MP-MBIR images from the objective noise present on the MP-FBP images.

Subjective image quality:

Subjective image quality parameters and grading systems were adapted from the European Guidelines on Quality Criteria for CT document (23) and were selected on the basis of findings of previous studies (15,17). One of the observers (MMM, 17 years experience) was familiar with these methods of assessment, having successfully used them previously (24-26) and trained the other reader (PMcL, 6 years experience) prior to analysis using a training set of five standard CTs. Diagnostic acceptability, subjective image noise and contrast resolution were scored in consensus (MMM, PMcL) using a ten-point scale at 5 anatomical levels: right hemi-diaphragm, porta hepatis, right renal hilum, iliac crest and roof of acetabulum. The presence and impact of streak artifact were also scored at each anatomical level using a 3-point scheme (0, no streak artifact; 1, streak artifact present but not interfering with image interpretation; 2 streak artifact present and interfering with image interpretation). Contrast resolution was scored using a ten-point scale at three levels: liver, spleen and gluteus maximus. Subjective image quality indices were recorded for SP-ASIR 40 and MP-FBP, MP-ASIR 40, MP-ASIR 70 and MP-MBIR images.

Diagnostic acceptability was graded as acceptable (score of 5), unacceptable (score of 1) or excellent (score of 10), if depiction of soft-tissue structures for diagnostic interpretation and degree of image degradation by beam-hardening artifacts was satisfactory, unsatisfactory, or considerably superior, respectively. Subjective image noise was graded according to the extent of “graininess” or “mottle” present on CT images and was graded as acceptable (score of 5) if average graininess was seen with satisfactory depiction of small anatomic structures such as the blood vessels and interface between structures of variable attenuation, unacceptable (score of 10) if graininess interfered with depiction of these structures, and excellent (score of 1) where there was minimal or no appreciable mottle. With regard to contrast resolution, a score of 10 represented superior contrast depiction between different soft tissues, a score of 1 indicated the poorest contrast and 5 indicated acceptable contrast.

Diagnostic accuracy:

Clinical Image Review:

MP-MBIR and SP-ASIR 40 images were clinically reviewed for findings by two fellowship-trained abdominal radiologists (KOR, SMS) with 9 and 8 years experience, respectively. Unlike the subjective image quality assessments, which were scored in consensus, the clinical reviews were completed independently. To minimize the effects of recall bias, all datasets were anonymized, reviewed in random patient order and a six-week delay was instituted between the review of MP-MBIR and SP-ASIR 40 images. Images were reviewed on 2mm axial and coronal reformats on soft-tissue window settings only (window width, 400 HU; window level, 40HU) using a commercial workstation (Advantage Workstation VolumeShare 2, Version 4.4, GE Medical Systems, Milwaukee, WI).

Disease Severity:

Crohn's disease related findings, such as the presence and severity of inflammation and/or strictures in the small and large intestine, were recorded. Changes in the peri-enteric tissues substantiating the presence of active inflammation or indicative of transmural disease were also recorded.

Extraintestinal manifestations of CD, evidence of previous surgery and any non-Crohn's related findings were also recorded. Disease severity was graded from zero to twelve using the Crohn's disease activity scoring system previously described by Desmond et al (1). This score is a summation of the presence and severity of findings in the small intestine (wall thickening=1, non-obstructing stricture=2, obstructing stricture=3), colon (wall thickening=1, non-obstructing stricture=2, obstructing stricture=3), mesentery (fat stranding=+1, hypervascularity=+1, lymphadenopathy=+1) and peri-enteric tissues (fistula=1, phlegmon=2, abscess=3). In additional a designation of A+ or A- was assigned to patients with or without acute complications such as obstruction, ileus or perforation. Utilizing this Crohn's disease activity score, disease severity was categorized into grade 0 (0/12), grade I (1-4/12), grade II (5-8/12) and grade III (9-12/12).

Method of Reference Case Review:

A final method of reference case review was performed in consensus by 2 readers (MM & KM). This was performed with all available current and prior imaging, results of prior radiological and non-radiological investigations, complete clinical histories, cellular pathology results (if acquired in the 1-month period before or 1-month period after CT examination) and surgical correlation (where available) (OOC, FS). This method of reference assessment of radiological findings utilized the same template as used in the initial clinical image review. The information from the initial clinical review was not available for the method of reference case review.

Statistical Analysis:

All statistical tests were performed with a commercially available medical statistical package (PASW version 20, SPSS Inc, Chicago, IL, USA). Wilcoxon signed rank test was used for statistical analysis to compare the qualitative parameters (diagnostic acceptability, image noise, streak artifact, spatial resolution and contrast resolution). Normally distributed quantitative indices were compared using a paired t-test. Correlation of parametric and non-parametric variables was performed using Pearson and Spearman's tests respectively. Agreement between the clinical findings was statistically compared using Cohen's κ test of inter-observer agreement. A difference with a *p* value of <0.05 was considered statistically significant. All data are presented as mean± standard deviation unless otherwise stated.

Results:

Thirty-four patients, 21 females and 13 males with a mean age of 37.8±13.7 years (range= 16-74 years) and mean BMI of 24.7±4.97kg/m^2 (range= 17.4-38.8kg/m^2) were included in this study.

Measurements of Radiation Exposure:

Mean DLP for MP CT (88±58mGy.cm) was significantly lower than the mean DLP for the SP CT (303±186mGy.cm)($p<0.001$). Mean ED was 1.27±0.87mSv for the MP protocol compared with 4.8±2.99mSv for the SP protocol and this difference was also statistically significant. MP CT had a DLP that was on average 71.4±2.4% less than that of the SP. A statistically significant increase in DLP was encountered with increasing BMI for both MP and SP (Spearman's correlation; MP=0.918, SP=0.908 $p<0.001$)(Table 1).

Image quality – objective analysis:

There was a statistically significant, progressive reduction in objective image noise when MP CT images were reconstructed with 40% ASIR (78±12.2HU), 70% ASIR (50±8.2HU) and MBIR (27±6.7HU)($p<0.000$ for all comparisons)(Figure 1). No significant difference in objective noise was found when MP-MBIR images were compared with SP-ASIR 40 (27±6.7HU vs. 26±4.9HU)(paired T test; $p=0.055$)(Figure 1).

Objective image noise was significantly higher in patients with a BMI of >25kg/m^2 (BMI>25kg/m^2) compared with a BMI of <25kg/m^2 (BMI<25kg/m^2) on the MP-MBIR images (32±8.1HU vs. 24±3.2HU, $p<0.001$). There was no significant difference in objective noise in patients with BMI>25kg/m^2 compared with those patients with BMI<25kg/m^2 on SP-ASIR 40 images (26±5HU vs. 26±5.5HU, $p=0.226$).

The magnitude of noise reduction (derived by subtracting the objective noise on MP from objective noise present on SP-FBP images) was then compared between patients with BMI>25kg/m^2 and BMI<25kg/m^2. Objective noise reduction was significantly less in patients with BMI>25kg/m^2 compared with those patients with BMI<25kg/m^2 for MP-ASIR 40, MP-ASIR 70 and MP-MBIR images ($p<0.001$ for all comparisons)(Figure 2).

Image quality – subjective analysis:

Median diagnostic acceptability, spatial resolution and contrast resolution scores were significantly higher and subjective noise scores were significantly lower on the SP-ASIR 40 images compared with all MP datasets (MP-FBP, MP-ASIR 40, MP-ASIR 70, MP-MBIR) (Wilcoxon signed rank test, $p<0.001$ for all comparisons) (Figure 3). Subjective image quality scores were significantly better for MP-MBIR images compared with the MP datasets reconstructed with ASIR and FBP ($p<0.001$ for all comparisons) (Figure 3). MP-MBIR images had above average to excellent diagnostic acceptability, subjective noise, spatial and contrast resolution scores. Median streak artifact scores were significantly less on the MP-MBIR images compared with the SP-ASIR 40 images ($p<0.001$). There was no significant difference between patients with BMI<25kg/m^2 and those with BMI>25kg/m^2 for either MP-MBIR or SP-ASIR 40 datasets ($p>0.066$ for all comparisons).

Diagnostic accuracy:

Median CD activity scores were comparable for MBIR and SP-ASIR 40 images for both readers (Reader 1: MBIR – 4±3, SP-ASIR 40 – 4±3) (Reader 2: MBIR – 5±1.75, SP-ASIR 40 – 5±2) (GS: 4±2). 10 patients had pathological correlation and 5 patients had surgical resection, the results of which corroborated the method of reference clinical reads and resultant scores. CD activity grades showed excellent intra-observer and method of reference agreement (Table 2). The detection of Crohn's related findings in the small intestine, colon and peri-enteric tissues on MP-MBIR vs. SP-ASIR 40 images is summarized in Table 2. There was perfect intra-observer agreement between MP-MBIR and SP-ASIR 40 images for the detection of abscesses and fistulas for both readers in addition to complete agreement for the detection of abscesses for both readers when compared with the method of reference reads. There was almost complete intra-observer and method of reference agreement for MP-MBIR and SP-ASIR 40 images for the detection of enteritis and colitis. Individual agreement was weakest for the detection of strictures (Table 2). All strictures recorded were subjectively short and were non-obstructing on both the MP-MBIR and SP-ASIR 40 images.

Data regarding the detection of extra-intestinal findings in the abdomen and pelvis on MP-MBIR vs. SP-ASIR 40 images are summarized in Table 3. Reviewer 2 missed a single 3mm renal calculus and a 6mm hepatic simple cyst when interpreting the SP-ASIR 40 images. No extra-intestinal findings were missed when independent interpretations of the MP-MBIR images were compared with the SP-ASIR 40 images for both readers.

Discussion:

The primary aim of this study was to demonstrate the feasibility of a modified dose CT protocol, which would reduce the effective dose of a CT abdomen and pelvis to within the one-millisievert range using pure IR in patients with active CD. The mean ED achieved using the MP CT was 1.27mSv (DLP 88mGy.cm), which compares favorably with other recent low dose CT studies including Kambadakone et al who achieved a DLP of 380.3mGy.cm when performing low dose MDCT with hybrid IR on a cohort of 48 patients with CD and a DLP of 408mGy.cm when performing low dose CT enterography with hybrid IR on a cohort of 16 Crohn's patients (7). Lee et al achieved a DLP of 182 mGy.cm when performing low dose CT enterography with hybrid IR in a further 91 patients with CD (6). Vardhanabhuti et al (27) reported dose reductions of 76% with preservation of image quality but suboptimal assessment at 85% dose reduction at low dose abdominal CT with MBIR.

The scale of dose reduction desired for our MP CT (less than 50% of DLP reported in other low dose studies involving Crohn's patients) necessitated a feasibility study with careful intra-individual control, using contemporaneously acquired SP CT as the reference standard. Comparison of the diagnostic yield of the index test (MP-MBIR) and reference standard (SP-ASIR 40) in our study indicates that sub-100mGy.cm abdominopelvic CT is feasible in patients with active CD. The clinical indication for CT was addressed and answered satisfactorily in all cases. There was perfect agreement for the detection of extramural penetrating complications such as abscess, which would significantly alter patient management, albeit in a small number (n=5) of patients in this study. Nevertheless, a large proportion of patients had enteritis or colitis, and these were appropriately detected and characterized. There was almost complete agreement between MP-MBIR and SP-ASIR 40 images for the detection of enteritis and colitis but agreement was admittedly weaker for the detection of intestinal strictures. The strictures imaged in our study sample were uniformly low grade, which may have contributed to subjective interpretation discrepancies and, importantly, no stricture was missed on the MP-MBIR images. The issue of detection and characterization of strictures is a difficult one. CT abdominopelvic acquisitions and even CT enterography are disadvantaged when compared to MR enterography or barium studies because CT enterography relies on a single image acquisition compared with the feasible acquisition of multiple and even cine views with MR enterography or barium studies. Therefore, peristalsis can be confused with non-obstructing strictures; this is a possible explanation for lower than expected correlation between image sets. Similarly, there were discrepant interpretations of the presence of other Crohn's complications such as colitis. It is important to remember that interpretation of findings such as these in everyday practice is very often subjective, even among experts in the field. The clinical review in this study was performed by two experienced fellowship-trained abdominal radiologists. As in the case of the strictures, only five patients each had endoscopy or surgery, therefore it is not possible to make a judgment of who "over-called" or "under-called". We would argue however, that the purpose of this study is the assessment of whether MP (low dose) studies reconstructed with full IR can retain diagnostic accuracy versus a standard dose protocol and that intra-reader agreement is vitally important in answering that question. However, intra-reader correlation for detection of a wide range of Crohn's complications for MP-MBIR and SP-MBIR was overall very satisfactory (Table 2). In addition, it is reassuring that in the five patients who had surgery during the follow-up period, the findings on CT were confirmed in all cases at the time of surgery.

Image quality analysis demonstrated no statistically significant difference in objective image noise between the MP-MBIR and SP-ASIR 40 images acquired at almost four times the radiation dose of the MP protocol. Interestingly we found that objective image noise was higher in patients with a BMI of greater than 25kg/m^2 when our MP protocol was employed and this finding was not replicated with the SP. In an attempt to determine the cause of this difference we retrospectively reviewed the peak mA data from the MP and SP CT images and found that the automated tube current modulation maximum tube current threshold (350mA) was not reached in any case while using the MP or SP protocol. It is therefore likely the statistical difference in image noise between the BMI>25kg/m^2 and BMI<25kg/m^2 subgroups in the MP protocol may be related to the reduced tube voltage of 100kV and greater specified noise index (70 vs. 38) employed in the MP protocol. CT of the abdomen and pelvis using a reduced tube voltage has previously been shown to accentuate beam hardening and streak artifacts in patients with an increased BMI (28).

The performance of MBIR in this subgroup of patients with an increased BMI and higher image noise was of immediate interest. We subtracted the objective noise on the MP-MBIR images from the objective noise present on the MP-FBP images to calculate magnitude of noise reduction achieved by the pure IR algorithm in both groups. We found that the objective noise reduction when using MBIR was significantly less in patients with BMI>25kg/m^2 compared with those patients with BMI<25kg/m^2. This finding was also demonstrated in the hybrid IR images and may indicate that the efficiency of iterative reconstruction algorithms is at least partly dependent on photon fluence at the time of CT acquisition.

In a previous study using an identical CT acquisition protocol we found that diagnostic accuracy was maintained when the modified dose images were reconstructed with 40% ASIR (8). The key difference between our previous work and this study is that we now demonstrate that image quality is compromised to a far less degree when a pure iterative reconstruction algorithm is employed. Subjective analysis of the low dose images in this study showed reduced subjective noise and significantly superior diagnostic acceptability, contrast and spatial resolution when the MP-MBIR images were compared with MP images reconstructed with hybrid IR (ASIR). Diagnostic acceptability, spatial resolution and contrast resolution were graded as acceptable to poor when 40% ASIR was employed. In comparison, the MBIR images were graded as above average to excellent. Median image quality scores were significantly lower when the MP-MBIR images were compared with SP-ASIR 40 and subjective image noise was also graded to be significantly worse on the MP-MBIR images. We therefore found a discrepancy between the subjective comparison of image noise, which demonstrated superiority of the SP-ASIR 40 dataset, and objective image noise analysis, which showed no significant difference between the MP-MBIR and SP-ASIR 40 images. One possible explanation for this discrepancy was that the reviewers who performed the subjective analysis were not accustomed to the different appearance of the images reconstructed with pure IR. We would describe the different quality of the MP-MBIR images as being mildly “mottled” or “pixelated” but expert opinion in this area suggests that imagers tend to adapt to the new quality of these images in a relatively short period of time (18).

There are a number of limitations to this study; radiation exposure was slightly underestimated as the dose imparted during topogram acquisition was excluded from calculation. Our scanning protocol was designed to improve the detection of extramural complications, which were clinically suspected in all recruited patients. Positive rather than neutral oral contrast agents were specifically used to increase the conspicuity of small abscesses and localized perforations as recommended by the second European evidence-based consensus on Crohn’s disease (29). The delay in imaging after administration of IV contrast in our study was (40 seconds after ‘peak aortic opacification’ which equates to 60-65 seconds; use of this protocol in patients with known CD has been shown to result in satisfactory depiction of small and large intestinal inflammation when compared with magnetic resonance enterography (29).

It should be emphasized that the reduction in dose achieved in this study was achieved by design of the MP protocol, which included a lower tube voltage of 100kV. The role of pure IR was to reduce noise, improve spatial resolution and ultimately improve diagnostic acceptability and yield from these low dose images. With regard to the MP protocol, the tube potential difference was not varied with BMI or patient size, in order to standardize the protocol. It is worth noting that encouraging results have been shown with automated attenuation-based tube voltage selection (31–34) with dose reductions of up to 56% reported. Automated tube voltage modulation was not utilized in our study, as this technology was not locally available. However, we decided to reduce the tube peak kilovoltage from 120 to 100kV for the MP protocol to allow sufficient mA range for effective tube current modulation but this reduction potentially introduces bias related to the increased attenuation of iodinated contrast on the MP compared with SP images. Blinding of the reviewers as to the scanning protocol during clinical interpretation was also not possible as the MP-MBIR images had an obviously different appearance compared with SP-ASIR 40 images. Hybrid and pure iterative reconstruction algorithms from only a single vendor (GE Healthcare, Waukesha, WI) were assessed and pure IR currently has a relatively long reconstruction time (10-90minutes per dataset) compared with FBP and hybrid IR, which are computationally efficient and quick. Perhaps the greatest limitation of our study is the narrow subgroup included, namely patients with an exacerbation of known CD who had clinically suspected extramural complication. It is therefore not possible to extrapolate our study findings to other gastrointestinal and abdominal disorders. We did not include pediatric Crohn's patients and we did not include patients who presented to the emergency department acutely. The results of our study would therefore not be entirely applicable to these groups at present. Importantly our findings also do not apply to patients who do not yet have a confirmed diagnosis of CD; magnetic resonance or CT enterography would be more appropriate for imaging in that clinical context (30).

MBIR reduces image noise to the level found in images acquired at a 344% higher dose reconstructed with 40% ASIR and results in complete clinical agreement for the detection of extramural complications and satisfactory agreement for the detection of enteritis and colitis. Abdominopelvic CT using pure IR is feasible in patients with active Crohn's disease. Dose reductions in the range of 70-90% over standard protocol are possible with little compromise in image quality using pure IR. Further research should focus on the dose limits of this technique, particularly in patients with a high BMI and the interpretation of IR images, which have an unfamiliar quality.

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Figure 1. Changes in mean objective noise (mean standard deviation of HU measured in 5 anatomical levels) when MP images were reconstructed with FBP, ASIR-40, ASIR-70 and MBIR. Mean objective noise when SP images were reconstructed with ASIR 40 algorithm also included (Star symbol denotes statistically significant difference $p<0.05$)

Figure 2. The magnitude of objective noise reduction (derived by subtracting the objective noise on the MP IR images from the objective noise present on the MP-FBP images) is presented for MP-ASIR 70 and MP-MBIR in patients with BMI>25 and with a BMI<25. (Star symbol denotes statistically significant difference $p<0.05$)

Figure 3. Changes in subjective image quality parameters (median score as measured at 5 anatomical levels of A. Diagnostic Acceptability, B. Subjective Noise, C. Spatial Resolution and D. Contrast Resolution) encountered when MP images were reconstructed with FBP, ASIR-40, ASIR-70 and MBIR. (All differences were statistically significant).

Figure 4. 26-year-old female patient (BMI 17.8 kg/m^2) with increasing pain in her back and lower abdomen accompanied with recent fever on a background of active Crohn's disease. Coronal MP-CT images acquired at **1**00kV and a noise index of 70HU (0.52mSv) reconstructed with **A.** 40% ASIR, **B.** 70% ASIR and **C.** Model Based Iterative Reconstruction demonstrating a 10cm terminal ileal stricture and ileo-ileal fistula. **D.** For comparison we also present a coronal SP-CT image acquired at **1**20kV and a noise index of 38HU (2.8mSv) reconstructed with 40% ASIR.