



Influence of diffusion weighted imaging and contrast enhanced T1 sequences on the diagnostic accuracy of magnetic resonance enterography for Crohn's disease

Gauraang Bhatnagar^a, Sue Mallett^a, Richard Beable^b, Rebecca Greenhalgh^c, Rajapandian Ilangovan^c, Hannah Lambie^d, Evgenia Mainta^c, Uday Patel^c, François Porté^c, Harbir Sidhu^a, Arun Gupta^{c,e}, Anthony Higginson^b, Andrew Slater^f, Damian Tolan^d, Ian Zealley^g, Steve Halligan^a, Stuart A Taylor^{a,*}, on behalf of the METRIC study investigators

^a Centre for Medical Imaging, University College London, Charles Bell House, 43-45 Foley Street W1W 7TS, UK

^b Department of Radiology, Portsmouth Hospitals NHS Trust, Portsmouth, UK

^c Intestinal Imaging Centre, St Mark's Hospital, LNWUH NHS Trust, Harrow, UK

^d Department of Radiology, St James's University Hospital, Leeds Teaching Hospitals NHS Trust, Beckett Street, Leeds LS9 7TF, UK

^e Department of Surgery and Cancer, Imperial College London, Exhibition Rd, South Kensington, London SW7 2BX, UK

^f Department of Radiology, Oxford University Hospitals NHS Trust, Oxford, UK

^g Department of Radiology, Ninewells Hospital, Dundee DD1 9SY, UK

ARTICLE INFO

Keywords:

Crohn Disease
Magnetic Resonance Imaging
Diagnosis

ABSTRACT

Objectives: To evaluate the additional diagnostic benefit of diffusion weighted imaging (DWI) and contrast enhanced (CE) images during MR enterography (MRE) of Crohn's disease.

Methods: Datasets from 73 patients (mean age 32; 40 male) (28 new-diagnosis, 45 relapsed) were read independently by two radiologists selected from a pool of 13. Radiologists interpreted datasets using three sequential sequence blocks: (1) T2 weighted and steady state free precession gradient echo (SSFP) images alone (T2^{*}); (2) T2 weighted and SSFP images with DWI (T2 + DWI^{*}) and; (3) T2 weighted images, SSFP, DWI and post-contrast enhanced (CE) T1 images (T2 + DWI + CE^{*}), documenting presence, location, and activity of small bowel disease. For each sequence block, sensitivity and specificity (readers combined) was calculated against an outcome-based construct reference standard.

Results: 59/73 patients had small bowel disease. Per-patient sensitivity for disease detection was essentially identical (80 % [95 % CI 72, 86], 81 % [73,87], and 79 % [71,86] for T2^{*}, T2 + DWI^{*} and T2 + DWI + CE^{*} respectively). Specificity was identical (82 % [64 to 92]). Per patient sensitivity for disease extent was 56 % (47,65), 56 % (47,65) and 52 % (43 to 61) respectively, and specificity was 82 % (64 to 92) for all blocks. Sensitivity for active disease was 97 % (90,99), 97 % (90,99) and 98 % (92,99), and specificity was also comparable between all sequence combination reads. Results were consistent across segments and newly diagnosed/relapse patients.

Conclusion: There is no additional diagnostic benefit of adding either DWI or CE to T2 FSE and SSFP sequences for evaluating small bowel Crohn's disease, suggesting MRE protocols can be simplified safely.

Abbreviations: DWI, diffusion weighted imaging; CE, contrast enhanced; MRE, MR enterography; SSFP, steady state free precession gradient echo images; CD, Crohn's disease; ESGAR, European Society of Gastrointestinal and Abdominal Radiology; NIHR HTA, National Institute of Health Research health technology assessment programme; BSGAR, British Society of Gastrointestinal and Abdominal Radiology; CRF, Clinical research form; DP, disease positive; TP, true positive; FN, false negative; DN, disease negative; TN, true negative; FP, false positive.

* Corresponding author at: Centre for Medical Imaging, University College London, Charles Bell House, 43-45 Foley Street W1W 7TS.

E-mail address: stuart.taylor@ucl.ac.uk (S.A. Taylor).

<https://doi.org/10.1016/j.ejrad.2024.111454>

Received 22 February 2023; Received in revised form 5 March 2024; Accepted 4 April 2024

Available online 5 April 2024

0720-048X/© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Magnetic Resonance Enterography (MRE) is implemented widely for diagnosis, staging, and follow up of Crohn's disease (CD) [1–3]. Diagnostic accuracy depends on technique, including appropriate sequences [4,5]. A variety of protocols are employed in clinical practice. The European Society of Gastrointestinal and Abdominal Radiology (ESGAR) recommend acquisition of T2 weighted fast spin echo (with and without fat saturation), steady state free precession gradient echo (SSFP), and pre and post gadolinium enhanced fat saturated T1 weighted images, with additional sequences, including Diffusion Weighted Imaging (DWI) being optional [6].

In recent years, concerns have emerged regarding routine use of intravenous gadolinium, with studies demonstrating long-term brain retention [7], which might be detrimental [8]. This is of particular concern for the CD population, who are often young and frequently undergo multiple MRE examinations over their disease course. Patients also identify repeated breath holding, scan discomfort, and injections amongst their greatest concerns during MRE [9]. Shorter MRE protocols would likely improve patient experience as well as being quicker, more efficient, cheaper, and likely safer. While there is increasing evidence supporting replacement of contrast enhanced sequences with DWI [10–13] the diagnostic benefit of DWI over standard T2 weighted images remains unclear [14], and use is ad hoc.

We conducted a prospective multi-centre trial comparing the diagnostic accuracy of MRE with small bowel ultrasound (SBU) in CD [2,15]. The trial afforded the opportunity to evaluate the diagnostic benefit of DWI and contrast enhanced sequences over basic T2 weighted fast spin echo and steady state free precession gradient echo (SSFP) sequences as a pre-specified secondary outcome.

2. Methods

2.1. Study population

This study was conducted as a pre-specified secondary outcome of a larger multi-centre, prospective cohort trial investigating the sensitivity of MRE and SBU [15]. The trial recruited two patient cohorts: (1) newly diagnosed and, (2) established disease, clinically suspected of luminal relapse [2,15]. Full ethical permission was obtained (NRES Committee September 2013 reference 13/SC/0394). This work was supported by the National Institute of Health Research health technology assessment (NIHR HTA) programme (ISRCTN03982913).

2.2. Study design

MRE was performed as per usual clinical practice at recruitment sites with a minimum sequence set, including T2 weighted, SSFP, DWI and pre and post gadolinium enhanced fat saturated T1 weighted sequences. (Appendix 1).

2.3. Radiologists

Thirteen radiologists from seven of the eight trial recruitment sites participated in the current sub-study. All were affiliated with the British Society of Gastrointestinal and Abdominal Radiology (BSGAR), held the Fellowship of the Royal College of Radiologists with a least 1-year subspecialty training in gastrointestinal radiology.

2.4. MRE dataset selection and interpretation

All MRE datasets acquired as part of the main trial were uploaded to an online viewing platform (Biotronics 3Dnet, Biotronics 3D, London, UK) which afforded the full functionality of a standard PACS system. The first 75 consecutive recruits were selected for the current sub-study. This number was a pragmatic choice to balance between a sufficient number

of datasets to meet the study aims and the workload of participating radiologists, and no power calculation was undertaken. The study statistician randomly allocated datasets to participating radiologists for interpretation, ensuring no radiologist was allocated an examination they had already interpreted as part of the main trial. Each dataset was read twice, once by each of two separate radiologists. For each dataset, participating radiologists first interpreted T2 weighted fat sat and non-fat sat and SSFP images alone (T2^{*}), then these with the addition of DWI (T2 + DWI^{*}), and then finally with the addition of post-contrast T1 images (T2 + DWI + CE^{*}). The software allowed the radiologist to select only those sequences permitted for each of the three interpretations. The readers read all three sequence blocks related to an individual study in a single sitting.

For each individual sequence combination read, radiologists were asked to record segmental disease presence, activity and extra-enteric manifestations on a trial clinical research form (CRF) (Appendix 2). The small bowel and colon were divided into 4 and 6 segments respectively (duodenum, jejunum, ileum, terminal ileum, rectum, sigmoid, descending colon, transverse, ascending and caecum) using previously published definitions [16]. Radiologists documented their diagnostic confidence for disease presence in each bowel segment from 1 to 6. Radiologists also recorded the time to interpret each of the three sequence blocks. Radiologists were blinded to all other imaging, endoscopic and clinical data as well as the reference standard results.

2.5. Reference standard

The reference standard for disease presence, extent and activity for each patient was that used by the main trial, i.e. an outcome-based, construct reference standard (Appendix 3) [2,15].

2.6. Statistical analysis

The primary outcome was to compare per patient interpretation sensitivity and specificity for small bowel disease presence, (irrespective of segmental location and disease activity) for each MRE sequence block against the consensus reference standard. Secondary outcome measures were comparisons (1) per patient sensitivity and specificity for small bowel disease extent (incorporating correct segmental localisation) (2) sensitivity and specificity for disease presence in individual small bowel segments, (3) per patient sensitivity and specificity for small bowel disease activity, (4) per patient sensitivity and specificity for colonic disease presence and (5) colonic disease activity.

The 6 point confidence scale for disease presence and activity were converted to a binary outcome; “no disease/ not active” (confidence levels 1 and 2) or “disease present/ disease active” (confidence levels 3 to 6), mirroring the main trial analysis [2]. Radiologist interpretations for each outcome were classified as true positive, false negative, true negative or false positive by comparison to the consensus reference. For disease extent, radiologists had to agree both on disease presence and (all) segmental location(s). Colonic segments were grouped into right (caecum, ascending, transverse colon segments) and left (descending, sigmoid, rectum). Sensitivity was calculated as the percentage of true positive over reference standard positive. Specificity was calculated as the percentage of true negative over reference standard negative. 95 % confidence intervals (CI) were calculated using the Wilson method [17]. Results were presented as Forest plots of sensitivity and specificity.

As patients were interpreted by the same radiologist for the three sequence blocks with few missing data, multilevel analysis was not required to demonstrate no difference, as unclustered analysis provided conservative estimates. Similar methods were used for 95 % CI, data and interpretation of significance for reporting time and detection of extra enteric complications.

A less-detailed analysis of a small proportion of these data (on the same 73 patients) has been published previously at the requirement of the funder [18]. The current report presents a more detailed analysis and

description of study findings.

3. Results

Two of the 75 patients initially recruited were excluded as their final diagnosis was not CD. Of the remaining 73 patients (40 Male, mean age 32) 28 were newly diagnosed and 45 had suspected relapse. Full patient characteristics are presented in Table 1. Ultimately, 59 of the 73 (81 %) patients had small bowel disease based on the reference standard and 31 of the 73 (42 %) had colonic disease. As each dataset was read twice, there were 146 reads. Seven CRFs omitted information for the contrast enhanced T1 weighted images: a single MRE (two reads) omitted the contrast enhanced sequences and in another 5 MREs one of the two readers failed to comment upon the CE sequences, resulting in 139 reads for block 3 (T2 + DWI + CE⁺) (Fig. 1).

Sensitivity and specificity for small bowel disease presence was very similar between the 3 sequences blocks both overall, and for both patient cohorts (Fig. 2). Specifically, sensitivity was 80 % (95 %CI 72–86 %), 81 % (95 %CI 73–87 %) and 79 % (95 %CI 71–86 %) for (T2⁺), (T2 + DWI⁺) and (T2 + DWI + CE⁺) respectively and specificity 82 % (95 %CI 64–92 %) for all three sequence blocks.

Sensitivity and specificity for each individual small bowel segment was also very similar between the 3 sequence blocks (Fig. 3). As outcome point estimates are all within the 95 % CI of compared sequences, it is appropriate and conservative to base conclusions of no difference between sequences without requiring formal calculation of differences [19].

Sensitivity and specificity for small bowel disease extent (Fig. 4) was

Table 1
Characteristics of patients according to patient cohort.

Characteristics	All patients N = 73	
	Newly diagnosed patients [n (%)] N = 28	Suspected relapse patients [n (%)] N = 45
Age – yrs., median (IQR)	32 (24 to 48)	33 (23 to 46)
Male	16 (57)	24 (53)
Previous enteric surgery		
Yes	1 (4) ^a	27 (60)
Colonoscopy available to consensus reference panel	27 (96)	17 (38)
Disease presence		
Small bowel	26 (93)	33 (73)
Colon	14 (50)	17 (38)
Disease duration		
< 1 year	NA	1 (2)
1–5 years	NA	12 (27)
6–10 years	NA	11 (24)
> 10 years	NA	21 (47)
Previous disease location (Montreal classification)		
L1	NA	14 (31)
L2	NA	8 (8)
L3	NA	22 (49)
L4	NA	1 (2)
Previous disease behaviour (Montreal classification)		
B1	NA	24 (54)
B1p	NA	1 (2)
B2	NA	14 (31)
B3	NA	5 (11)
B3p	NA	1 (2)
Inclusion criteria for suspected relapse cohort patients		
Raised CRP > 8 mg/l	NA	21 (47)
Raised calprotectin > 100	NA	3 (7)
Obstructive symptoms	NA	24 (53)
Abnormal endoscopy	NA	3 (7)

Of the 75 patients recruited for the study, 2 patients were withdrawn due not having Crohn's disease at consensus stage.

NA – not applicable as characteristics are only relevant to relapse patients.

^a Surgical resection for inflammatory mass 1 year prior to Crohn's disease diagnosis.

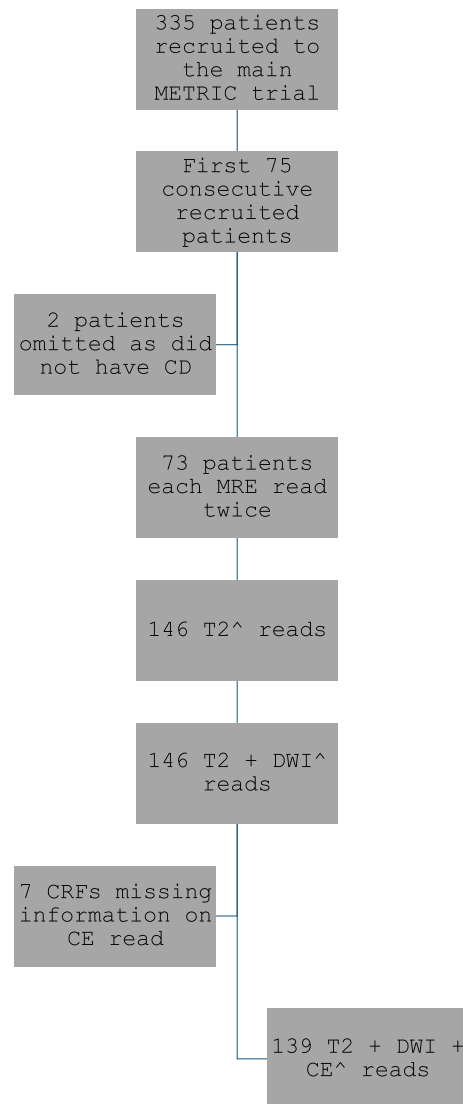


Fig. 1. Flow diagram showing participants included in this sub-study.

lower than that for small bowel disease presence but remained very similar between the 3 sequences blocks. Specifically, sensitivity was 56 % (95 %CI 47–65 %) for both (T2⁺) and (T2 + DWI⁺) and 52 % (95 %CI 43–61 %) for (T2 + DWI + CE⁺).

Specificity was 82 % (95 %CI 64–92 %) for all three sequence blocks.

Sensitivity and specificity for small bowel disease activity was also essentially equal between the three sequence blocks. Sensitivity was 97 % (95 %CI 90–99 %), 97 % (95 %CI 91–99 %) and 98 % (95 %CI 92–99 %) for (T2⁺), (T2 + DWI⁺) and (T2 + DWI + CE⁺) respectively. Small bowel disease was classified as inactive by the reference standard in only a small number of patients (n = 11 patients), including by chance over half the interpretations resulting from 3 patients with false positive activity ratings in the main trial. Specificity was similar between all 3 sequences, although estimates were low and imprecise due to small sample size and sample selection (8 % (95 %CI 2–35 %), 33 % (95 %CI 14–61 %), 18 % (95 %CI 5–48 %)) (Fig. 5).

Sensitivity and specificity for colonic disease presence, segmental location and activity are shown in appendix 4 and 5. While both sensitivity and specificity were generally lower than for small bowel, there was no meaningful difference between the 3 sequences blocks overall, according to patient cohort or between the left and right colon.

The readers correctly diagnosed an abscess in 75 % (6/8) cases on (T2⁺). No additional abscess was diagnosed with the addition of DWI.

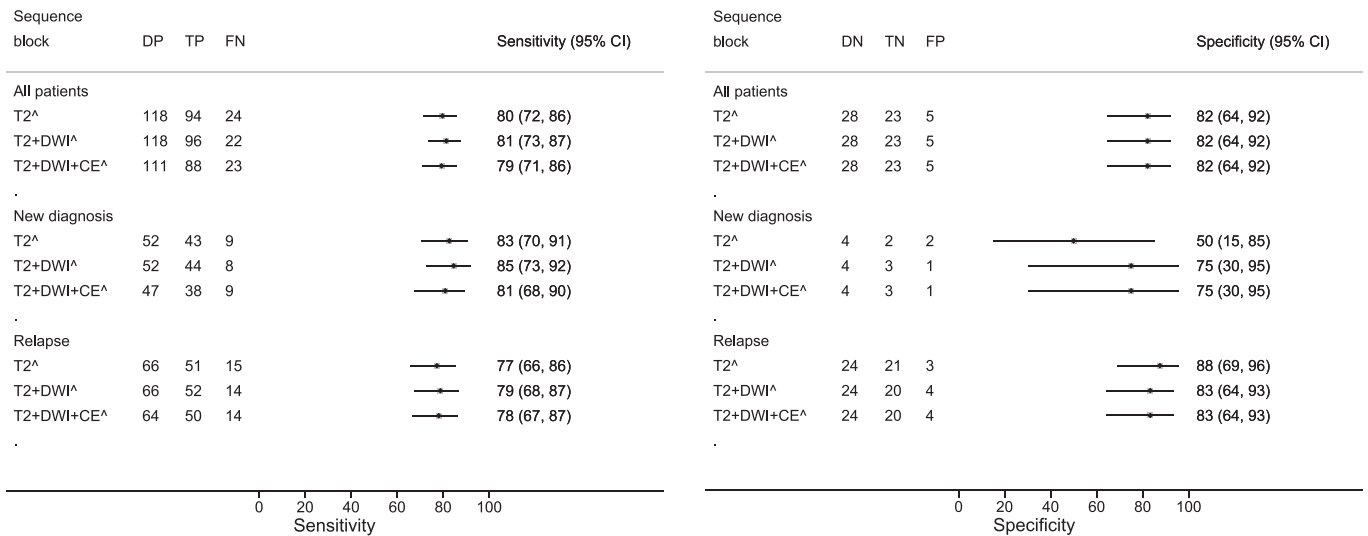


Fig. 2. Forest plot demonstrating sensitivity and specificity of T2[^](T2 and SSFP), T2 + DWI[^](T2, SSFP and DWI) and T2 + DWI + CE[^](T2, SSFP, DWI and post contrast sequences) for small bowel disease presence in all patients, new diagnosis and relapse cohorts. DP (disease positive), TP (true positive), FN (false negative), DN (disease negative), TN (true negative), FP (false positive).

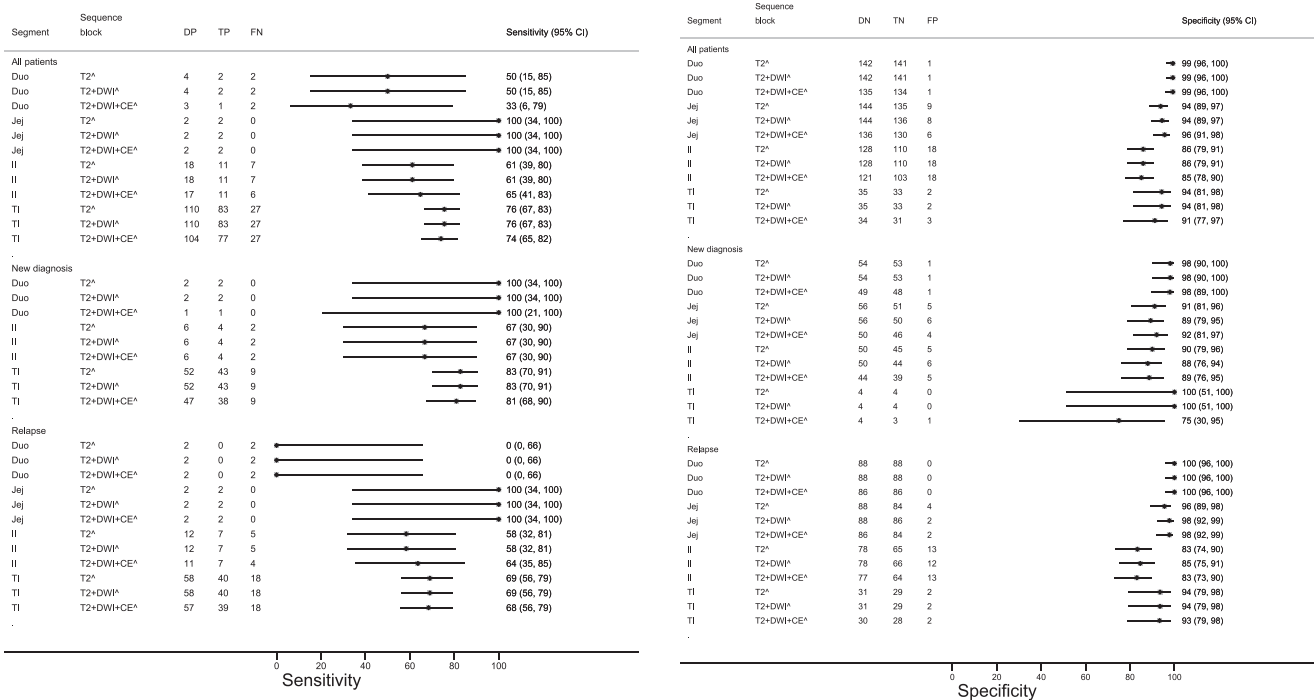


Fig. 3. Forest plot demonstrating sensitivity and specificity of T2[^](T2 and SSFP), T2 + DWI[^](T2, SSFP and DWI) and T2 + DWI + CE[^](T2, SSFP, DWI and post contrast sequences) for segmental small bowel disease presence in all patients, new diagnosis and relapse cohorts. DP (disease positive), TP (true positive), FN (false negative), DN (disease negative), TN (true negative), FP (false positive). Duo (duodenum), Jej (jejunum), Il(ileum), TI (terminal ileum).

One additional abscess was diagnosed with the addition of post contrast T1 sequences [88 % (7/8)]. Readers correctly diagnosed a fistula in 90 % (9/10) cases on (T2[^]) alone. No additional fistula was diagnosed with the addition of either DWI or post contrast T1 sequences.

(T2[^]) alone took a median 7 min (min) (IQR 5–10 min.) to interpret. The additional DWI images took a further median 3 min. (IQR 2–5 min.) and interpretation of post-contrast T1 images added a further median 3 min. (IQR 2–5 min.). In total, interpretation of (T2 + DWI + CE[^]) took a further median 6 min. (IQR 4–10 min.) over (T2[^]) alone.

4. Discussion

MR enterography is established for management of Crohn’s disease, although resource intensive and relatively burdensome for patients [9]. Using a locked sequential read paradigm, we found no additional diagnostic benefit from adding DWI and then post contrast enhanced T1-weighted imaging to a basic T2 and SSFP sequence. Our findings therefore suggest shorter and simpler MRI protocols are sufficient for diagnostic purposes and would reduce radiologists’ interpretation times by a median of 6 min. Reducing scan time and omitting intravenous gadolinium is undoubtedly advantageous by reducing unit-cost [20–22]

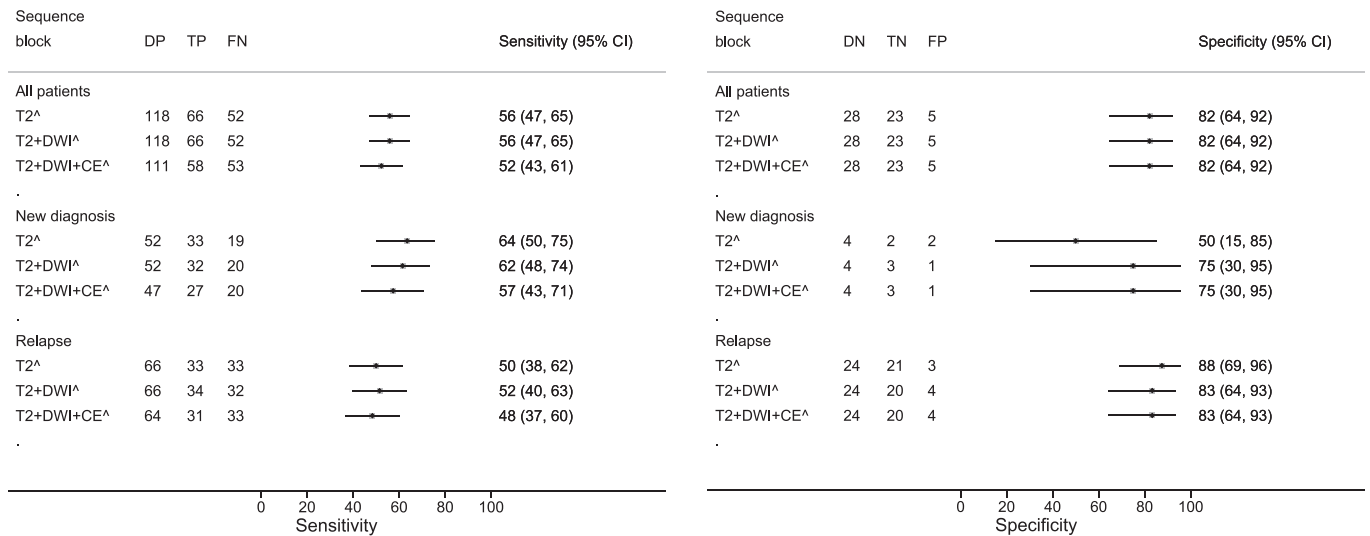


Fig. 4. Forest plot demonstrating sensitivity and specificity of T2^(T2 and SSFP), T2 + DWI^(T2, SSFP and DWI) and T2 + DWI + CE^(T2, SSFP, DWI and post contrast sequences) for small bowel disease extent in all patients, new diagnosis and relapse cohorts. DP (disease positive), TP (true positive), FN (false negative), DN (disease negative), TN (true negative), FP (false positive).

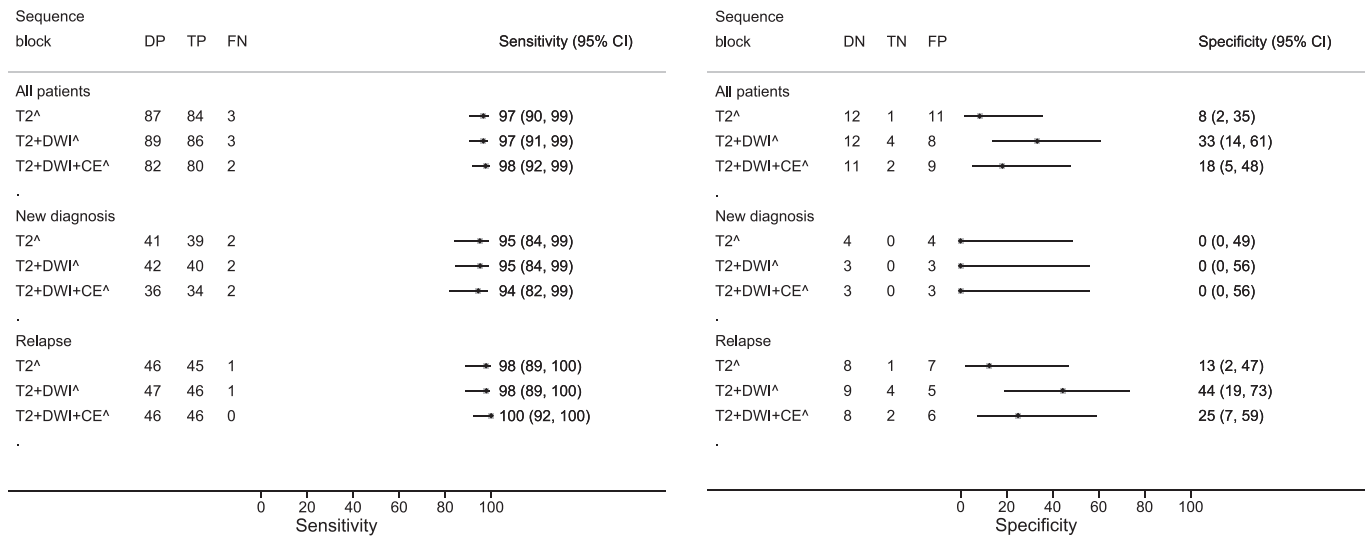


Fig. 5. Forest plot demonstrating sensitivity and specificity of T2^(T2 and SSFP), T2 + DWI^(T2, SSFP and DWI) and T2 + DWI + CE^(T2, SSFP, DWI and post contrast sequences) for small bowel disease activity in all patients, new diagnosis and relapse cohorts.

and improving safety and patient experience.

Our MRI data was acquired prospectively as part of a multicenter study using a range of scanners, and consecutive in accrual, with no pre-selection of included datasets. Furthermore, we included patients newly diagnosed with Crohn’s disease as well as those suspected of relapse, and used a robust outcome-based, construct reference standard. Our data are therefore likely to generalise to routine clinical practice, which strengthens our conclusions. We also used a pool of 13 radiologists to increase generalisability further.

Our findings concur with much of the emerging literature around the diagnostic utility or otherwise of gadolinium enhanced sequences. In a study of 59 patients, Maccioni et al directly compared T2 weighted images with post contrast T1 weighted images and found them almost identical in terms of disease detection (95 % vs. 93 %), although T2 weighted images had higher sensitivity for stenosis [23].

Seo et al, demonstrated that MRE with DWI was non-inferior to MRE with CE T1 for evaluation of inflammation in CD (in a study of 50 patients, there was agreement in 91.8 % (157 of 171 segments) [12].

Similar findings were reported by Neubauer et al in a cohort of 33 children and young adults, where DWI and CE-MRI correctly identified Crohn’s disease in 32 and 31 patients [13]. Our findings do however differ from those of Low et al who, in a small retrospective study of 28 patients, reported much higher sensitivities of 89 % and 85 % for post contrast sequences in comparison to 51 % and 52 % for T2 images alone (p < 0.001) [24].

Importantly, we also found the addition of DWI conveyed no advantage over simple T2, and SSFP images alone, suggesting DWI may not be required even when gadolinium enhanced image are omitted also. In a retrospective study of 112 patients without any independent reference standard, Jhaveri et al reported high levels of intra-reader agreement for disease detection and activity assessment using SSFP images alone, compared to a full MRE protocol including T2 weighted and gadolinium enhanced images [25], supporting our findings.

Our dataset contained relatively few penetrating complications. In general, most complications were detected using T2 and SSFP images alone, although one additional abscess was detected using gadolinium.

Seo et al also reported that a small number of penetrating complications were better detected/characterised using gadolinium [12]. Gadolinium may therefore be indicated in patients with known penetrating disease or when such complications are suspected clinically. However, the vast majority of MRE is performed in patients without a penetrating disease phenotype, and those with penetrating disease are usually pre-identified based on clinical findings and records. Targeting gadolinium administration to such patients rather administering it for all MRE examinations is clearly a more efficient policy.

Anecdotally, we believe less-experienced radiologists have greater confidence when viewing contrast enhanced images. During the initial MRE interpretations in the main trial, reporting radiologists documented the subjective impact of DWI and gadolinium enhanced images on their decision making. Although they reported increased diagnostic confidence in 64 % (168/263) and 70 % (189/271) of cases after reviewing the DWI and post contrast sequences respectively [18], actual diagnosis changed in just 6 % (15/263) and 5 % (14/271). These data further reinforce the concept that diffusion weighted and post-contrast sequences have little impact on diagnostic accuracy in the majority of MRE examinations.

Our study does have limitations. Our sample size was pragmatic, and although reasonable compared to existing studies of sequence impact, was not based on any power calculation. However, we found no evidence in the data that would suggest DWI or contrast enhancement has any major impact on diagnostic accuracy. The 146 reads incorporated in this study consisted of two individual opinions on 73 MREs and was specifically designed to be performed as part of a detailed study investigating interobserver agreement in MRE interpretation [26]. We therefore did not specifically measure interobserver agreement in the current study given this data has been already published from the same cohort. The analyses of this study was designed specifically to address generalizability by using multiple readers and multiple cases to evaluate whether additional sequences were helpful. The incidence of subtle disease as judged by a mural thickness of 3 mm was low, reported in only 8/146 reads (5 %), as such we were not able to make any conclusions on the contribution of these sequences in the diagnostic accuracy for cases of subtle disease. Readers had a declared interest in gastrointestinal radiology and it is possible if we had used very inexperienced readers the conclusions could have been different. This study, akin to the main trial was not designed to evaluate for fibrotic or mixed disease which would need surgical specimens as a standard of reference. The current study evaluated the diagnostic accuracy of disease presence and activity only. The absolute values for specificity related to active disease are lower than in the main trial. This was secondary to oversampling of false positive results for active disease from the main trial in this subset. As such the specificity values on their own are unreliable but still apply in comparing between the differing sequence reads. As noted above, our dataset included few penetrating complications and our interpretation cannot be extrapolated to those with complex penetrating disease. Whilst the order of revelation of the different sequences were discussed, including a randomized approach, we determined that revealing sequences in this specific order ((1)T2', (2) T2 + DWI' and (3) T2 + DWI + CE') optimized this study to demonstrate the diagnostic advantage or otherwise of contrast-enhanced images over an optimised MRE sequence protocol. Whilst we acknowledge that this may have biased some readers who wished not to change their opinion following the first sequence read we felt this was a stronger methodology to truly assess the impact of the additional sequences and especially the advantage or otherwise of gadolinium administration which has significant potential medical and financial implications. Finally, this study does not evaluate the impact of radiomics which is an area demonstrating promise in evaluating disease activity [27,28].

In summary, we found no significant diagnostic impact on accuracy for small bowel (or colonic) Crohn's disease presence, extent, or activity (1) when adding diffusion weighted imaging to basic T2 weighted and steady state free precession gradient echo images alone or (2) when

adding gadolinium enhanced T1 weighted sequences to a combination of T2 weighted, steady state free precession gradient echo images and diffusion weighted imaging. The majority of MRE examinations can be performed with no impact on diagnostic accuracy with a reduced sequence protocol.

5. Funding source

This work was supported by the National Institute of Health Research health technology assessment NIHR HTA programme (project number 10/68/01).

The project is supported by researchers at the National Institute of Health Research University College London Hospitals Biomedical Research Centre. The views and opinions expressed by authors in this publication are those of the authors and do not necessarily reflect those of the NHS, NIHR, NIHR Evaluation, Trials and Studies Coordinating Centre (NETSCC), HTA programme, or the Department of Health.

6. List of METRIC study investigators

Rachel Baldwin-Cleland, Stuart Bloom, Peter J Hamlin, Ailsa L Hart, Antony, Ilan Jacobs, Sara McCartney, Anne Miles, Charles D Murray, Andrew A Plumb, Richard C Pollok, Shonit Punwani, Laura Quinn, Manuel Rodriguez-Justo, Zainib Shabir, Simon Travis, Alastair Windsor, Peter Wylie, Jade Dyer, Pranitha Veeramalla, Sue Tebbs, Steve Hibbert, Richard Ellis, Fergus Thursby-Pelham, Richard Beable, Nicola Gibbons, Claire Ward, Anthony O'Connor, Hannah Lambie, Rachel Hyland, Nigel Scott, Roger Lapham, Doris Quartey, Deborah Scrimshaw, Helen Bungalow, Maggie Betts, Simona Fourie, Niall Power, Phillip Lung, Ian Johnston, Mani Naghibi, Morgan Moorghen, Adriana Martinez, Christopher Alexakis, James Pilcher, Anisur Rahman, Jonny Vlahos, Anita Wale, Teresita Beeston, Wivijin Piga, Joey Clemente, Farooq Rahman, Simona de Caro, Shameer Mehta, Roser Vega, Roman Jastrub, Harbir Sidhu, Hameed Rafiee, Mairead Tennent, Caron Innes, Craig Mowat, Gillian Duncan, and Steve Morris.

CRediT authorship contribution statement

Gauraang Bhatnagar: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Sue Mallett:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Beable:** Investigation. **Rebecca Greenhalgh:** Investigation. **Rajapandian Ilangovan:** Investigation. **Hannah Lambie:** Investigation. **Evgenia Mainta:** Investigation. **Uday Patel:** Investigation. **François Porté:** Investigation. **Harbir Sidhu:** Investigation. **Arun Gupta:** Investigation. **Anthony Higginson:** Investigation. **Andrew Slater:** Investigation. **Damian Tolan:** Investigation. **Ian Zealley:** Investigation. **Steve Halligan:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Stuart A Taylor:** Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization, Writing – original draft, Writing – review & editing.

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.

STaylor has shares in Motilent, research support from Takeda and research consultant to Aztrazeneca.

Appendices. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ejrad.2024.111454>.

References

- [1] J. Panés, R. Bouzas, M. Chaparro, et al., Systematic review: The use of ultrasonography, computed tomography and magnetic resonance imaging for the diagnosis, assessment of activity and abdominal complications of Crohn's disease, *Aliment Pharmacol. Ther.* 34 (2011) 125–145, <https://doi.org/10.1111/j.1365-2036.2011.04710.x>.
- [2] S.A. Taylor, S. Mallett, G. Bhatnagar, et al., Diagnostic accuracy of magnetic resonance enterography and small bowel ultrasound for the extent and activity of newly diagnosed and relapsed Crohn's disease (METRIC): A multicentre trial, *Lancet Gastroenterol. Hepatol.* 3 (2018) 548–558, [https://doi.org/10.1016/S2468-1253\(18\)30161-4](https://doi.org/10.1016/S2468-1253(18)30161-4).
- [3] C.A.J. Puylaert, J.A.W. Tielbeek, S. Bipat, J. Stoker, Grading of Crohn's disease activity using CT, MRI, US and scintigraphy: A meta-analysis, *Eur. Radiol.* 25 (2015) 3295–3313, <https://doi.org/10.1007/s00330-015-3737-9>.
- [4] K. Jesuratnam-Nielsen, V.B. Løgager, B. Rezanavaz-Gheshlagh, et al., Plain magnetic resonance imaging as an alternative in evaluating inflammation and bowel damage in inflammatory bowel disease - A prospective comparison with conventional magnetic resonance follow-through, *Scand. J. Gastroenterol.* 50 (2015) 519–527, <https://doi.org/10.3109/00365521.2014.1003398>.
- [5] D.H. Bruining, G. Bhatnagar, J. Rimola, et al., CT and MR enterography in Crohn's disease: Current and future applications, *Abdom. Imaging* (2015), <https://doi.org/10.1007/s00261-015-0360-9>.
- [6] Taylor SA, Avni F, Cronin CG, Hoeffel C, Kim SH, Laghi A, Napolitano M, Petit P, Rimola J, Tolan DJ, Torkzad MR, Zappa M, Bhatnagar G, Puylaert CAJ SJ (2017) The first joint ESGAR/ ESPR consensus statement on the technical performance of cross-sectional small bowel and colonic imaging. *Eur Radiol* 27:2570–2582. Doi: 10.1007/s00330-016-4615-9.
- [7] C. Olchoway, K. Cebulski, M. Łasecki, et al., The presence of the gadolinium-based contrast agent depositions in the brain and symptoms of gadolinium neurotoxicity-A systematic review, *PLoS One* 12 (2017) 1–14, <https://doi.org/10.1371/journal.pone.0171704>.
- [8] Iyad N, S.Ahmad M, Alkhatib SG, Hjouj M (2023) Gadolinium contrast agents-challenges and opportunities of a multidisciplinary approach: Literature review. *Eur. J. Radiol. Open* 11. DOI 10.1016/j.ejro.2023.100503.
- [9] A. Miles, G. Bhatnagar, S. Halligan, et al., Magnetic resonance enterography, small bowel ultrasound and colonoscopy to diagnose and stage Crohn's disease: Patient acceptability and perceived burden, *Eur. Radiol.* 43–45 (2018), <https://doi.org/10.1007/s00330-018-5661-2>.
- [10] A. Dohan, S. Taylor, C. Hoeffel, et al., Diffusion-weighted MRI in Crohn's disease: Current status and recommendations, *J. Magn. Reson. Imaging* 44 (2016) 1381–1396, <https://doi.org/10.1002/jmri.25325>.
- [11] S.H. Choi, K.W. Kim, J.Y. Lee, et al., Diffusion-weighted magnetic resonance enterography for evaluating bowel inflammation in Crohn's disease, *Inflamm. Bowel Dis.* (2015) 1, <https://doi.org/10.1097/MIB.0000000000000607>.
- [12] N. Seo, S.H. Park, K.J. Kim, et al., MR enterography for the evaluation of small-bowel inflammation in Crohn disease by using diffusion-weighted imaging without intravenous contrast material: A prospective noninferiority study, *Radiology* 278 (2016) 762–772, <https://doi.org/10.1148/radiol.2015150809>.
- [13] H. Neubauer, T. Pabst, A. Dick, et al., Small-bowel MRI in children and young adults with Crohn disease: Retrospective head-to-head comparison of contrast-enhanced and diffusion-weighted MRI, *Pediatr. Radiol.* 43 (2013) 103–114, <https://doi.org/10.1007/s00247-012-2492-1>.
- [14] K.-J. Kim, Y. Lee, S.H. Park, et al., Diffusion-weighted MR enterography for evaluating Crohn's disease: How does it add diagnostically to conventional MR enterography? *Inflamm. Bowel Dis.* 21 (2015) 101–109, <https://doi.org/10.1097/MIB.0000000000000222>.
- [15] S. Taylor, S. Mallett, G. Bhatnagar, et al., METRIC (MREnterography or ulTRAsound in Crohn's disease): A study protocol for a multicentre, non-randomised, single-arm, prospective comparison study of magnetic resonance enterography and small bowel ultrasound compared to a reference standard in those, *BMC Gastroenterol.* 14 (2014) 142, <https://doi.org/10.1186/1471-230X-14-142>.
- [16] S.A. Taylor, S. Halligan, V. Goh, et al., Optimizing colonic distention for multi-detector row CT colonography: Effect of hyoscine butylbromide and rectal balloon catheter 1, *Radiology* 229 (2003) 99–108.
- [17] E.B. Wilson, Probable inference, the law of succession, and statistical inference, *J. Am. Stat. Assoc.* (1927), <https://doi.org/10.2307/2276774>.
- [18] Taylor SA, Mallett S, Bhatnagar G, et al (2019) Magnetic resonance enterography compared with ultrasonography in newly diagnosed and relapsing crohn's disease patients: The METRIC diagnostic accuracy study. *Health Technol Assess (Rockv)* 23:vii–161. Doi: 10.3310/hta23420.
- [19] N. Schenker, J.F. Gentleman, On judging the significance of differences by examining the overlap between confidence intervals, *Am. Stat.* (2001), <https://doi.org/10.1198/000313001317097960>.
- [20] K. Bekker, A. Garcés-Descovich, J. Mangosing, et al., Optimizing MRI logistics: Prospective analysis of performance, efficiency, and patient throughput, *Am. J. Roentgenol.* 209 (2017) 836–844, <https://doi.org/10.2214/AJR.16.17698>.
- [21] C.J. Roth, D.T. Boll, L.K. Wall, E.M. Merkle, Evaluation of MRI acquisition workflow with lean six sigma method: Case study of liver and knee examinations, *Am. J. Roentgenol.* 195 (2010) 150–156, <https://doi.org/10.2214/AJR.09.3678>.
- [22] U. Streit, J. Uhlrig, J. Lotz, et al., Analysis of core processes of the MRI workflow for improved capacity utilization, *Eur. J. Radiol.* 138 (2021) 109648, <https://doi.org/10.1016/j.ejrad.2021.109648>.
- [23] F. Maccioni, A. Bruni, A. Viscido, et al., MR imaging in patients with Crohn disease: Value of T2- versus T1-weighted gadolinium-enhanced MR sequences with use of an oral superparamagnetic contrast agent, *Radiology* (2006), <https://doi.org/10.1148/radiol.2381040244>.
- [24] R.N. Low, C.P. Sebregts, D.A. Politoske, et al., Crohn disease with endoscopic correlation: Single-shot fast spin-echo and gadolinium-enhanced fat-suppressed spoiled gradient-echo MR imaging, *Radiology* 222 (2002) 652–660, <https://doi.org/10.1148/radiol.2223010811>.
- [25] K.S. Jhaveri, S. Sagheb, L. Guimaraes, et al., Evaluation of crohn disease activity using a potential abbreviated MRE protocol consisting of balanced steady-state free precession MRI only versus full-protocol MRE, *Am. J. Roentgenol.* (2021), <https://doi.org/10.2214/AJR.20.22856>.
- [26] G. Bhatnagar, S. Mallett, L. Quinn, et al., Interobserver variation in the interpretation of magnetic resonance enterography in Crohn's disease, *Br. J. Radiol.* (2022), <https://doi.org/10.1259/bjr.20210995>.
- [27] Grassi G, Laino ME, Fantini MC, et al (2022) Advanced imaging and Crohn's disease: An overview of clinical application and the added value of artificial intelligence. *Eur. J. Radiol.* DOI: 10.1016/j.ejrad.2022.110551.
- [28] H. Ding, J. Li, K. Jiang, et al., Assessing the inflammatory severity of the terminal ileum in Crohn disease using radiomics based on MRI, *BMC Med. Imaging* (2022), <https://doi.org/10.1186/s12880-022-00844-z>.