MR Angiography of Abdominal Ischemia

King C.P. Li

Advances during the past decade in MRI have made this modality increasingly suitable for evaluating abdominal vascular diseases. Preliminary results in canine models and humans suggest that MRI has the potential of becoming a definitive, noninvasive test for the diagnosis of both acute and chronic mesenteric ischemia. MRI can provide both morphological information about the patency or degree of stenosis in mesenteric vessels as well as quantitative functional information such as blood flow and blood oxygen saturation in these vessels. The MR techniques developed for studying the mesenteric circulation also can be used for improving the diagnosis and posttreatment evaluation of vascular diseases in other abdominal organ systems.

CHRONIC mesenteric ischemia is a difficult diagnostic problem with no definitive confirmatory test available currently.[1] Acute mesenteric ischemia is a devastating disease process with mortality rates ranging from 40% to 90% overall, and more than 70% if the diagnosis is not made before intestinal infarction occurs.[2-9] Contrast-enhanced MR angiography (MRA), cine phase contrast (PC) MRI, and MR oximetry are MRI techniques that can be used to obtain anatomic and functional information about the mesenteric circulation. This article reviews the current status of how these techniques can be applied to the diagnosis of chronic and acute mesenteric ischemia.

CONTRAST-ENHANCED MRA OF MESENTERIC ARTERIAL STENOSIS

Contrast-enhanced MRA has been applied to the imaging of different vascular abnormalities with promising results.[10-14] However, the accuracy of this technique for diagnosing mesenteric arterial stenosis has not been well documented. The author has concluded a study of the accuracy of contrast-enhanced MRA in diagnosing superior mesenteric artery (SMA) stenosis in a canine model using digital subtraction arteriography (DSA) as the gold standard (unpublished data). Gradual SMA stenoses were induced in the dogs by surgically implanting ameroid rings around the SMAs. Twenty-one MRA and DSA studies were performed in seven dogs (Fig 1). SMA stenoses from 0% to 100% were included in the study. The technical factors for the contrast-enhanced MRA used are: three-dimensional (3D) Fourier transform fast-gradient–recalled (FGR) sequence, sagittal plane, repetition time (TR) of 15.1 msec, echo time (TE) of 2.7 msec, flip angle of 20 degrees, 256 × 128 matrix, 1 acquisition (NEX), 20-cm field of view, 12 slices per acquisition, 1.5-mm slice thickness, no interslice gap, and imaging time of 32 sec. Three blinded reviewers interpreted the MRA and DSA images independently and separately recorded the degree of SMA stenoses in each study. By linear regression analysis, the MRA results correlated very well with DSA results with r being equal to 0.88, 0.95, and 0.96 for the three reviewers. The MRA and DSA results of the three reviewers also correlated well, with little interobserver variation. Our results showed that contrast-enhanced MRA has potential value as a noninvasive test for obtaining anatomic information about the mesensteric circulation.

CINE PC MRI

Cine PC MRI combines the flow-dependent contrast of PC MRI with the ability to produce images throughout the cardiac cycle. Cine PC MRI produces images in which contrast is related to flow velocity and also produces magnitude images such as those used in conventional cine MRI. The images can be interpreted qualitatively to show the presence, magnitude, and direction of flow. In addition, the data obtained can be used to provide estimates of flow velocity, volume flow rate, and displaced volumes. The accuracy of cine PC MRI has been verified repeatedly in vitro and in vivo.[15,16]

From the Department of Radiology, Stanford University Medical Center, Stanford, CA.
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Address reprint requests to King C.P. Li, MD, Department of Radiology, Room H-1307, Stanford University Medical Center, 300 Pasteur Dr, Stanford, CA 94305.

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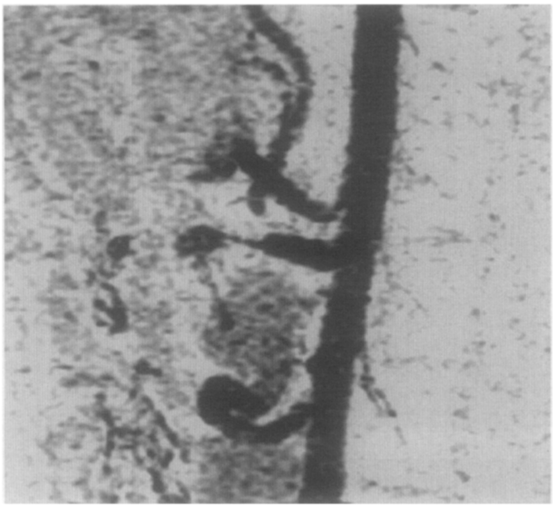

Fig 1. Contrast-enhanced MRA image of a severely stenosed SMA. Notice the high-quality image without significant flow artifacts. The degree of stenosis corresponded very well with that seen on conventional x-ray arteriography (not shown).

The author and others[16-21] have used cine PC MRI successfully for measuring SMA and superior mesenteric vein (SMV) blood flow in animal models and in patients. They typically obtain one 5-mm-thick axial section at the level of the pancreatic head (Fig 2) with the following parameters: cardiac or peripheral gating, respiratory compensation, 24-cm field of view, 16 phases per cardiac cycle, 256 × 128 matrix, 25 msec TR, 10 msec TE, 30-degree flip angle, and two signal averages. They use a through-plane flow-encoding strength (v_{enc}) of 100 cm/sec after fasting and 150 cm/sec after meals (Fig 3). The flow-encoding strength is chosen to be just high enough to avoid aliasing in the SMA. With this protocol, SMA and SMV flow can be measured simultaneously.

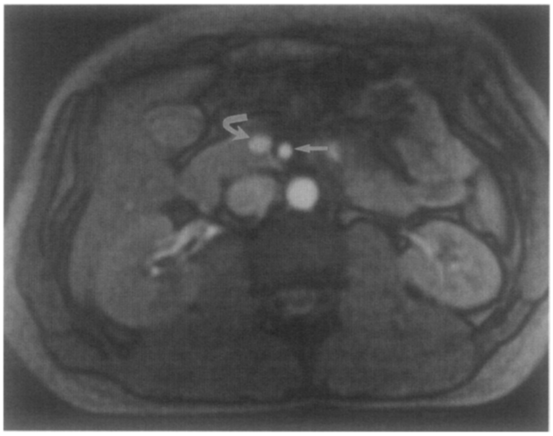

Fig 2. Axial localizer image (gradient-recalled acquisition in the steady state, 34 msec TR, 13 msec TE, 30-degree flip angle) illustrates the typical level for cine PC MR acquisitions. Note that the plane of section is at the level of the pancreatic head, proximal to the first branch of the SMA (straight arrow), and distal to the last branch of the SMV (curved arrow). Also note the rounded configurations of the SMA and SMV, indicating that these vessels are nearly perpendicular to the axial plane at this level. (Reprinted with permission.[18])

IN VIVO MR OXIMETRY

The theory and technique used for in vivo MR oximetry have been fully described previously.[22,23] MR oximetry relies on the fact that deoxyhemoglobin in red blood cells is paramagnetic but that oxyhemoglobin is not. The paramagnetic deoxyhemoglobin in red blood cells changes the local susceptibility, which in turn causes a change in the effective field strength experienced by the protons near the deoxyhemoglobin. Spins that undergo exchange and/or bounded diffusion through the deoxyhemoglobin-induced gradient fields in and around intact red blood cells are dephased irreversibly, leading to a decrease in the T2 relaxation time of blood ($T2_b$). The rapid and regular application of 180-degree pulses reduces this loss of coherence by reducing the range of frequencies a spin experiences before it is "refocused." Thus, the time between refocusing pulses (τ_{180}) and the external field strength (B_0) mediate the dependence of $T2_b$ on blood oxygen saturation (%HbO_2). The author has obtained a simple functional model from previous studies that can be parametrized experimentally[22]:

$$\frac{1}{T2_b} = \frac{1}{T2_0} + K(\tau_{180}, B_0)\left[1 - \frac{\%HbO_2}{100}\right]^2$$

where $T2_b$ is the T2 of fully oxygenated blood and K is a constant for a given τ_{180} and B_0. To take advantage of this calibration for in vivo blood oxygen saturation measurement, an accurate estimate needs to be made of the T2 of blood in vivo at a selected τ_{180}. The author has developed a modified Carr-Purcell-Meiboom-Gill (CPMG) sequence for this purpose[22,23] (Fig 4). Typically, the author uses a TR of 2 seconds; τ_{180} of 12 msec with four echoes acquired at 30, 78, 126, and 222 msec on consecutive interleaves of the sequence; and 40 spiral acquisitions at 17 msec each per image with a

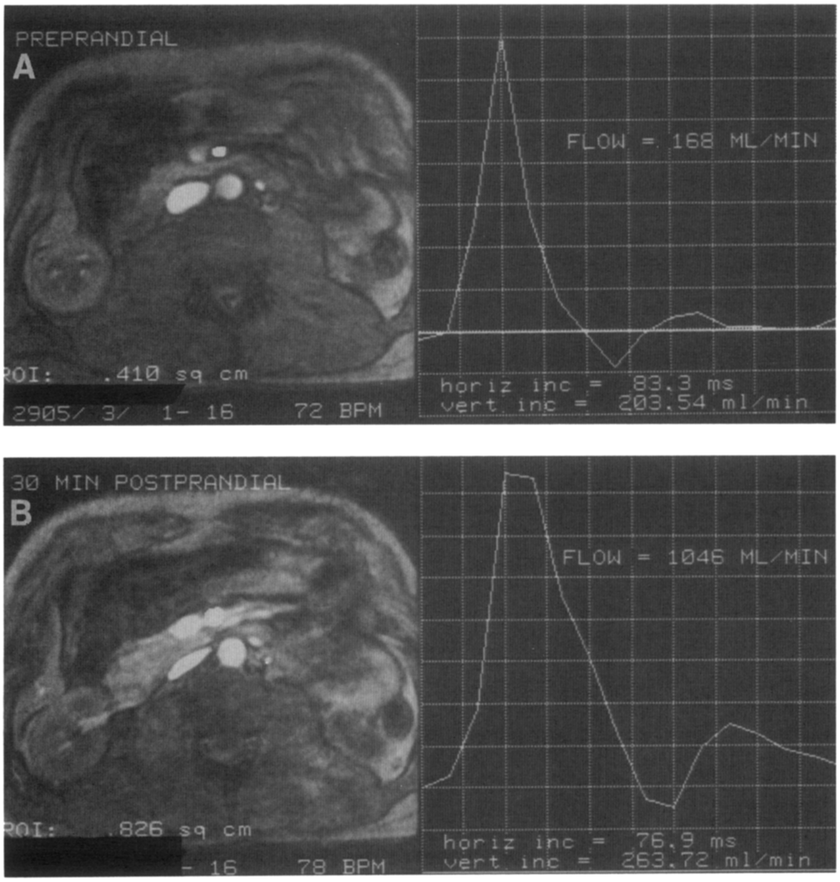

Fig 3. Cine PC MR images obtained with cardiac gating and plots of SMA blood flow in a healthy subject (A) before and (B) 30 min after food intake. Note the low SMA blood flow and the reverse early diastolic flow in the fasting state. There is a marked increase in SMA blood flow 30 min after food intake, and the reverse early diastolic flow has disappeared. (Reprinted with permission.[17])

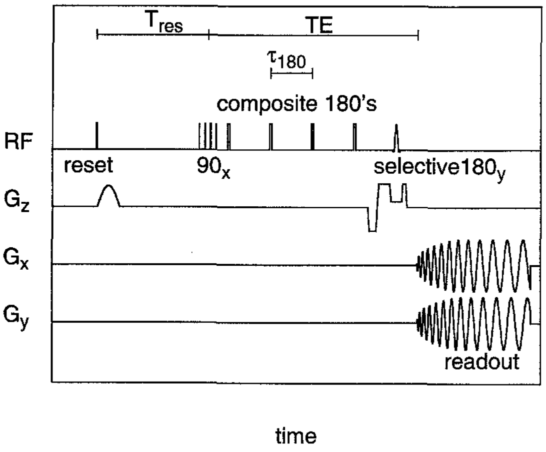

Fig 4. Pulse sequence for the in vivo estimation of $T2_b$. As shown, the sequence images an axial section. T_{res}, time from reset to excitation; RF, envelope of the radiofrequency signal applied to the object; G_x, G_y, and G_z, field gradients applied along the corresponding spatial axes. (Reprinted with permission.[23])

total imaging time of 4 minutes and 20 seconds (Fig 5). To establish a quantitative relationship between $T2_b$ and blood oxygen saturation for each individual subject, approximately 15 to 20 mL of peripheral venous blood is drawn and then aerated to varying levels of blood oxygen saturation and put into separate tubes. The $T2_b$ of the various blood samples is measured using a simplified version of the sequence described previously. By applying a least-square fit of the equation presented previously to the resulting data set of ($T2_b$ and blood oxygen saturation) pairs, the best estimates of the parameters $T2_0$ and K for that subject can be found. This calibrated equation is then used to map the in vivo $T2_b$ measurements to the corresponding blood oxygen saturation. The author has verified the accuracy of this noninvasive methodology for estimating SMV blood oxygen saturation in vivo in a canine model.[23] The author found an excellent correlation between

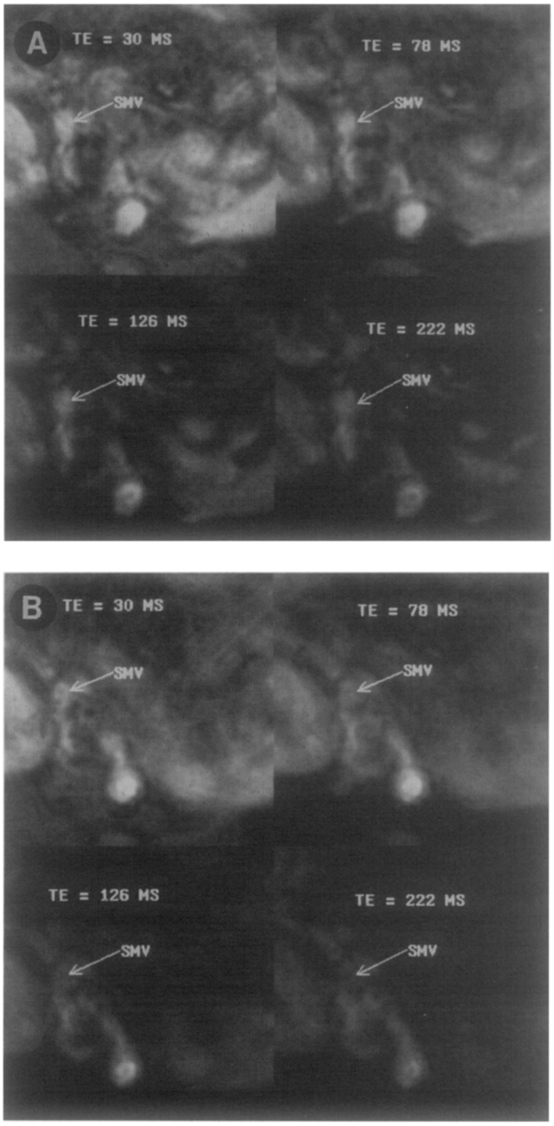

Fig 5. MR images of the canine SMV obtained for T2 measurement of blood. Images depict the same axial section through the abdomen. (A) Preocclusion MR images show that the signal intensity of blood within the SMV remains relatively high, even in the late-echo images, indicating a longer T2 relaxation time and a higher blood oxygen saturation. (B) Postocclusion MR images show a more rapid decrease in the blood signal intensity with an increase in echo time, indicating a shorter T2 relaxation time and lower blood oxygen saturation. (Reprinted with permission.[23])

MR oximetry measurements and reflectance oximeter measurements ($r = .969$ with τ_{180} of 12 msec) (Fig 6). Since then, this technique has been applied successfully in measuring SMV blood oxygen saturation in many human and canine subjects.

RELATIONSHIP OF BLOOD FLOW AND OXYGEN CONSUMPTION TO ISCHEMIC INJURY OF THE SMALL INTESTINE

It has been well established in animal models that the intestine maintains a constant level of oxygen uptake as blood flow is decreased. Initially, oxygen uptake is maintained by compensating, reciprocal changes in intestinal oxygen extraction[24-29]; however, when intestinal blood flow decreases to a threshold below which intestinal oxygen extraction can no longer increase, then a further decrease in blood flow leads to a decrease in oxygen uptake (calculated as the product of blood flow and arteriovenous oxygen difference). When intestinal oxygen uptake decreases to below 50% of normal, pathological ischemic changes begin to develop. These data suggest that in vivo measurements of intestinal blood flow and oxygen extraction can provide very important functional information regarding mesenteric ischemia.

MR DIAGNOSIS OF CHRONIC MESENTERIC ISCHEMIA

Chronic mesenteric ischemia is characterized by a triad of clinical symptoms that include postprandial abdominal pain, food aversion, and weight loss.[1] Atherosclerosis is the etiology in more than 95% of cases of chronic mesenteric ischemia. Angiography is currently the most frequently used test for confirming the

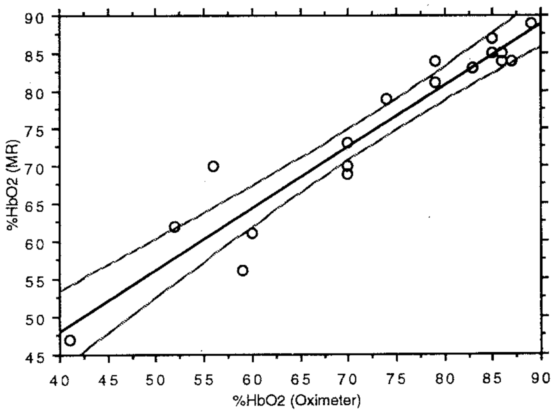

Fig 6. SMV blood oxygen saturation measurements with MR imaging (y axis) obtained with a τ_{180} of 12 msec versus oximetry (x axis). The solid line indicates the best linear fit to the data ($y = 0.959x + 5.3$; $r = 0.969$); the dashed line is the 95% confidence interval. (Reprinted with permission.[23])

diagnosis. Significant stenosis or occlusion of at least two of the major mesenteric arteries is regarded as supportive of the diagnosis. However, because there can be extensive communication between the celiac artery, SMA, inferior mesenteric artery (IMA), and other vessels of the upper abdomen, it has been observed that chronic stenosis or even occlusion of all three major mesenteric arteries can occur without any abdominal symptoms.[30,31] Therefore, anatomic data alone are insufficient for diagnosing chronic mesenteric ischemia, and many investigators have begun exploring the possibility of using functional data for the diagnosis. Duplex sonography has been used to study the blood flow of mesenteric vessels, but this technique is operator dependent, accurate flow volume data are difficult to obtain, and overlying bowel gas or excessive adipose tissue may preclude an optimal examination. Initial results of using cine PC MRI for diagnosing chronic mesenteric ischemia are very encouraging.

In the author's preliminary study of 10 healthy subjects, 4 asymptomatic patients, and 1 symptomatic patient, it was found that the percentage change in SMA blood flow, as measured by cine PC MRI, at 30 minutes after ingestion of a standardized meal (240 mL of Ensure [Abbott Laboratories, Columbus, OH]) can be used to distinguish between healthy subjects and individuals with mesenteric ischemia (Fig 7). In healthy volunteers, SMA blood flow at 15, 30, and 45 minutes postprandial were all significantly higher than fasting SMA flow.[17] This finding was confirmed by Naganawa et al[19] in a study of 5 healthy volunteers. In a subsequent study of 6 healthy volunteers, 6 asymptomatic patients, and 2 symptomatic patients,[18] simultaneous measurements of SMA and SMV blood flow were obtained after fasting and at 15, 30, and 45 minutes postprandial. It was found that postprandial SMV and SMA flow increased substantially less in patients with mesenteric vascular disease than in volunteers (Figs 8 and 9). It was also found that with increasing severity of mesenteric vascular disease, as shown by conventional x-ray angiography, the ratio of increase in SMV flow to the increase in SMA flow decreased (Fig 10). These data suggest that as mesenteric vascular disease becomes more severe, the mesenteric flow reserve decreases and the normal postprandial shunting of blood into the small bowel via collateral vessels diminishes. Burkart et al[20] confirmed in a study of 10 volunteers and 10 patients that postprandial augmentation of peak flow in the SMV was significantly less in patients with symptomatic chronic mesenteric ischemia, compared with volunteers. In this study, SMV flow augmentation in patients without mesenteric ischemia did not differ significantly from that in volunteers. The author recently concluded a study that

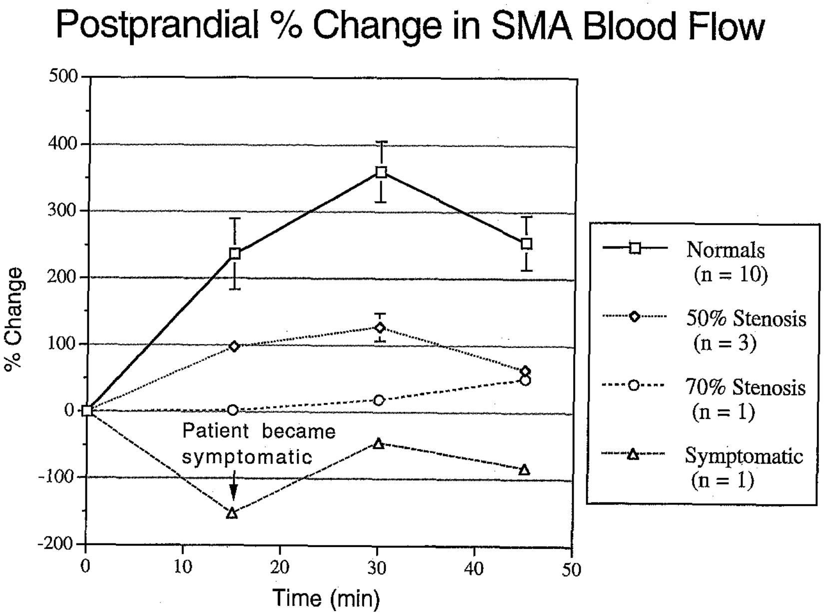

Fig 7. Percentage change in SMA blood flow versus time after food intake in healthy subjects and patients with SMA stenosis. Note that the percentage change in postprandial SMA blood flow in the healthy subjects is greater than that in the patient group. The difference in postprandial blood flow between the four groups is seen best at 30 minutes. (Reprinted with permission.[17])

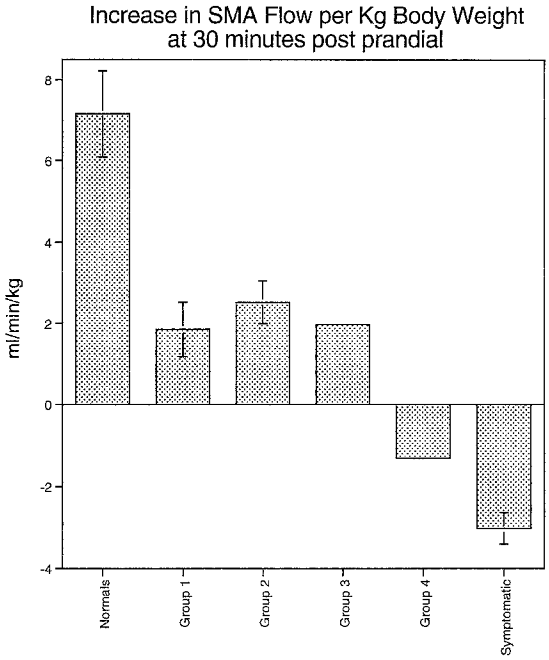

Fig 8. Increase in flow rate in the SMA per kilogram of body weight (mean ± SE) at 30 minutes after a meal. Group 1, <50% SMA stenosis; Group 2, <50% SMA stenosis and occluded IMA; Group 3, >70% SMA stenosis; and Group 4, >70% SMA stenosis, >50% celiac stenosis, and occluded IMA. (Reprinted with permission.[18])

investigated the use of in vivo MR oximetry for diagnosing chronic mesenteric ischemia in human subjects and in a canine model (unpublished data). The author found that in volunteers and asymptomatic patients, the SMV blood oxygen saturation either increases or remains unchanged after a meal challenge; whereas in

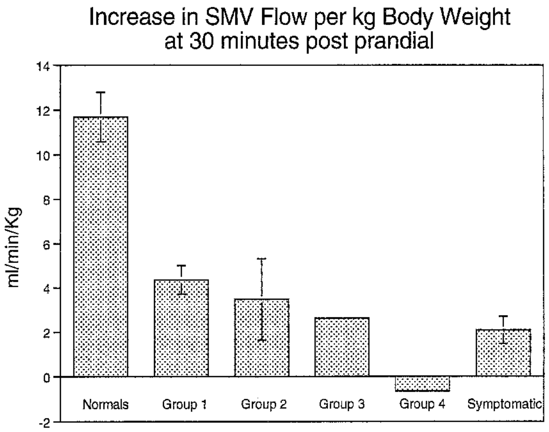

Fig 9. Increase in flow rate in the SMV per kilogram of body weight (mean ± SE), at 30 minutes after a meal. (See Fig 3 for the definition of groups 1 through 4.) (Reprinted with permission.[18])

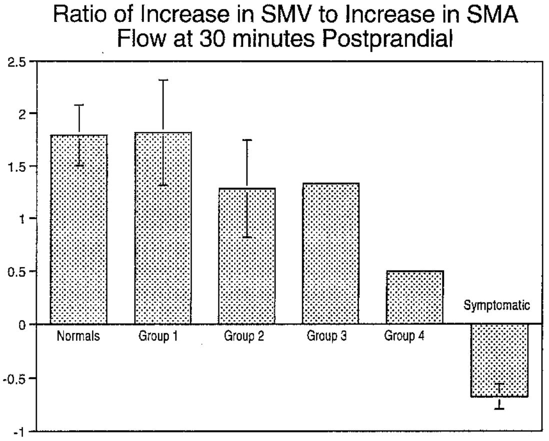

Fig 10. Ratio of the increase in SMV flow to the increase in SMA flow (mean ± SE) at 30 minutes after a meal. (See Fig 3 for the definition of groups 1-4.) (Reprinted with permission.[18])

the symptomatic patients, a postprandial decrease in the SMV blood oxygen saturation was found. This result was confirmed in a canine model in which 10 dogs were studied.

MR DIAGNOSIS OF ACUTE MESENTERIC ISCHEMIA

Acute mesenteric ischemia is a devastating disease that without early intervention proceeds to intestinal gangrene and its associated high morbidity, mortality, and health care cost. Early diagnosis of this disease currently relies on a high index of suspicion by the clinician in patients who have significant risk factors for this disease. In an attempt to improve diagnostic accuracy, many modalities, including enzyme screening, radiography, laparoscopy, sonography, and angiography, have been explored, but at present there is no test that allows for an accurate early diagnosis of acute mesenteric ischemia.[32-34] In the study described previously, in which the author obtained simultaneous SMA and SMV measurements in volunteers and patients with various degrees of mesenteric vascular disease, the author found a large overlap between the fasting SMA and SMV flow measurements in the volunteers as well as in the different groups of patients. This result suggests that MR flow measurement alone probably is insufficient for the diagnosis of acute mesenteric ischemia. Similar results have been reported in the ultrasound literature.[31-33] The author has started to investigate the use of in vivo

MR oximetry for this diagnosis. In a canine model, he showed that a decrease in the SMV blood oxygen saturation, as measured by MR in vivo, correlates well with the degree of SMA flow reduction. The relationship follows a sigmoidal curve: As SMA flow decreases initially, little change occurs in the SMV blood oxygen saturation, probably because of collateral flow from celiac artery branches. As SMA flow decreases further, SMV flow also decreases, until oxygen extraction is maximized (at approximately 10% of normal SMA flow).[35] These results suggest that MR measurements of SMV blood oxygen saturation may be an accurate, sensitive, and noninvasive method for diagnosing acute mesenteric ischemia. The author also has obtained MR SMA and SMV flow measurements and SMV blood oxygen saturation measurements in patients suspected of having acute mesenteric ischemia. In one patient with acute SMA occlusion, the fasting SMV blood oxygen saturation was found to be lower than the IVC blood oxygen saturation (unpublished data). In normal volunteers and patients proven free of acute mesenteric ischemia, the fasting SMV blood oxygen saturation was at least as high as the IVC blood oxygen saturation.

CONCLUSION

MRI potentially can provide morphological information about the patency of the mesenteric vessels and quantitative functional information about blood flow and blood oxygen saturation in these vessels. Thus far, the preliminary results in dogs and humans have been very encouraging. Studies with larger numbers of patients are required, however, before MRI can be established as a definitive, noninvasive test for the diagnosis of both acute and chronic mesenteric ischemia. In the long term, we hope that these MR techniques also can be used for improving the diagnosis and posttreatment evaluation of vascular diseases in other organ systems.

REFERENCES

1. Cunningham CG, Reilly LM, Stoney R: Chronic visceral ischemia. Surg Clin North Am 72:231-244, 1992

2. Levy PJ, Krausz MM, Manny J: Acute mesenteric arterial occlusion: A plea for early diagnosis. Surgery 83:482-485, 1978

3. Batellier J, Kieny R: Superior mesenteric artery embolism: Eighty two cases. Ann Vasc Surg 4:112-116, 1990

4. Finucane PM, Arunachalam T, O'Dowd J, et al: Acute mesenteric infarction in elderly patients. J Am Geriatr Soc 37:355-358, 1989

5. Georgiev G: Acute obstruction of the mesenteric vessels: A diagnosis and therapeutic problem. Khirugliia (Mosk) 42:23-29, 1989

6. Clark RA, Gallant TE: Acute mesenteric ischemia: Angiographic spectrum. AJR Am J Roentgenol 142:555-562, 1984

7. Sachs SM, Morton JH, Schwartz SI: Acute mesenteric ischemia. Surgery 92:646-653, 1982

8. Rogers DM, Thompson JE, Garrett WV, et al: Mesenteric vascular problems: A 26 year experience. Ann Surg 195:554-565, 1982

9. Marston A: Vascular Disease of the Gastrointestinal Tract: Pathophysiology, Recognition and Management. Baltimore, Williams & Wilkins, 1986

10. Adamis MK, Li W, Wielospolski PA, et al: Dynamic contrast-enhanced subtraction MR angiography of the lower extremities: Initial evaluation with a multisection two-dimensional time-of-flight sequence. Radiology 196(3):689-695, 1995

11. Douek PC, Revel D, Chazel S, et al: Fast MR angiography of the aortoiliac arteries and arteries of the lower extremity: Value of bolus-enhanced, whole-volume subtraction technique. AJR Am J Roentgenol 165(2):431-437, 1995

12. Snidow JJ, Sawchuk AP, Dalsing MC: Iliac artery MR angiography: Comparison of three-dimensional gadolinium-enhanced and two-dimensional time-of-flight techniques. Radiology 196(2):371-378, 1995

13. Prince MR: Gadolinium-enhanced MR aortography. Radiology 19(1):155-164, 1994

14. Prince MR, Yucel EK, Kaufman JA, et al: Dynamic gadolinium-enhanced 3DFT abdominal MR arteriography. J Magn Reson Imaging 3:877-881, 1993

15. Evans AJ, Iwai F, Grist TM, et al: Magnetic resonance imaging of blood flow with a phase subtraction technique. In vitro and in vivo validation. Invest Radiol 28:109-115, 1992

16. Pelc LR, Pelc NJ, Rayhill SC, et al: Arterial and venous blood flow: Noninvasive quantitation with MR imaging. Radiology 185:809-812, 1992

17. Li KCP, Whitney WS, McDonnell CH, et al: Chronic mesenteric ischemia: Evaluation with phase-contrast cine MR imaging. Radiology 190:175-179, 1994

18. Li KCP, Hopkins KL, Dalman RL, et al: Simultaneous measurement of flow in the superior mesenteric vein and artery with cine phase-contrast MR imaging: Value in diagnosis of chronic mesenteric ischemia. Radiology 194:327-330, 1995

19. Naganawa S, Cooper TG, Jenner G, et al: Flow velocity and volume measurement of superior and inferior mesenteric artery with cine phase contrast magnetic resonance imaging. Radiat Med 12(5):213-220, 1994

20. Burkart DJ, Johnson CD, Reading CC, et al: MR measurements of mesenteric venous flow: Prospective evalu-

ation in healthy volunteers and patients with suspected chronic mesenteric ischemia. Radiology 194(3):801-806, 1995

21. Burkart DJ, Johnson CD, Ehman RL: Correlation of arterial and venous blood flow in the mesenteric system based on MR findings. AJR Am J Roentgenol 161(6):1279-1282, 1993

22. Wright GA, Hu BS, Macovski A: Estimating oxygen saturation of blood in vivo with MR imaging at 1.5 T. J Magn Reson Imaging 1:275-283, 1991

23. Li KCP, Wright GA, Pelc LR, et al: Oxygen saturation of blood in the superior mesenteric vein: In vivo verification of MR imaging measurements in a canine model. Radiology 194:321-325, 1995

24. Kvietys PR, Granger DN: Relation between intestinal blood flow and oxygen uptake. Am J Physiol 242 (Gastrointest Liver Physiol 5): G202-208, 1982

25. Hamar J, Ligeti L, Kovach AGB: Intestinal O_2 consumption under low flow conditions in anesthetized cats. Adv Exp Med Biol 94:573–578, 1977

26. Granger HJ, Norris CP: Intrinsic regulation of intestinal oxygenation in the anesthetized dog. Am J Physiol 238(Heart Circ Physiol 7):H836-H843, 1980

27. Shepherd AP: Metabolic control of intestinal oxygenation and blood flow. Fed Proc 41:2084-2089, 1982

28. Granger DN, Kvietys PR, Perry MA: Role of exchange vessels in the regulation of intestinal oxygenation. Ann Rev Physiol 43:409-418, 1981

29. Bulkley GB, Kvietys PR, Parks DA, et al: Relationship of blood flow and oxygen consumption to ischemic injury in the canine small intestine. Gastroenterology 89:852-857, 1985

30. Kurland B, Brandt LJ, Delany HM: Diagnostic tests for intestinal ischemia. Surg Clin North Am 72(1):85-105, 1992

31. Williams LF Jr: Mesenteric ischemia. Surg Clin North Am 68(2):331-353, 1988

32. Kaleya RN, Sammartano RJ, Boley SJ: Aggressive approach to acute mesenteric ischemia. Surg Clin North Am 72(1):157-182, 1992

33. Wolf EL, Sprayregen S, Bakal CW: Radiology in intestinal ischemia: Plain film, contrast, and other imaging studies. Surg Clin North Am 72(1):107-124, 1992

34. Bakal CW, Sprayregen S, Wolf EL: Radiology in intestinal ischemia: Angiographic diagnosis and management. Surg Clin North Am 72(1):125-141, 1992

35. Li KC, Pelc LR, Dalman RL, et al: Use of in vivo MR imaging measurements of superior mesenteric vein blood oxygen saturation for determining the degree of acute superior mesenteric artery stenosis in a canine model. Radiology 197(P):246, 1995 (abstr)