Computed Tomography Enterography and Magnetic Resonance Enterography: The Future of Small Bowel Imaging

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ABSTRACT

In the last 5 years, computed tomography enterography (CTE) and to a lesser extent magnetic resonance enterography (MRE) have supplanted the routine small bowel series and enteroclysis in the evaluation of many small bowel diseases, especially Crohn's disease. Both CTE and MRE use similar methods of bowel lumen opacification and distension and both have distinct advantages and disadvantages. Both have been most extensively studied in patients with Crohn's disease. What is certain is that these cross-sectional examinations have largely replaced the historic fluoroscopic examinations in the evaluation of the small bowel.

KEYWORDS: Computed tomography enterography, magnetic resonance enterography, Crohn's disease, chronic obscure gastrointestinal bleeding

Objectives: On completion of this article, the reader should be able to understand the technique and role of computed tomography enterography (CTE) and magnetic resonance enterography (MRE) in evaluating Crohn's disease and chronic obscure gastrointestinal bleeding.

Historically, radiologic evaluation of the small bowel was performed with either a dedicated small bowel series or small bowel enteroclysis. In the new millennia, computed tomography enterography (CTE) and magnetic resonance enterography (MRE) will supplant the standard approaches in almost all cases. In our institution before 2004, routine small bowel series were common—2 to 4 per day. In 2004 we started a CTE program and since then we have performed over 2,500 of these examinations—3 to 5 per day. As a result, in 2008 the routine small bowel series is now uncommonly ordered for Crohn's disease and chronic gastrointestinal bleeding—less than 5 per week. We

started an MRE program in mid-2007 and have performed over 70 since then.

In this review, we will discuss the techniques of CTE and MRE, their strengths and weaknesses, and their application to patients with known or suspected small bowel disease.

THE DEVELOPMENT OF COMPUTED TOMOGRAPHY ENTEROGRAPHY

Multidetector row CT (MDCT) examines any body part in a continuous fashion, yielding a volume of information.¹ This information can be reconstructed, or "sliced

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and diced," in any plane and produces high-resolution scans with superb image quality.^{2,3} MDCT was the first technologic advance in imaging that facilitated cross-sectional enterography.

The second shift in scanning technique dealt with oral contrast agents. Historically, oral agents in abdominal CT scanning were high attenuation barium or iodine-containing products, defining the intestinal lumen much like arteries and veins are opacified after intravenous iodinated contrast media injection. Although this technology easily defined bowel loops, the high attenuation oral contrast agents obscured the mucosa and inner bowel wall. Low attenuation agents such as water have been used for years, especially in the duodenum and proximal small bowel.⁴⁻⁹ Unfortunately, water is normally absorbed as it traverses the small bowel, such that very little remains at the level of the ileum.

In Europe, where radiation exposure is a major public issue, magnetic resonance oral contrast agents were developed to opacify and distend the small bowel.¹⁰⁻¹⁵ In Essen, Germany, an agent containing mannitol and locust bean gum was developed to distend the small bowel lumen and maintain that distension throughout the small bowel.¹⁶⁻¹⁸ This product was then modified in the United States by E-Z-EM Inc. (Lake Success, NY) to produce a low-attenuation, oral agent for CT that mimics water. However, because it contains nonabsorbable agents, bowel distension is maintained or improved over water.¹⁹ Other agents, such as polyethylene glycol, milk, and lactulose have also been used by investigators with similar results.²⁰⁻²²

COMPUTED TOMOGRAPHY ENTEROGRAPHY TECHNIQUE

The specific technique of CT enterography requires several critical steps. First, the referring physician must inform the patient that the mode and method of oral contrast ingestion is vastly different than previously experienced in CT. Most radiology departments have become complacent as to how much and how fast positive agents should be ingested. Therefore, many patients who have had a prior CT scan, will not expect how much and how often they will need to ingest the oral agent. They must be told that they will be required to drink >1 L of oral contrast in one hour. In our department, we use VoLumen[®] (E-Z-EM, Lake Success, NY). Our protocol is as follows: the patients ingest 450 cc of VoLumen[®] over 20 minutes, followed by another 450 cc of VoLumen[®] over the next 20 minutes. At 40 minutes, they are given an additional 450 cc of VoLumen[®], and an intravenous catheter line (IV) is started. At 60 minutes, they ingest 250 cc of water. The total amount of VoLumen[®] plus water is 1600 cc. At 70 minutes, they are placed on the scanner,

and the CT is performed. Other centers use similar oral contrast regimens.¹⁸ If patients cannot ingest the oral agent in a timely fashion, a judgment is made as to whether a nasogastric or feeding tube is placed to administer the agent. But we have found that patients are much more compliant with this rigorous oral contrast regimen if the ordering physician explains this process to the patient. Preparing the patient by the ordering physician provides an understanding that this rigorous regimen is vital to the scan result and not a demand on the part of an unknown, unseen radiologist.

The second critical step is to enlist the radiology technologist support of the examination and the rigorous oral contrast agent ingestion protocol. Most technologists are comfortable with a laissez-faire approach to oral contrast media ingestion. Because of faster, high-resolution CT scanners, it is often not difficult to identify and distinguish the small bowel from other organs. Consequently, radiologists have not demanded that any oral agents be given in a routine and regimented fashion. With CTE, the technologist must take ownership of the process with the patient and closely monitor the oral contrast intake.

The third step is to understand that CTE requires intravenous contrast enhancement. Intravenous contrast enhancement is essential in the detection and characterization of Crohn's disease, the identification of tumors causing chronic small bowel hemorrhage, the causes of both acute and chronic intestinal ischemia, etc. If the patient cannot receive iodinated contrast media, an adequate CTE cannot be performed. If the reason is chronic kidney disease, a frank and open discussion with the radiologist must occur, as gadolinium-enhanced MRI may not be a reasonable alternative with the identification of nephrogenic systemic fibrosis (NSF), which appears to be related to gadolinium MR contrast agents (see discussion below).²³⁻²⁶

We have two different scanning protocols after the intravenous injection of contrast media: a uniphasic scan and a biphasic scan. The uniphasic scan consists of one examination of the abdomen and pelvis during the portal venous phase, starting 70 seconds after the injection of the contrast (Fig. 1). We use this for patients with Crohn's disease and nonspecific abdominal pain. The biphasic scan consists of two examinations, the first of which is performed during the arterial phase of the exam (typically 20 to 30 seconds after the start of contrast media injection) (Fig. 2). The second phase of the examination is performed during the portal venous phase. We use this technique in patients with obscure gastrointestinal bleeding as well as in patients with suspected ischemic bowel. Because we have two methods of scanning vis-à-vis contrast media administration, it is important for the radiologist to understand the clinical question to protocol the examination appropriately.

Figure 1 (A) Normal uniphasic computed tomography enterography (CTE). Axial scan through the upper abdomen shows the normal, redundant, fold pattern of the jejunum (arrows). The lumen is filled with low Hounsfield unit oral contrast media. (B) Normal uniphasic CTE. Coronal, thin MIP (maximum intensity projection) reconstruction of thin slice axial CTE data. Scan shows the normal, redundant fold pattern of the jejunum (long, thin arrow) and the normal, smooth fold pattern of the ileum (short, fat arrow). (C) Normal uniphasic CTE. Axial scan through the pelvis shows the smooth fold pattern of the ileum (long, thin arrow). The terminal ileum (short, fat arrow) is distended by low Hounsfield oral contrast media. (D) Normal uniphasic CTE. Coronal, thin MIP reconstruction shows the normal terminal ileum (arrowhead).

CTE requires a MDCT scanner, with at least 8 detector rows, preferably 16. Most modern radiology departments have these scanners available, so this should not be an issue. The MDCT scanners with more than 8 rows of detectors allow us to scan and reconstruct both

axial and coronal images (Figs. 1 and 2). Because the small bowel may be oriented in different planes in the abdomen, we find that orthogonal views are essential in detecting disease as well as strictures and fistulae. Additionally, because gastroenterologists and surgeons

Figure 2 (A) Normal biphasic computed tomography enterography (CTE). Coronal, thin MIP (maximum intensity projection) reconstruction obtained during the arterial phase (first phase of a biphasic CTE) shows the normal left colic artery (arrows). More superiorly the left colic becomes the marginal artery. (B) Normal biphasic CTE. Coronal, thin MIP reconstruction obtained during the arterial phase (first phase of a biphasic CTE) shows branches of the inferior mesenteric artery (arrows). (C) Normal biphasic CTE. Sagittal, thin MIP reconstruction shows the origin of the celiac axis (arrow) and superior mesenteric artery (arrowhead).

historically visualized the small bowel on standard small bowel series, they are more comfortable viewing the coronal scans as these are more analogous to barium studies.

MAGNETIC RESONANCE ENTEROGRAPHY

MRE is a technically challenging imaging procedure made possible by several technical developments in MR hardware and software. Oral contrast agent and patient preparation are just as important for MRE as with CTE. MRE requires a scanner that is capable of parallel imaging.²⁷ This technique has markedly reduced scan times by shortening the acquisition time of traditional imaging sequences. This in turn allows rapid, three-dimensional (3D), gradient echo T1-weighted images of the entire abdomen and pelvis in 15 to 20 seconds. Rapid, parallel imaging in conjunction with fat-suppression (a technique used to reduce the high-signal fat) as well as intravenous gadolinium-diethylene triamine pentacetate (DTPA) enhancement, gives us the ability to identify the bowel wall and enhancement. We perform both axial and coronal images, as with CTE (Fig. 3). Additionally, using different techniques, multiple images can now be rapidly obtained at a specific anatomic region, such that a cine-loop of that region can be viewed. This technique allows us to view peristalsis, assessing a small bowel loop proximal to a possible stricture to determine the degree of obstruction.

MRE uses the same oral contrast regimen as CTE. It also requires intravenous contrast administration, using Gd-DTPA instead of iodinated contrast media. The scanning technique is straightforward, but requires a technologist that understands the goals of the examination. Scan setup is more complex than for CTE. The MRE technologist must understand that the goal of the examination is to assess the bowel, and not the entire abdomen and pelvis. Further, rather than including the entire liver and spleen, the perineum must be included to identify perianal/perirectal fistulae/disease.

At our institution, we start with single-shot, axial and coronal HASTE (half-Fourier acquisition single-shot turbo spin-echo), which are heavily T2-weighted to assess the small bowel morphology, and for anatomic detail (Fig. 3). Because these images are acquired very rapidly, motion is not an issue. However, the relatively long, 12 to 18 second, T1-weighted, gradient echo sequences are motion sensitive. Because of motion artifact created by bowel peristalsis, we then inject 1 mg of glucagon intravenously prior to the subsequent sequences. In Europe, scopolamine used as an antispasmodic agent and is considered a superior agent. Unfortunately, this drug is not available in the United States. We then perform a very fast, T1-weighted, gradient echo, fat-suppressed, 3D sequence in both the coronal and axial planes, both before and after gadolinium-DTPA, con-

trast injection (Fig. 3). These are equivalent to enhanced CTE scans. However, we perform these rapid sequences multiple times after the start of contrast injection (often 20 seconds, 60 seconds, 90 seconds, etc., after contrast injection). This gives us the ability to look at wall enhancement over time. We do not as yet know if this aids in detection or characterization of the inflammatory process. We occasionally add True FISP (fast imaging with steady-state precession) sequences to create a cine-loop evaluation of a bowel loop proximal to a potential stricture. To properly perform this, a stricture must be identified prospectively. Once identified, these rapidly acquired sequences can be performed in the area of the stricture to determine whether there is a change in bowel diameter proximal to the stricture during peristalsis. In our experience, only a radiologist directly supervising the examination can consistently and accurately do this.

COMPUTED TOMOGRAPHY ENTEROGRAPHY ADVANTAGES

There are many advantages to CTE. First, MDCT scanners are readily available and the technique is not complex. The scanning parameters are easy to set up and perform by even a novice technologist. The room time to perform a CTE is less than 10 minutes. An entire CTE, from start of oral contrast ingestion to end of scan, takes less than 1.5 hours. Most standard small bowel series take at least 2 to 3 hours. The spatial resolution of a CTE is superb and bowel motion is not a significant problem. We do not routinely use antiperistaltic agents such as glucagon or scopolamine. Most gastroenterologists and surgeons are familiar with CT images and are comfortable viewing the scans. Lastly, when compared with a dedicated small bowel series or an enteroclysis, there is potentially less patient radiation. Fluoroscopy can deliver a significant dose to the patient. Although CT uses ionizing radiation like fluoroscopy, it is at least equivalent to pulsed fluoroscopy and often less. A recent investigation reported that CTE can deliver a greater dose than a dedicated small bowel series.²⁸ However, this investigation used a higher CT tube output than commonly used and underestimated the amount of fluoroscopy for a dedicated small bowel series (5 minutes). Typically, a dedicated small bowel series requires at least 10 minutes of fluoroscopy. By reducing CT tube output and using various tube modulation approaches, CTE dose can equal or even be below the dose received in fluoroscopy.

COMPUTED TOMOGRAPHY ENTEROGRAPHY DISADVANTAGES

The major disadvantage of CTE is ionizing radiation exposure. In a preliminary, unpublished study in our

Figure 3 (A) Magnetic resonance enterography (MRE) of distal ileal Crohn's disease. Axial T2-weighted, HASTE (half-Fourier acquisition single-shot turbo spin-echo) scan thru the terminal ileum (arrows) shows marked wall thickening. (B) MRE of distal ileal Crohn's disease. Coronal T2-weighted HASTE scan through the terminal ileum (arrows) shows marked wall thickening. (C) MRE of distal ileal Crohn's disease. Axial, postcontrast T1-weighted, gradient echo, fat-suppressed, 3D scan through the affected terminal ileum shows near uniform, wall hyperenhancement (arrows) (there is almost no mural stratification) with luminal narrowing (stricture). (D) MRE of distal ileal Crohn's disease. Coronal, postcontrast T1-weighted, gradient echo, fat-suppressed, 3D scan through the affected terminal ileum shows near uniform, wall hyperenhancement with luminal narrowing (large arrow); thus there is a stricture. The vas recta are engorged (known as the Comb sign) (thin arrows).

institution, for adult Crohn's patients, the single dose for a CTE is ~ 10 to 20 mSv. Other institutions have presented or published similar doses.^{28,29} We are making efforts to reduce the overall dose to less than 12 to 15 mSv without any loss in diagnostic image quality. Presented data from the Mayo Clinic suggests that a lower dose technique of 12 mSv will not alter the detection rate of Crohn's disease.²⁹ Other techniques such as using "de-noising" postprocessing of low-dose imaging may also provide a means of reducing patient dose.

MAGNETIC RESONANCE ENTEROGRAPHY ADVANTAGES

There are three major advantages of MRE over CTE. The first obvious advantage is that MRE does not use ionizing radiation to produce images. For young patients, who will be imaged over the course of a chronic disease such as Crohn's, accumulated dose is a significant and concerning issue. The second advantage is that the patient can be imaged with repeated sequences over time after contrast media injection. As of yet, we do not know if this will have any predictive value. However, it is easy to produce contrast enhancement curves of affected bowel segments. Lastly, motion-sensitive techniques mimic fluoroscopy in detecting subtle strictures and relative obstruction.

MAGNETIC RESONANCE ENTEROGRAPHY DISADVANTAGES

The first significant disadvantage of MRE is the availability of magnet time. Most MR imaging units are filled with neurological and musculoskeletal patients. The major reason why we have performed more CT enterography is that CT is much more readily available. Additionally, there are fewer MRI technologists as well as radiologists that can perform high-quality MRI scans of the abdomen when compared with CT technologists and radiologists. Although the pulse sequences are not difficult, dedicated body MRI technologists are uncommon. It is important to have the MRI technologist act much like a sonographer, especially when scan coverage is planned. The technologist must understand that it is not necessary to include the entire upper abdomen to perform a MRE. They only need to include the jejunum in the left upper quadrant. On the other hand, including the perineal region is important in Crohn's patients to assess for perianal fistulae. Also, if pulse sequences used to produce cine-loop scan through abnormal bowel segments, they must be performed in areas of abnormal bowel. In many instances, this requires that the radiologist directly supervise the examination. In most busy practices, this is not practical. Room time for an MRE takes at least 15 to 20 minutes, and can

be longer, depending upon the pulse sequences used. Antiperistaltic or antispasmodic agents such as glucagon or scopolamine must be used during the static phase of the examination. We have noticed that glucagon is not consistently effective in reducing motion artifact from bowel peristalsis. Most of the MR pulse sequences require a breath hold of 13 to 18 seconds. Although most patients can cooperate, some cannot. Lastly, we have anecdotally noted a relatively steep learning curve with MRE. In fact, without our prior, 2-year experience with CTE, we doubt that we would have been as successful with MRE. The spatial resolution of MRE is not as good as CTE and the motion artifact often makes evaluation difficult.

The other potential limitation of MRE is with the use of intravenous contrast media. In the recent past, performing MRE with gadolinium enhancement was considered safe in patients with renal insufficiency, especially because there was no deleterious effect on the kidneys with the small volumes of gadolinium injected. Unfortunately, in the last 18 months a debilitating, potentially fatal disease known as nephrogenic systemic fibrosis (NSF) has been identified in patients with chronic kidney disease (CKD), especially in patients on dialysis, with estimated glomerular filtration rate (eGFRs) < 15 mL/min/1.73 m² who have received gadolinium for MRI.²³⁻²⁶ Although this is an evolving area of investigation and much more work must be done, some radiologists may be reluctant to inject gadolinium into patients with chronic kidney disease. Most patients with NSF have eGFRs < 30 mL/min/1.73 m². NSF has also been reported in a few patients with eGFRs up to 60 mL/min/1.73 m².²⁴ Thus, gadolinium enhanced MRI in any patient with CKD must be individually evaluated and a determination must be made if the MRE is better than an enhanced CTE. Some nephrologists may prefer to treat contrast-induced nephropathy from a iodinated-contrast enhanced CT rather than deal with NSF.

COMPUTED TOMOGRAPHY ENTEROCLYSIS AND MAGNETIC RESONANCE ENTEROCLYSIS

In a few centers, a modification of the CTE and MRE technique is used by means of placing a naso- or orojejunal tube fluoroscopically and mechanically pumping oral contrast agent into the small bowel.^{27,30-34} This mimics the standard enteroclysis technique performed exclusively in the fluoroscopy suite. The advantage of CT enteroclysis or MR enteroclysis over standard enteroclysis is that the entire bowel length and wall is visualized as well as extraintestinal structures. The advantage of CT enteroclysis or MR enteroclysis over standard CTE is that it increases the likelihood that the bowel lumen will be more consistently distended over its

Figure 4 (A) Computed tomography enterography (CTE) of strictured, ileal Crohn's disease. Axial scan through the pelvis shows narrowed, strictured neo-terminal ileum (large arrow). Note the thin, inner wall hyperenhancement and the peripheral wall hypoenhancement giving a target appearance or mural stratification. Additionally, the inner portion of the wall of the immediate upstream ileum (long, small arrow) also hyperenhances. The stricture causes significant upstream obstruction. (B) CTE of strictured, ileal Crohn's disease. Coronal, thin MIP (maximum intensity projection) scan through the pelvis shows narrowed, strictured neo-terminal ileum (arrow) just proximal to the cecum (C).

length and a greater number of subtle strictures identified. However, the major disadvantages of CT/MR enteroclysis are the time it takes to perform and the patient discomfort experienced in placing the tube. We currently can perform 10 to 20 CT enterographies per day. It would be difficult for us to perform five CT or MR enteroclyses per day.

Figure 5 (A) Computed tomography enterography (CTE) of distal ileal Crohn's disease. Axial scan through the pelvis shows a long segment of disease proximal to an end ileostomy (arrows). Note the inner wall enhancement (mural stratification) is thicker than in Fig. 3. There is mild to moderate upstream small bowel (B) dilation. Interestingly, the endoscopy was normal, but the pathology was positive for active disease. (B) CTE of distal ileal Crohn's disease. Coronal thin MIP (maximum intensity projection) reconstruction through the pelvis shows a long segment of disease proximal to an end ileostomy (arrows).

CTE AND MRE COST

Although we do not publish our examination costs, both CTE and MRE have a greater impact on the cost of health care when compared with the standard small bowel examination. One could argue that what we are reimbursed for a small bowel examination underpays us

Figure 6 (A) Computed tomography enterography (CTE) of distal ileal Crohn's disease with an abscess. Axial scan through the pelvis shows a short segment, distal ileal stricture (arrow). The inner wall enhancement is minimal. The bowel (B) upstream is mildly dilated. (B) CTE of distal ileal Crohn's disease with an abscess. Coronal, thin MIP (maximum intensity projection) reconstruction through the pelvis shows the marked wall thickening of the distal ileum (arrows) with only minimal inner wall enhancement. (C) CTE of distal ileal Crohn's disease with an abscess. Axial scan just above the stricture shows an abscess containing gas (arrows). (D) CTE of distal ileal Crohn's disease with an abscess. Coronal, thin MIP (maximum intensity projection) reconstruction just above the stricture shows an abscess (arrows).

for our efforts. But, the reality is that both CT and MRI have greater reimbursement levels. At our institution, the global Medicare reimbursement for an abdomen and pelvis CT with intravenous contrast (what is billed for a CTE) is 8 times and MRI without and with intravenous contrast (what is billed for an MRE) is 24 times the reimbursement for a small bowel series. The global Medicare reimbursement for an MRI is 2.9 times the reimbursement of a CT. At our institution, the total third-party reimbursement (professional and technical combined) for an abdomen and pelvis CT with intravenous contrast is 9 times and MRI without and with intravenous contrast is 17 times the reimbursement for a small bowel series. The total reimbursement for an MRI is 1.9 times the reimbursement for a CT. Although it is very likely that reimbursement for both CT and MRI will decrease, these two examinations will remain more costly.

CTE AND MRE FINDINGS IN CROHN'S DISEASE

There are both intestinal and extraintestinal findings of Crohn's disease on CTE and MRE. The intestinal findings include wall hyperenhancement, wall thickening (generally >3 mm), and luminal narrowing (Figs. 3–10). Wall hyperenhancement is variable. In some patients, only the inner layer of the bowel wall may hyperenhance, giving a target appearance or mural stratification, whereas in other patients, the entire bowel wall may hyperenhance.^{35–43} The most sensitive finding in Crohn's disease is thought to be bowel wall hyperenhancement. Nonetheless, wall thickening almost always accompanies an abnormal segment of hyperenhancing bowel wall. Both the Mayo Clinic and we have confirmed that normal collapsed small bowel wall enhances greater than normal distended small bowel.^{43,44} Further, the normal duodenum enhances greater than the jejunum and the jejunum greater than the ileum.⁴⁴ The extraintestinal findings include peribowel vascular engorgement (known as the Comb sign) (Fig. 3), peribowel fat proliferation, strictures, fistulae, and abscesses.

A stricture is present whenever there is luminal narrowing accompanied by wall thickening and hyperenhancement (there is no quantitative, established pathologic definition of a stricture from Crohn's disease) (Figs. 3, 4, 6–11). These strictures may vary in length from 2 to 3 cm to as long as 20 to 30 cm. Strictures may be due to acute inflammation accompanied by spasm or chronic fibrostenotic, fixed lesions. There are several important points in the detection and description of strictures. First, distinguishing a stricture from a normal nondistended loop of bowel or peristalsis is almost always possible. A strictured loop of bowel always demonstrates some degree of hyperenhancement and wall thickening. Second, as a corollary to the first,

Figure 7 (A) Computed tomography enterography (CTE) of multiple, obstructing, strictured Crohn's disease. Axial scan shows a short segment jejunal stricture (arrow) with marked, upstream small bowel (B) dilation. There are multiple, downstream jejunal and ileal strictures (arrowheads). Note the mural stratification. (B) CTE of multiple, obstructing, strictured Crohn's disease. Coronal, thin MIP (maximum intensity projection) reconstruction shows a short segment jejunal stricture (long, thin arrow) with marked, upstream small bowel (B) dilation. There are enteroliths (arrowhead) just above the stricture. There are multiple, downstream jejunal and ileal strictures (arrows).

pure, fibrostenotic disease is almost never present. That means that some active inflammation is present (manifest by hyperenhancement). Third, there is almost always some degree of bowel dilation upstream to a stricture. In that dilated bowel loop, there is often wall hyperenhancement. In our experience, we can accurately identify strictures and differentiate them from peristalsis. In terms of description, it is important to determine the degree of small bowel dilation proximal to the stricture, for this may alter the method of treatment. Bowel lumen

Figure 8 (A) Computed tomography enterography (CTE) in a patient with Crohn's disease and four jejunal strictures and one proximal ileal stricture. Axial scan shows the most proximal jejunal stricture (arrow). (B) CTE in a patient with Crohn's disease and four jejunal strictures and one proximal ileal stricture. Coronal, MIP (maximum intensity projection) reconstruction shows the most proximal jejunal stricture (arrow) and dilated jejunum (J) upstream to the stricture. (C) CTE in a patient with Crohn's disease and four jejunal strictures and one proximal ileal stricture. Axial scan shows the proximal ileal stricture (arrow). (D) CTE in a patient with Crohn's disease and four jejunal strictures and one proximal ileal stricture. Coronal, thin MIP shows proximal ileal stricture (arrow).

Figure 9 (A) Computed tomography enterography (CTE) of end ileostomy Crohn's disease with enterocutaneous fistula. Axial scan shows that the end ileostomy bowel wall (arrow) nearly uniformly enhances. (B) CTE of end ileostomy Crohn's Disease with enterocutaneous fistula. Coronal, thin MIP (maximum intensity projection) reconstruction through the end ileostomy (arrowhead) shows the fistula (arrow).

narrowing or structuring can be a result of spasm from inflammation or from a more fixed narrowing caused by predominant fibrostenotic disease. Strictures caused by spasm cause little to no significant upstream bowel dilation; strictures caused by more fixed, stenotic disease cause more significant upstream bowel dilation.

Fistula detection is aided by one major principle in Crohn's disease: no stricture = no fistulae (Figs. 9–11). If there is no stricture, there cannot be a fistula. Thus, if

Figure 10 (A) Magnetic resonance enterography (MRE) of distal ileal Crohn's disease with an ileocolic fistula. Axial T1-weighted, gradient echo, fat-suppressed, three-dimensional (3D) scan through the terminal ileum (TI) (arrow) shows a thickened, hyperenhancing bowel wall and a fistula (arrowhead) from the TI to the cecum. The TI is strictured. (B) MRE of distal ileal Crohn's disease with an ileocolic fistula. Coronal T1-weighted, gradient echo, fat-suppressed, 3D scan through terminal ileum (TI) (arrow) shows the start of the TI to cecal (C) fistula (arrowhead).

strictures are present, one must carefully scrutinize the images in both the axial and coronal planes to look for the findings of fistulae. The findings of fistulae include bowel angulation associated with bowel wall contiguity and linear tracts between these loops of bowel. Whenever we detect a stricture, we look carefully at the relationship between the strictured loop and the adjacent bowel loops (both small and large bowel) as well as adjacent structures such as the urinary bladder and other pelvic organs and musculature. Interestingly, most urinary bladder fistulae we have identified do not have urinary bladder gas on a CTE. The only finding may be a linear, soft tissue tract between a bowel loop and the urinary bladder. One inferential finding of an enterosigmoid fistula is the presence of oral contrast media in

Figure 11 (A) Magnetic resonance enterography (MRE) of Crohn's disease with complex pelvic fistulae. Axial T1-weighted, gradient echo, fat-suppressed, three-dimensional (3D) scan through the distal ileum (short, fat arrow) shows a fistula (arrowhead) between the ileum and the sigmoid (long arrow with S). The distal ileal wall uniformly hyperenhances, is thickened and strictured. (B) MRE of distal ileal Crohn's disease with complex pelvic fistulae. Coronal T1-weighted, gradient echo, fat-suppressed, 3D scan through the distal ileum (short, fat arrow) shows the complex fistulae between the distal ileum (long arrow), the sigmoid (arrowhead), and the urinary bladder (B).

the small bowel to the level of a stricture, oral contrast media in the rectosigmoid, but no oral agent in the colon between the small bowel stricture and rectosigmoid.

One objection raised to the use of low-Hounsfield unit oral contrast agents is the potential difficulty in distinguishing a low attenuation abscess from a loop of small bowel. Although a potential pitfall, we have not found this to be the case (Fig. 6).⁴⁵ Careful scrutiny of the images in two planes, especially with following the bowel loops using a manual cine format, allows a careful reader to identify extraluminal collections. We do use positive contrast (both oral and rectally administered) in the perioperative period, even in patients with Crohn's

disease to identify extravasation from enterotomies or anastomotic leaks.

Because of the proven sensitivity in detecting Crohn's disease, we now use CTE or MRE as the test of first choice in evaluating almost all patients with Crohn's disease, in lieu of a standard small bowel series or enteroclysis. Additionally, CTE or MRE is used to evaluate almost all patients with an indeterminate colitis or in colitis in whom a small bowel series would have been performed 5 years ago. We prefer to perform MRE on younger patients, but find that a timely examination is often impossible due to our full MRE schedule.

EFFICACY OF CTE AND MRE IN CROHN'S DISEASE

The efficacy of CTE and MRE has been most extensively studied in Crohn's disease. To date, multiple groups have studied the sensitivity of CTE and MRE in detecting terminal ileal Crohn's disease and distinguishing it from normal. One study from the Mayo Clinic has shown that CTE detects active Crohn's disease with a sensitivity as well as ileocolonoscopy, using absolute bowel wall enhancement (ROC analysis: $Az = 0.81$).⁴¹ In our presented, but as yet unpublished experience, we found that both absolute bowel wall enhancement/bowel wall thickness and relative bowel wall enhancement/bowel wall thickness models accurately distinguished Crohn's of the terminal ileum from normal (ROC analysis: Az of absolute wall enhancement/wall thickness model = 0.913; Az of relative wall enhancement/wall thickness model = 0.895; no statistically significant difference; $p = 0.267$).⁴⁴ Thus, we found that both wall enhancement and wall thickness together are important covariables in distinguishing Crohn's disease from normal. Other studies of CTE and MRE have not been as extensive or as rigorous, but show similar efficacy.⁴⁶⁻⁵¹

In a retrospective review of 36 patients undergoing surgical exploration for Crohn's disease we were able to detect complications of Crohn's with a high accuracy.⁴⁵ Per patient, we were able to detect strictures, fistulae, and abscesses 100% of the time. On a per lesion basis, we were able to detect the number of strictures and fistulae two-thirds of the time. To our knowledge, this is the first correlation of surgical results with CTE findings.

CTE and MRE have been compared with other modalities in several studies. The most interesting is a presented, but unfortunately, unpublished work performed at the Mayo Clinic prospectively comparing CTE, ileocolonoscopy, capsule endoscopy, and small bowel follow-through in the detection of Crohn's disease. The sensitivity and specificity was as follows, respectively: CTE = 82%/89%; ileocolonoscopy = 83%/100%; capsule = 74%/53%; and small bowel follow-through = 65%/94%.⁵² Bodily et al compared CTE

with ileoscopy in detecting active terminal ileal disease using biopsy as the reference standard. The sensitivity of the two methods was 81%, but specificity was greater for ileocolonoscopy (97% vs 70%).⁴¹ Wold et al studied a relatively small number of patients with CTE, CT enteroclysis, and small bowel follow-through. They concluded that the sensitivity and specificity of these tests for the detection of disease was equivalent, but that the CT examinations were more sensitive in identifying the complications, especially fistulae.³⁸ In our anecdotal experience comparing CTE and standard small bowel follow-through (our test of choice before CTE), we detect far more strictures and fistulae using CTE.

Capsule endoscopy has become an attractive method of detecting small bowel disease, especially in identifying the source of obscure gastrointestinal bleeding. In a small study comparing CTE with capsule, Hara et al showed that capsule endoscopy identified Crohn's disease in 12 of 17 patients (71%), ileoscopy in 11 of 17 patients (65%), and CTE in 9 of 17 patients (53%).⁴⁰ Using a meta-analysis, Triester et al showed that capsule was diagnostic of Crohn's disease in 69%, yet CTE or CT enteroclysis was diagnostic in only 30%.⁵³ In a study by Voderholzer et al, capsule endoscopy was compared with CT enteroclysis in the detection of small bowel Crohn's disease.⁵⁴ Only 41 of 56 patients were studied with both methods. Capsule endoscopy detected jejunal or ileal lesions in 25 patients, whereas CT enteroclysis was able to detect lesions in 12. Interestingly, the methods were not significantly different in detecting ileal lesions, raising the question as to whether the more proximal lesions missed by CT were in fact true positive lesions resulting from Crohn's disease. No reference standard such as surgery confirmed the

presence of proximal Crohn's disease in this series. Golder et al has published similar results comparing capsule endoscopy with MR enteroclysis: significantly more proximal small bowel Crohn's disease is detected with capsule endoscopy, but the MRE is equivalent to capsule endoscopy in the terminal ileum.⁵⁵

There are two basic problems with capsule endoscopy. The first is that it is very sensitive, especially in Crohn's disease, but this is offset by low specificity. Findings of Crohn's disease have been found in up to 20% of healthy patients, and up to 70% of patients on medications, especially nonsteroidal antiinflammatory drugs.^{56,57} This has raised serious questions about the use of capsule endoscopy in patients with suspected Crohn's disease.⁵⁸ The other major problem with the use of capsule endoscopy is that significant small bowel strictures will obstruct the capsule passage, necessitating surgical removal of the capsule. Indeed, in the study by Voderholzer et al, capsule endoscopy was not performed in 15 of 56 patients (27%) because of strictures detected by CT enteroclysis.⁵⁴ Because of the dual problems of nonspecificity as well as small bowel strictures, we do not routinely use capsule endoscopy in the evaluation of patients with suspected Crohn's disease.

To date, there have been no studies evaluating the specificity of bowel hyperenhancement identified on CTE, but it seems very reasonable to assume that wall hyperenhancement, in conjunction with wall thickening are nonspecific findings (Fig. 12). We know that a target sign can be identified in patients with small bowel ischemia. In our practice, we have identified terminal ileal hyperenhancement in patients who did not have Crohn's disease endoscopically and pathologically. Although we have not identified an enteric pathogen

Figure 12 (A) Computed tomography enterography (CTE) of radiation enteritis. Axial scan shows mural stratification (arrowhead) in a mildly thick-walled small bowel loop. (B) CTE of radiation enteritis. Coronal, thin MIP (maximum intensity projection) reconstruction shows mural stratification (arrow) in a mildly thick-walled small bowel loop.

in any of these patients, it is likely they had infectious enteritis.

CORRELATION OF CTE AND MRE FINDINGS AND DISEASE ACTIVITY

Some have speculated that the depth of hyperenhancement is related to the degree of inflammation.⁵⁹ Choi et al attempted to correlate mural enhancement patterns with inflammatory disease activity.⁵⁹ Unfortunately, the pathologic grades in this investigation are poorly described; therefore, the conclusions drawn are limited. In a small retrospective pilot evaluation, not published, we have found that there does not appear to be a direct correlation between the specific pathologic findings and pattern of wall enhancement. Unfortunately, there are no established pathologic grades of inflammation in Crohn's disease. Thus, we have no established gold standards. What we do know is that the mucosa is often completely destroyed in these patients, replaced with different manifestations of inflammation. There has been preliminary work correlating the pattern of bowel wall enhancement with the degree of inflammation as well as Crohn's disease activity index (CDAI) and other measures of disease activity. Hassan et al compared wall enhancement on CT enteroclysis in patients with active Crohn's disease with clinical activity as measured by the CDAI. There was a significant correlation between the degree of wall enhancement and CDAI ($r=0.81$, $p<0.001$).⁴⁷ Sempere et al showed that active-phase Crohn's disease had significantly greater wall enhancement and thickness compared with normal segments and controls.⁵¹ They also found that when in remission, the degree of wall hyperenhancement decreased toward normal, but wall thickening remained.⁵¹ Florie et al compared bowel wall enhancement ratios with overall clinical grade, CDAI and Van Hees activity index in patients with active Crohn's disease. Their data suggested that the enhancement ratio of the bowel wall and wall thickness were weak to moderate indicators of Crohn's disease severity. There does seem to be some correlation between the degree of enhancement and disease activity. Anecdotally, we have examined the CTE in patients on infliximab, and do not identify bowel wall hyperenhancement.

To date, no one knows what the bowel enhancement patterns mean pathologically. Some have suggested that mural stratification represents active inflammation, whereas homogeneous, transmural enhancement represents fibrostenotic disease. Colombel et al correlated CTE findings with endoscopic severity, histology graded from 0 to 3 (based upon the greatest severity of inflammation) and C-reactive protein levels.⁶⁰ They found mild to moderate correlation between bowel enhancement, comb sign, and fat density with endoscopic score (Spearman correlation coefficients 0.33

to 0.39). The correlation between wall enhancement and histologic grade was also mild to moderate ($r=0.34$ – 0.38). C-reactive protein (CRP) was elevated when fat density was increased and not with wall hyperenhancement. Lee et al demonstrated that patients with the comb sign were sicker and had higher levels of CRP levels.⁶¹ Florie et al compared MRE using qualitative assessment as well as wall thickness and enhancement with endoscopic disease severity grading as well as Crohn's Disease Endoscopic Index of Severity (CDEIS).⁶² There was a moderate to strong correlation ($r=0.61$ and $r=0.62$ for the two radiologists) between severity rated at MRI and CDEIS. Wall thickness correlated moderately to strongly as well with CDEIS ($r=0.57$ and 0.50). Enhancement correlated weakly to moderately with CDEIS ($r=0.45$ and 0.42). Unfortunately, the authors did not measure wall thickness and wall enhancement was not performed; only nonparametric, qualitative assessment was performed. All of these studies show that we have very poor gold standards for measuring inflammatory activity.

A recent, innovative, retrospective study from Indiana University correlated CT enteroclysis with surgical pathology.⁶³ These investigators created a qualitative and quantitative scoring system based upon the Simple Endoscopic Score for Crohn's Disease (SES-CD).⁶⁴ The CTE and pathology was scored for inflammation from mild to severe and fibrostenosis from none to severe. Although this is again a qualitative score, specific definitions were given. Additionally, wall thickness was measured (interestingly mural enhancement was only qualitatively assessed; the enhancement patterns were not correlated with pathology). The overall accuracy of CTE was 76.6% for inflammation using a 4-point scale and 78.7% for fibrostenosis using a 3-point scale. Spearman correlation between CTE and inflammation was $r=0.7$ and CTE and fibrostenosis was $r=0.6$. Using logistic regression, there was a significant association between the comb sign and adenopathy and the pathology inflammatory score. There was also a significant association between the presence of stenosis on CTE and the fibrostenosis score.

OBSCURE GASTROINTESTINAL BLEEDING

Capsule endoscopy is considered the imaging method of choice in evaluating patients with obscure gastrointestinal bleeding.⁶⁵ When the small bowel is the source of blood loss, angiodysplasias and then small bowel tumors are the most common causes. The efficacy of CTE in detecting the cause of chronic small bowel blood loss has not been extensively studied. Voderholzer et al studied a heterogeneous group of patients with small bowel pathology with both capsule endoscopy and CT enteroclysis.⁶⁶ Capsule endoscopy identified the cause of bleeding in 4 patients, while CT enteroclysis was positive in

1 patient. Johanssen et al found that capsule endoscopy identified more small bowel neuroendocrine tumors than CTE and that CTE had more false positive findings.⁶⁷ In a more recent study, contrast-enhanced, CT enteroclysis was used to evaluate 219 patients with suspected small bowel neoplasms; the results were compared with surgical or endoscopic findings. The overall sensitivity and specificity for small bowel lesions was 85%/97% respectively.⁶⁸ In a presented, unpublished series from the Mayo Clinic, CTE was complementary to capsule endoscopy in detecting lesions such as carcinoid, metastases, and vascular malformations. Anecdotally, we are detecting more, small subtle lesions as well (Figs. 13–15). CTE detected lesions that capsule

endoscopy did not and vice versa.⁶⁹ What seems clear from anecdotal findings is that CTE may very well supplant the small bowel series and small bowel enteroclysis in evaluating patients with occult small gastrointestinal bleeding.

CTE AND MRE IN SMALL BOWEL OBSTRUCTION

In patients with acute small bowel obstruction, most would consider that a standard abdomen and pelvis CT would be indicated. Because of the fact that most of these patients cannot ingest any oral contrast, the resulting examination is virtually a CTE as the proximally

Figure 13 (A) Biphase computed tomography enterography (CTE) of metastatic, distal ileal carcinoid. Axial scan through the pelvis during the arterial contrast enhancement phase of the examination shows a small, hyperenhancing polypoid mass (arrow) representing the primary carcinoid tumor. (B) Biphase CTE of metastatic, distal ileal carcinoid. Axial scan through the pelvis during the portal venous contrast enhancement phase of the examination shows a small, hyperenhancing polypoid mass (arrow) representing the primary carcinoid tumor. During this phase of the examination, the mass is not as well seen. (C) Biphase CTE of metastatic, distal ileal carcinoid. Coronal, thin MIP (maximum intensity projection) reconstruction through the pelvis during the arterial phase of the examination shows a small, hyperenhancing polypoid mass (arrow) representing the primary carcinoid tumor. Hyperenhancing, hepatic metastases are also identified (arrowheads).

Figure 14 (A) Computed tomography enterography (CTE) of obscure gastrointestinal bleeding in a patient with a Plasma cell neoplasm. Axial scan through the pelvis shows a large, nonobstructing, ulcerated mass (arrows) in continuity with the small bowel. (B) CTE of obscure gastrointestinal bleeding in a patient with a plasma cell neoplasm. Coronal, thin MIP (maximum intensity projection) reconstruction shows a large, nonobstructing, ulcerated mass (arrows) in continuity with the small bowel. There is confluent lymphadenopathy (L.N.) in the mesenteric root.

obstructed, dilated bowel is filled with low attenuation fluid.

Patients with chronic, recurrent small bowel obstructions present the clinician with a different

Figure 15 (A) Computed tomography enterography (CTE) in obscure gastrointestinal bleeding in a patient with cecal arteriovenous malformation (AVM). Axial scan obtained during the arterial contrast enhancement phase of a biphasic examination shows a tangle of vessels (arrows) adjacent to the cecum (arrowhead). (B) CTE in Obscure gastrointestinal bleeding in a patient with cecal AVM. Coronal, thin MIP (maximum intensity projection) reconstruction obtained during the arterial contrast enhancement phase of a biphasic examination shows a tangle of vessels (arrows) adjacent to the cecum (C).

diagnostic problem. In patients with prior surgery, adhesive disease remains the most common cause, especially when there is not concurrent chronic gastrointestinal bleeding. The use of CTE in these patients has not been studied. However, in our opinion, the examination of choice in evaluating these patients should be an enteroclysis. With this technique, the consistent delivery of contrast into the bowel via a mechanical pump is the best means of distending and stressing the bowel. CTE relies on the ability of the patient to rapidly ingest the oral agent as well as the rate of gastric emptying.

Patients with chronic, recurrent small bowel obstructions who have not had prior surgery may have a tumor as the cause of the obstruction. Although there has been no investigation in these patients, it would seem reasonable that a biphasic CTE (scanning in both the arterial and portal venous phase) be performed in these patients as the first test.

CTE AND MRE IN ACUTE AND CHRONIC INTESTINAL ISCHEMIA

Cross-sectional enterography has not been studied in intestinal ischemia. However, the use of low-attenuation oral contrast agents or even no oral contrast agents has been used consistently in patients suspected with both acute and chronic intestinal ischemia. If positive oral contrast agents are used, 3D postprocessing techniques to produce angiograms cannot be easily used.

CTE AND MRE IN PATIENTS WITH NONSPECIFIC, CHRONIC ABDOMINAL COMPLAINTS

Patients with nonspecific, chronic abdominal complaints present the clinician with a challenging problem. Most of these patients have irritable bowel syndrome, and yet, the workup of these patients had traditionally included extensive evaluations of upper and lower endoscopy, ERCP, small bowel follow-through, enteroclysis, and a standard CT of the abdomen and pelvis. In our practice, we have seen a dramatic shift in the evaluation of these patients. In lieu of an ERCP, we now perform an MRI examination of the pancreas and the biliary system. In lieu of a standard small bowel follow-through and CT of the abdomen and pelvis, we now perform a CTE. We have no data that suggests that these detect more disease than the prior workup. But, it is clear that if a clinician intends to perform both a small bowel barium exam and a CT, that a CTE is likely a reasonable replacement of these two exams. In almost all cases, the results of these examinations will be negative.

FUTURE DIRECTIONS

In Crohn's disease, the relative roles of CTE and MRE must be explored. There is no doubt that CTE is cheaper, easier, and more readily available and provides consistently high quality studies when compared with MRE. But, most patients with Crohn's disease are young and will be evaluated repeatedly over the course of their disease. Thus, accumulated radiation dose becomes a very real concern. Further, disease activity may be more readily assessed with contrast enhancement curves using MRI data, as repeated imaging after contrast media injection can yield multiple points on the curve without any radiation. It may be that CTE will

provide the high-quality spatial data for initial diagnosis or preoperative planning, and MRE for ongoing disease monitoring.

In the evaluation of obscure gastrointestinal bleeding, more investigations will be needed to determine the relative roles of CTE and capsule endoscopy. From our perspective, CTE is certainly easier and faster and may obviate a subsequent capsule endoscopy study, if disease is detected.

The role of CTE and CT enteroclysis must also be studied in patients with recurrent small bowel obstruction. In our opinion, a standard enteroclysis, with in-room radiologist supervision and patient palpation and rotation remains the gold standard in the detection of adhesive disease. It may be that CTE or CT enteroclysis will be a superior examination in these patients.

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