Mesenteric Circulation: Three-dimensional MR Angiography with a Gadolinium-enhanced Multiecho Gradient-Echo Technique[1]

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To evaluate the mesenteric circulation with magnetic resonance (MR) angiography, the authors examined 16 individuals (12 patients, four volunteers) with a gadolinium-enhanced, breath-hold, fat-saturated, multiecho, three-dimensional, gradient-echo sequence. Twenty examinations were performed. Grades of 3 or 4 (on a five-point scale [4 = best seen, 0 = not seen]) were applicable to 17 (85%) of 20 MR angiograms obtained in superior mesenteric artery trunks, 15 (75%) in celiac arteries, five (25%) in inferior mesenteric arteries; 15 (75%) of first-order branching, 12 (60%) of second-order branching, and 10 (50%) of third-order branching; 17 (85%) in superior mesenteric veins; and 17 (85%) in portal veins. MR angiography with this technique depicted the mesenteric arterial and venous circulation and the portal vein with excellent resolution in a short time.

Index terms: Arteries, mesenteric, 95.129412, 95.12942, 95.12943 • Intestines, MR, 95.129412, 95.12943 • Magnetic resonance (MR), vascular studies, 95.129412, 95.12943 • Portal vein, MR • Veins, mesenteric, 95.129412, 95.12942, 95.12943, 957.129412, 957.12942, 957.12943

Radiology 1997; 202:257–261

Magnetic resonance (MR) angiography has been used extensively to image vascular anatomic structures noninvasively without use of intravenous contrast media (1,2). The majority of MR angiography techniques have involved use of both two-dimensional and three-dimensional (3D) approaches, which are based on time-of-flight or phase-contrast methods (3,4). Vessels with normal caliber have strong continuous laminar flow, which is readily detectable with time-of-flight methods and is usually seen in healthy individuals. In patients with vascular disease, however, the normal laminar flow is disturbed, and images obtained with a time-of-flight method are degraded. For example, when the inflow is reduced due to a vessel abnormality or to reduced cardiac output, there will be a loss in signal intensity. In addition, when a time-of-flight method is used, tortuous vessels that are not perpendicular to the plane of imaging will cause a loss of signal intensity from in-plane saturation. Use of a body coil in the abdomen will affect image quality because of a lower signal-to-noise ratio (5). Images are often blurred at the distal vascular segments because of abdominal motion, which is further complicated by the prolonged imaging time.

The problems associated with in-plane saturation and artifacts from motion can be avoided by using 3D techniques in a breath-hold period. Because of advances in gradient technology, it is possible to shorten the acquisition time to the duration of a breath hold. When a very short repetition time is used, however, a lack of contrast between blood and tissue will be evident, even with sufficient inflow of unsaturated blood. Poor inflow enhancement causes blood to appear nearly isointense with muscle. By using paramagnetic contrast agents, however, the contrast can be improved due to a relative reduction in the T1 value of blood compared with tissue. Because the improvement in contrast is due primarily to shortening of the T1 value of blood, the improvement is independent of the plane of orientation. Breath holding provides a means of imaging a motion-prone anatomic region such as the mesenteric vasculature. To improve signal-to-noise ratio, a body phased-array coil can be used instead of a body coil.

Use of intravenous paramagnetic contrast agents has been advocated by many investigators to shorten the T1 value of blood flow in relation to that of fat and muscle and other background tissues (6–9). With fat suppression and appropriate timing of data acquisition, one can easily avoid the presence of signal from background tissue and venous enhancement. In this article, we describe a breath-hold fat-suppressed 3D method for MR angiography of the mesenteric circulation. This method does not depend on blood inflow or blood motion and thereby circumvents many of the problems encountered in conventional time-of-flight or phase-contrast MR angiography.

Materials and Methods

Sixteen individuals (12 patients, four volunteers; 10 women, six men) aged 20–75 years (mean patient age, 60 years; mean volunteer age, 36 years) underwent 20 MR angiography examinations to evaluate the mesenteric circulation. Partitions were divided into several segments, each of which contained a different echo of the echo-train data (10). For each partition, conventional in-plane encoding was performed. The echo center was 2.2 msec, and the receiver bandwidth was 650 Hz per pixel. The echo was slightly asymmetric, with its center at the 110th point in 256 readout points. A 3D fast low-angle shot, or FLASH, sequence was used in which k space was segmented with 12 lines per repetition-time interval, similar to a segmented echo-planar readout (10). In addition, a fat-suppressed pulse was implemented as a single event, and suppression was achieved with use of a frequency-selective but spatially nonselective radio-frequency pulse (11).

Before the MR angiography examination, the magnet homogeneity was improved by means of a standard shim procedure built into the system. The repetition time necessary to enclose 12 lines with fat suppression was 41 msec, and the number of 3D partitions was fixed at 24. The field of view was 370–390 mm, and the slab thickness was 72 mm, with an effective section thickness of 3 mm. The flip angle was kept relatively high at 45° to minimize blood saturation during the acquisition of all lines. The imaging time for a single measurement was 21 seconds when a matrix size of 224 × 256 was used. Examinations were performed with a commercially available unit (Vision [1.5 T]; Siemens Medical Systems, Iselin, NJ) equipped with 25 mT/m gradients and a slew rate of 40 mT/m/msec. Because a short imaging time was used, glucagon was not administered. During data acquisition, use of the coronal plane with the slab posi-

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tioned parallel to the aorta appeared to be most beneficial because of the mesenteric orientation and the ability to cover more mesenteric area with a 72-mm slab thickness. A sagittal orientation was used in only one case, and it provided clear visualization of the origin of the normal superior mesenteric artery (SMA).

The feeding status of volunteers and patients (fasting or after a high caloric meal) was varied in the examinations. Five examinations were performed while the subjects were fasting, and in 10 examinations the individuals had been given no instructions. Five volunteer examinations were performed after a standard fatty meal. One can of fluid nutrition (Clintec, Nutren 2.0; Nestle and Baxter, Deerfield, Ill) was provided as a standard meal that consisted of 43 g carbohydrate, 20 g protein, and 26.5 g fat (500 calories). All patients were positioned supine within the magnet after insertion of an intravenous catheter in the antecubital fossa. For a baseline comparison, imaging was performed with the 3D sequence once before administration of contrast material, and a single measurement was made. Then, in 10 examinations, a single dose of gadopentetate dimeglumine (0.1 mmol per kilogram of body weight) (Magnevist; Berlex Laboratories, Wayne, NJ) was administered; in the other 10 examinations, a double dose (0.2 mmol/kg) of gadoteridol (ProHance; Bracco Diagnostics, Princeton, NJ) was injected by hand as a bolus. The injections were performed at a rate of approximately 2 mL/sec, and then 10 mL normal saline solution was administered as a bolus injection.

The transit time of a bolus of contrast material depends on the circulation time and the cardiac status of the patient. Several methods have been reported to estimate the transit time accurately so that the central k-space data can be acquired during the arterial peak of the bolus (12). In this study, the delay between the beginning of administration of the bolus and the beginning of the sequence was 6 seconds; during this time, the patients were asked to take a deep breath in and hold it. A fixed 6-second delay was chosen because the central lines of k space are obtained half way through the sequence. This delay would assume a transit time of approximately 16 seconds to reach an arterial peak in mesenteric circulation. The sequence was repeated during two additional sequential breath holds with a 6-second interval, during which the patients were allowed to take a breath. The additional measurements provided images that displayed both arterial and venous systems. The data from each of the three measurements were then subjected to a

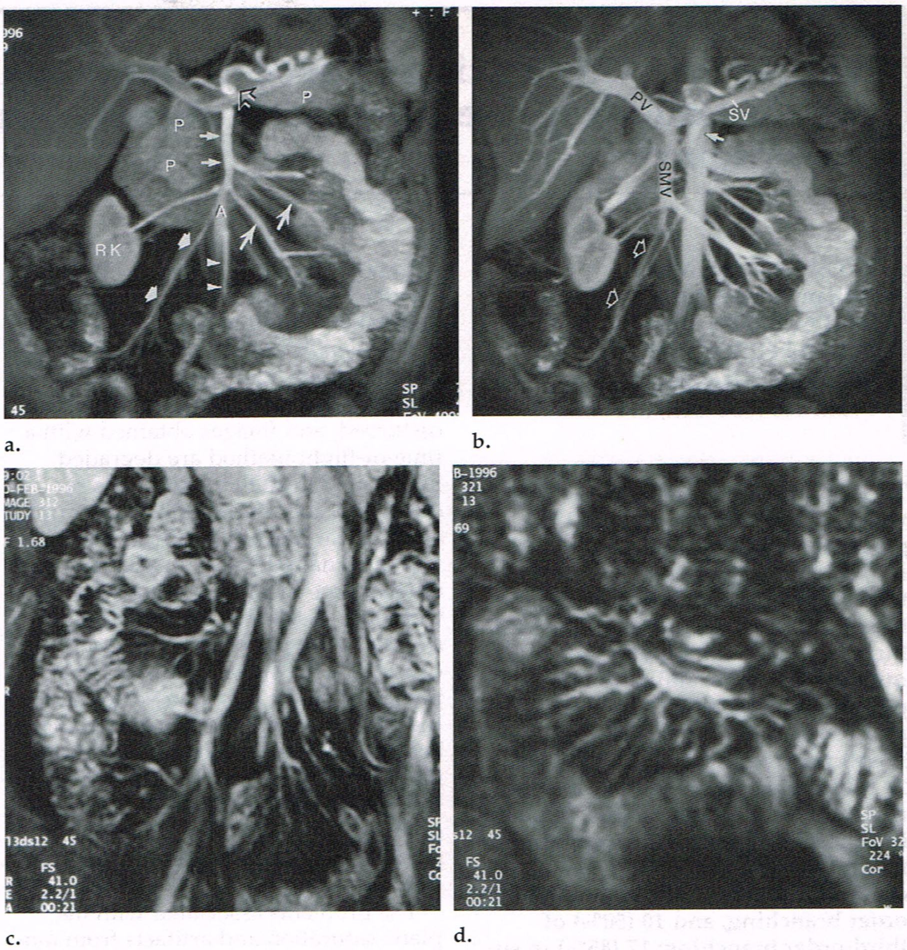


Figure 1. Normal mesenteric arterial and venous MR angiography. **(a)** Maximum intensity projection image obtained during the arterial phase shows the SMA (short, thin, solid arrows) and its tributaries, the inferior mesenteric artery (arrowheads), and the celiac artery (open arrow), all graded 4. Early visualization of the venous phase is provided. Normal pancreatic (*P*) enhancement is seen. *A* = aorta, *RK* = right kidney. Short wide solid arrows = ileocolic artery, long solid arrows = jejunal branches. **(b)** Maximum intensity projection image obtained during the venous phase shows the mesenteric arterial and venous system (graded as 4). The SMV, portal vein (*PV*), and splenic vein (*SV*) are well illustrated. White solid arrow = SMA, open arrows = ileocolic vein. **(c)** Second- and third-order branching of the SMA and SMV in a volunteer are seen in this partition (second measurement MR angiogram) (graded as 4). **(d)** Third measurement MR angiogram shows details of the venous drainage of a bowel loop (right lower quadrant) in the same volunteer as in **c**. Notice the normal bowel enhancement (graded as 3) in **a–d**.

maximum-intensity-projection, or MIP, algorithm. For images obtained in both patients and volunteers, two readers (A.S., O.K.) used a five-point grading system (4 [best seen] to 0 [not seen]) to subjectively grade the conspicuity of the SMA; the first-, second-, and third-order branches of the SMA; the celiac artery; the inferior mesenteric artery; bowel enhancement; the superior mesenteric vein (SMV); and the portal vein. Readings were performed in consensus.

Results

MR angiograms acquired immediately after the start of bolus injection of contrast material depicted only the arterial system. During the second and third measurements, however, both the arterial and venous systems could be seen. Among MR angiograms obtained in both patients and volunteers, grades of 3 or 4 were applicable to 17 (85%) of 20 MR angiograms obtained in SMA trunks, 15 (75%) in celiac arteries, five (25%) in inferior mesenteric arteries; 15 (75%) of first-order branching, 12 (60%) of second-order branching, and 10 (50%) of third-order branching; 17 (85%) in SMVs; and 17 (85%) in portal veins (Fig 1). Small-bowel enhancement was graded as 3 or 4 in six volunteer examinations (Fig 1) and in 11 patient examinations. In the patients, however, SMA occlusion was graded as 0 (Fig 2), SMA stenosis was graded as 2, celiac aneurysm was graded as 3, and SMV and portal vein invasion with pancreatic carcinoma (Fig 3) were graded as 0 and 1, respectively. In a patient with portal hy-

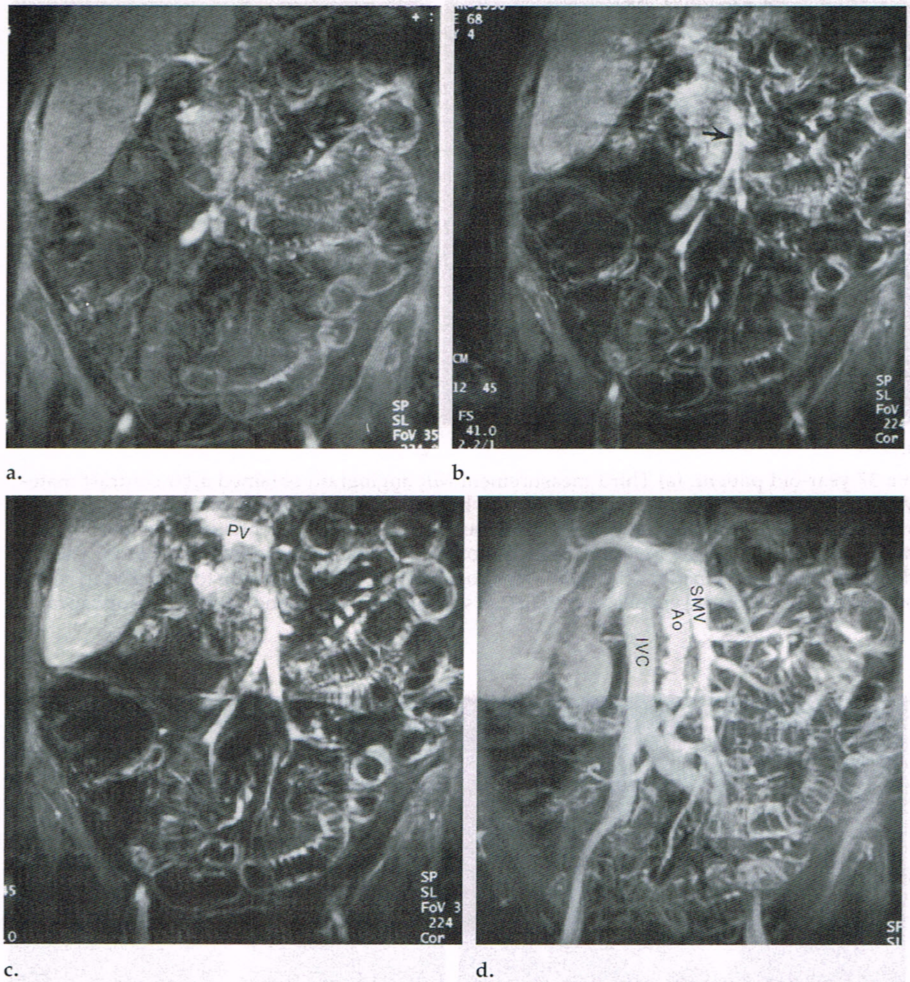


Figure 2. MR angiographic images in a 70-year-old patient with SMA occlusion and severe arteriosclerotic changes in the aorta. **(a)** First measurement MR angiogram obtained after bolus injection of contrast material does not depict the SMA (graded as 0). **(b)** Second measurement MR angiogram obtained in the early venous phase shows the SMV (arrow) and minimal enhancement of the bowel loops. **(c)** Third measurement MR angiogram further depicts the SMV and portal vein (*PV*) (graded as 3). In addition, there is delayed enhancement of the bowel loops, with indication of lack of enhancement in the right colon. **(d)** Maximum intensity projection image of the three measurement MR angiograms shows the normal SMV and portal vein, arteriosclerotic changes in the aorta (*Ao*), and a normal inferior vena cava (*IVC*).

pertension, the portal vein was graded as 1 (Fig 4). Also in the entire group, a grade of 0 or 1 was applicable to four examinations of first-order branching, to four examinations of second-order branching, and to seven examinations of third-order branching in the SMA.

In six patients, pathologic conditions included SMA stenosis (n = 1), SMA occlusion (n = 1 [Fig 2]), celiac arterial aneurysm (n = 1), SMV and portal vein invasion with pancreatic cancer (n = 1 [Fig 3]), vascular inversion in malrotation (n = 1 [Fig 5]), and portal hypertension with extensive varices (n = 1 [Fig 4]). The other six patients had other neoplasms (n = 3), inflammatory bowel disease (n = 1), and abdominal trauma (n = 2); in all six, the mesenteric vessels were normal.

When MR angiograms obtained in fasting individuals were compared with those obtained in individuals given a standard fatty meal, no visually detectable differences in the number or the conspicuity of vascular anatomic structures were found. Comparison of MR angiograms obtained after administration of a single dose or double dose of contrast material showed similar results. We did not, however, analyze the signal intensity values of vessels quantitatively.

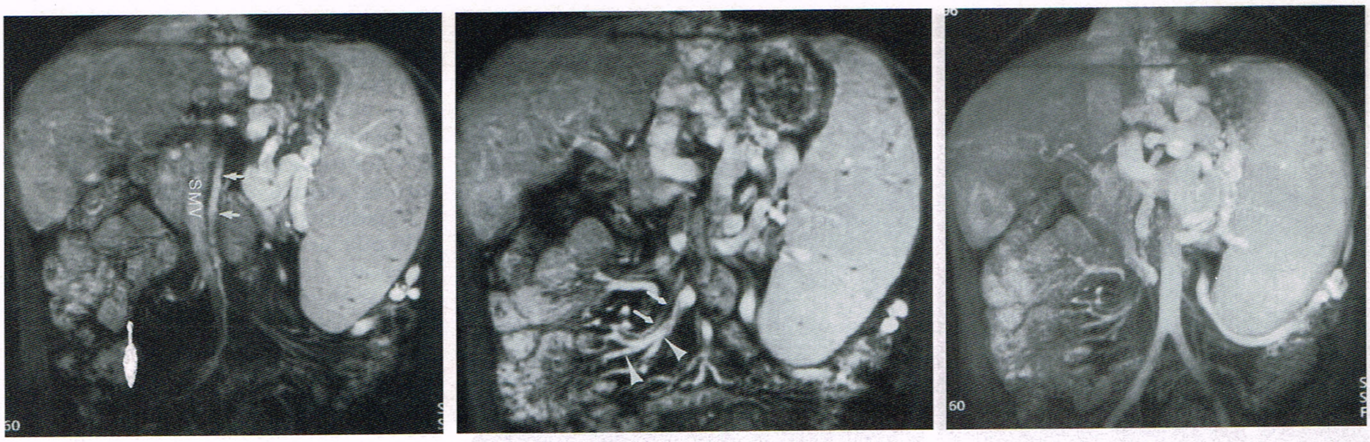
Discussion

The splanchnic circulation is a vascular bed with two major sources of arterial flow, namely, the celiac artery and the SMA. There is also a minor collateral source due to communications with the inferior mesenteric artery. Because such a rich arterial blood supply exists, stenosis and even occlusion in all three major arteries can occur without major abdominal symptoms (13,14). Stenoses are mostly due to atherosclerosis, which usually occurs at the origin of the mesenteric vessels and is responsible for more than 95% of cases of chronic mesenteric ischemia.

In patients with suspected mesenteric ischemia, arteriography is generally necessary to show the mesenteric vascular anatomic structures and to provide information for planning vascular interventional therapy (15). Because the ischemic tolerance of the intestine is estimated to be 2–3 hours (16), however, such a procedure may be too long. Also, although most complications associated with catheterization are minor, as many as 8% of patients will experience a complication, and 0.14% will require hospitalization (17–19). Also, an underlying renal failure or renal failure induced by vascular insufficiency and ischemia may be a contraindication to using iodinated contrast media. Recently, duplex Doppler sonography with color-flow imaging has been suggested as a primary screening procedure in patients suspected of having mesenteric ischemia (20,21). The ultrasound results must be viewed with caution because it is not uncommon to obtain an inadequate Doppler signal due to obscuration by bowel gas or vessel-wall calcification (21).

Recent developments in MR imaging technology, especially advances in 3D breath-hold, time-of-flight, and phase-contrast MR angiography, have provided the opportunity for high-resolution, noninvasive evaluation of vascular anatomic structures (4,22) and measurement of volumetric flow rates in arteries and veins with use of cine phase-contrast methods (1,23). Standard 3D phase-contrast MR angiography may fail to depict the SMA, however, because of the presence of a triphasic flow pattern in this vessel (4). The flow-velocity profile in the SMA has a high resistance pattern (under fasting conditions) with early diastolic flow reversal and slow late diastolic flow (24). In addition, owing to highly pulsatile blood flow in the SMA, MR angiography is often hindered by the presence of shift artifacts (ghosting), which result in reduced intravascular signal intensity and increased noise in the surrounding tissues. Systolic gating might be needed in such cases (4).

The goal of this study was to develop a method that would provide high-resolution imaging of the mesenteric circulation with use of breath-hold fat-suppressed 3D gadolinium-enhanced MR angiography. The basic fast low-angle shot pulse sequence, in which slab-selective radio frequency is followed by a series of gradient echoes similar to an echo-planar mode, was



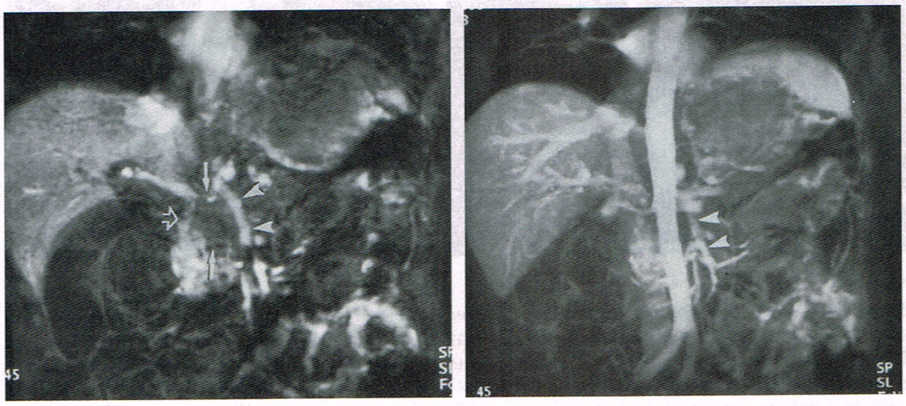
a. b. c.

Figure 4. Cirrhosis with portal hypertension in a 37-year-old patient. **(a)** Third measurement MR angiogram obtained after contrast material injection depicts the SMA (arrows) and SMV. Because of underlying cirrhosis and portal hypertension, the portal vein is not depicted, and splenomegaly and venous collateral vessels are seen. **(b)** Partition MR angiogram obtained during the venous phase at the level of the bowel loops illustrates the distal branching of the SMA (arrows) and the proximal branches of the SMV (arrowheads) (graded as 4). The collateral vessels, which extend to the level of the distal esophagus, are better illustrated. Heterogeneity of the liver is due to underlying cirrhosis. **(c)** Maximum intensity projection image shows extensive collateral vessels, spontaneous splenorenal shunt, and extensive esophageal varices.

modified. Each of the echoes is phase encoded to represent a single line in a 3D k space. In-plane encoding is performed in a conventional fashion. The section encoding is divided into partitions, each of which contains a different echo of the echo train. The sequence used in our study has 24 segments that are interleaved, similar to an interleaved echo-planar sequence (1,2).

It is known that with a standard time-of-flight technique, if a very short repetition time and a very small flip angle are used, then even the inflow effects will not be strong enough to offset the saturation effects (25). Therefore, under these circumstances, when intravenous contrast material is not used, blood will appear isointense to surrounding tissues. In such cases, one can take advantage of the T1 properties of blood. Intravenous contrast material reduces the T1 value of the blood, and therefore the blood signal recovers considerably and is greatly enhanced, even with rapid repetition of radio-frequency pulses and use of a very small flip angle (11). Because the overall enhancement in signal intensity is achieved by using a contrast agent, theoretically the signal intensity may be increased even more if T1 is further reduced by doubling the dose of contrast material. To prove this point, the images would need to be analyzed quantitatively, with a study of the effects of single versus double dose.

Fat also was suppressed to allow better visualization of enhancing vessels, which were surrounded by high-intensity fat. There could be a problem of associated field inhomogeneity if a large field of view were used. In our cases, the area of interest was confined to the mesentery, so we did not encounter such a problem.



a. b.

Figure 3. Carcinoma of the pancreas with vascular invasion in a 68-year-old patient. **(a)** Third measurement MR angiogram shows displacement of the SMA to the left side (arrowheads) by a mass with low signal intensity in the head of the pancreas (solid arrows). The SMA was also seen on the first and second measurement MR angiograms. The mass appears to have invaded the SMV and splenic vein and may have caused minimal enhancement (open arrow). There is a trace of contrast enhancement in the portal vein (graded as 1). **(b)** Maximum intensity projection image shows the displaced SMA (arrowheads) to the left of the midline. The SMV and splenic vein are not clearly depicted, and there probably is a trace amount of contrast material enhancing the portal vein. Percutaneous biopsy of the head of the pancreas with computed tomographic guidance proved the presence of pancreatic adenocarcinoma.

In patients with segmental or diffuse bowel ischemia, one would expect to see a lack of early enhancement of the bowel; when ischemia is segmental, one would expect to see this phenomenon only in segments of the bowel.

In summary, our preliminary experience shows that by using a gadolinium-enhanced, breath-hold, fat-saturated, segmented, echo-planar, 3D gradient-echo technique, the mesenteric arterial and venous circulation as well as the portal vein can be visualized with excellent resolution in a short time. Use of breath holding helps obviate motion artifact. Also, acquisition of a maximum-intensity-projection image from the 3D volume data allows evaluation of all the vascular anatomic structures at different phases (arterial and venous) of contrast enhancement. ■

Acknowledgments: The authors appreciate the help provided by Gerhard Laub, PhD, regarding the installation of a 3D, segmented, echo-planar sequence on our unit; the technical assistance of Ron Loretitsch, RT, and Janice Stopford, RT; and the secretarial help of Arlene Hill.

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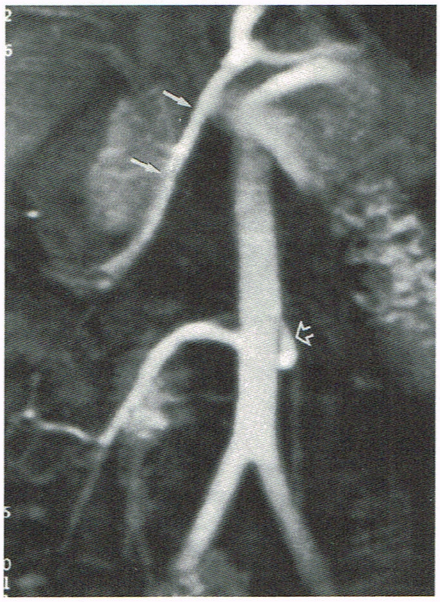
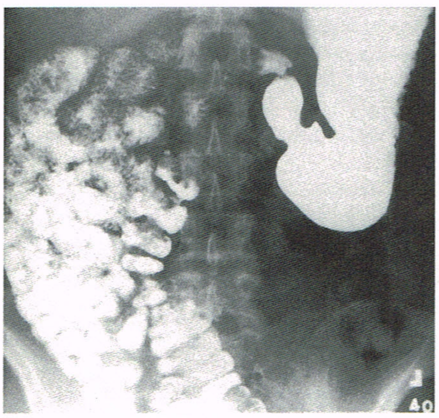


a.



b.

Figure 5. Vascular inversion in a 44-year-old volunteer. **(a)** Maximum intensity projection image depicts the SMA (solid arrows) and inferior mesenteric artery (open arrow) trunks coursing to the right side. The maximum intensity projection image was made from the MR angiograms obtained during the early phase of bolus injection of contrast material. **(b)** Upper gastrointestinal barium study shows small bowel loops in the right abdomen lateral to the ascending colon.

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