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Chronic Mesenteric Ischemia: Use of in Vivo MR Imaging Measurements of Blood Oxygen Saturation in the Superior Mesenteric Vein for Diagnosis[1]

PURPOSE: To determine if dogs and humans with chronic mesenteric ischemia demonstrate a decrease in the percentage of oxygenated hemoglobin ($\%Hb_{O_2}$) in the superior mesenteric vein (SMV) after a meal.

MATERIALS AND METHODS: In 10 dogs, ameroid rings were surgically implanted around the superior mesenteric arteries to create gradual stenosis. Pre- and postoperative angiograms and pre- and postprandial magnetic resonance (MR) oximetry measurements of the SMV $\%Hb_{O_2}$, with flow-independent T2 measurements of venous blood, were obtained at different times. In 10 patients with atherosclerotic disease and six patients with symptomatic chronic mesenteric ischemia, the same measurements were obtained after at least 6 hours of fasting and at 15, 35, and 45 minutes after ingestion of a liquid nutritional supplement.

RESULTS: In seven dogs, the postprandial SMV $\%Hb_{O_2}$ increased an average of 2.5% ± 0.8 before surgery and decreased an average of 6.3% ± 2.1 when hemodynamically significant (>70%) stenosis of the superior mesenteric artery developed 7–14 days after surgery. In the 10 patients without ischemia, the SMV $\%Hb_{O_2}$ increased by 4.6% ± 0.6, whereas in the symptomatic patients a postprandial decrease of 8.8% ± 0.7 occurred ($P < .0001$).

CONCLUSION: Measurement of the SMV $\%Hb_{O_2}$ with MR oximetry is a promising test for diagnosis of chronic mesenteric ischemia.

CHRONIC mesenteric ischemia is characterized by a triad of clinical symptoms including postprandial abdominal pain, food aversion, and weight loss (1,2). Since many other diseases including peptic ulcer disease and pancreatic and other types of intraabdominal neoplasia can have similar clinical symptoms, the clinical diagnosis of chronic mesenteric ischemia has traditionally been very difficult to make (1,2). Demonstration of stenosis or occlusion of at least two of the major mesenteric vessels at angiography is the most common confirmatory test used to diagnose chronic mesenteric ischemia, and communications between the mesenteric arteries and other vessels of the abdomen are well shown at angiography. However, anatomic information from angiography alone is also insufficient to establish the diagnosis of chronic mesenteric ischemia (3,4). Chronic stenosis or even occlusion of all three major mesenteric arteries has been found to occur without any abdominal symptoms (3,4). Mesenteric arterial stenosis without symptoms occurs mainly because extensive communications can develop between the mesenteric arteries and other vessels of the upper abdomen when the mesenteric arteries become stenotic.

Since patients with chronic mesenteric ischemia experience abdominal pain only after ingestion of a meal, it is reasonable to assume that the postprandial increase in mesenteric blood flow is insufficient to compensate for the increase in metabolic demand caused by food intake in these patients. As a result, the oxygen extraction, measured by means of the difference in mesenteric arterial-venous oxygen saturation, should increase, and the superior mesenteric vein (SMV) percentage of oxygenated hemoglobin ($\%Hb_{O_2}$) should decrease in these patients after ingestion of a meal.

It has been demonstrated that the SMV $\%Hb_{O_2}$ can be measured accurately in vivo with flow-independent T2 measurements of the venous blood (5). The purpose of this study was to determine if dogs and humans with chronic mesenteric ischemia demonstrate a decrease in the SMV $\%Hb_{O_2}$ after a meal, as measured with in vivo MR oximetry.

MATERIALS AND METHODS

In Vivo MR Oximetry

The theory and the technique used for in vivo MR oximetry have been fully de-

Index terms: Blood, flow dynamics, 70.91, 959.99 • Gastrointestinal tract, ischemia, 70.7619, 70.91 • Magnetic resonance (MR), oxygen transport, 70.7619, 70.91, 955.12949 • Magnetic resonance (MR), pulse sequences, 955.12944, 959.12944 • Mesentery, ischemia, 792.7619

Abbreviations: $\%Hb_{O_2}$ = percentage of oxygenated hemoglobin, SMA = superior mesenteric artery, SMV = superior mesenteric vein.

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scribed previously (5,6). MR oximetry operates on the principle that deoxyhemoglobin in red blood cells is paramagnetic but oxyhemoglobin is not. For in vivo measurement of the $\%HbO_2$, we needed to accurately estimate the T2 of blood in vivo. To achieve this, we modified the basic Carr-Purcell-Meiboom-Gill sequence used in spectrometer studies of blood to address the challenges of the in vivo environment. The resultant sequence has been fully described previously (6). For estimation of the SMV $\%HbO_2$, the sequence was performed with the body coil and the following parameters: repetition time, 2,000 msec; time between 180° pulses (τ_{180}) = 12 msec with four echoes acquired at 30, 78, 126, and 222 msec on consecutive interleaves of the sequence; 20 spiral acquisitions per image; and two signals acquired, yielding a total imaging time of 5 minutes 20 seconds. Section thickness was 7 mm and inplane resolution was 1.8 mm. This is a single-section technique. For the T2 measurements, a region of interest was selected to cover the SMV to a margin corresponding roughly to a threshold of 50% of the maximum signal intensity in the vessel. Typically, each region of interest covered 10–15 voxels that measured $2 \times 2 \times 7$ mm each.

To establish a quantitative relation between the T2 of blood and the $\%HbO_2$ for each subject, blood samples were obtained with a peripheral venous catheter. The citrated samples were aerated to varying levels of $\%HbO_2$ as measured with a clinical reflectance oximeter (Oxicom 2100; Waters Instruments, Rochester, Minn) before and after the in vitro MR oximetry studies. The test tubes were immersed in an insulated water bath doped with manganese chloride (T2 less than 2 msec) at 37°C to minimize B_0 (constant magnetic induction field) inhomogeneity due to susceptibility and to maintain the blood at body temperature throughout the experiment.

The T2 of blood was measured with the sequence described previously. The T2 of blood in each sample was estimated with a least squares fit of a monoexponential decay function to the average signal intensities at the four echo times determined from a small square region chosen near the center of the sample in the image. A least squares fit of the resultant data set of pairs (T2 of blood, $\%HbO_2$) was then used to map the in vivo measurements of the T2 of blood to the corresponding $\%HbO_2$.

Animal Experiments

All animal procedures used in the study were approved by the Stanford University Institutional Animal Care and Use Committee. Ten mongrel dogs (weight range, 20–30 kg) were studied. The animals fasted for 24 hours before surgery. The animals received 0.01 mg per kilogram of body weight acepromazine maleate (Butler, Columbus, Ohio) subcutaneously before the procedure. Anesthesia was achieved with intravenous administration of thiopental sodium (Pentothal; Abbott Laboratories, North Chicago, Ill) (25 mg per kilogram of body weight). The animals were then intubated and ventilated with an MR imaging–compatible ventilator (Omni Tech Medical, Topeka, Kan). Anesthesia was then maintained with 1.5%–2.0% halothane (Halocarbon Laboratories, River Edge, NJ).

Laparotomy was then performed on each dog under sterile conditions, and an ameroid constrictor (Research Instruments, Corvallis, Ore) was placed around the superior mesenteric artery (SMA) at its origin. Each ameroid constrictor was a ring-shaped device with an agar-impregnated center enclosed in a Lucite jacket; this construction permitted the ring to expand only centrally as it absorbed peritoneal fluid and slowly occluded the vessel lumen. A small opening in the circumference of the occluder allowed the constrictor to be placed around the vessel in the fashion of a pessary (7–9). Ameroid constrictors have been used to create gradual occlusion of various vessels including coronary arteries, portal veins, and renal arteries (7–9). The rate of occlusion is variable and is dependent on many factors including the size of the vessel and how tightly the constrictor was applied around the vessel.

In all dogs, MR imaging and x-ray angiography with arterial administration of contrast material were performed before surgery and at 2–5-day intervals after surgery. All dogs fasted for at least 12 hours before the imaging studies. All x-ray angiographic studies were performed with the dogs under general anesthesia and under standard sterile conditions. Femoral punctures were performed with the Seldinger technique. Frontal and lateral aortograms were obtained routinely in every session. Selective arteriograms of the superior mesenteric and celiac arteries were also obtained in cases in which overlap of vessels precluded optimal assessment of the mesenteric vessels. All angiograms were interpreted jointly by two experienced radiologists (K.C.P.L., I.Y.C.) in consensus without knowledge of the MR imaging results. All MR images were obtained with a 1.5-T whole-body imager (Signa; GE Medical Systems, Milwaukee, Wis) and a body coil. Axial and sagittal localizing images were obtained to ensure that the imaging plane was perpendicular to the SMV.

After MR oximetry was performed with the dogs in the fasting state, a liquid nutritional supplement (Ensure; Ross Laboratories, Columbus, Ohio), 3 mL per kilogram of body weight, was instilled into the stomach of each dog by means of an orogastric tube. MR oximetry was repeated at 15, 35, and 45 minutes after intake of the supplement. The arterial $\%HbO_2$ was monitored throughout the experiments with a pulse oximeter (model 8500V; Nonin Medical, Plymouth, Minn) placed on the tongue in each dog. In all dogs, in vitro calibrations of the T2 of blood and the $\%HbO_2$ were performed as described previously. X-ray angiographic examinations were performed within 24 hours of all MR imaging examinations, and in the majority of cases the two examinations were performed less than 2 hours apart. The maximum postprandial change in the SMV $\%HbO_2$ was calculated in all dogs at each point.

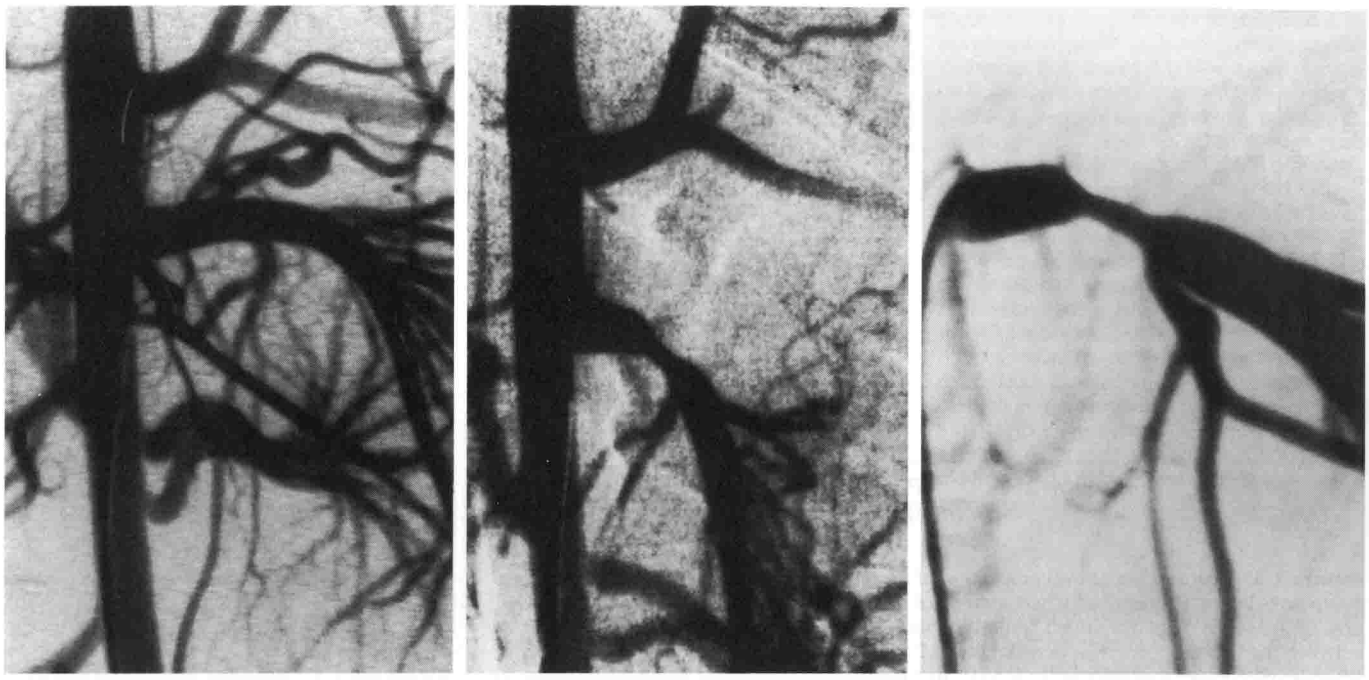
Demographic Data, Angiographic Findings, and Postoperative Follow-up Results in Symptomatic Patients

Patient/ Age (y)/Sex	Percentage of Stenosis at Angiography*	Postoperative Follow-up
1/37/M	100 in CA, 100 in SMA, 0 in IMA	Asymptomatic for 40 mo
2/82/F	70 in CA, 90 in SMA, 0 in IMA	Asymptomatic for 14 mo
3/74/F	100 in CA, 100 in SMA, 0 in IMA	Asymptomatic for 2 mo and then died of multiorgan failure unrelated to mesenteric ischemia
4/64/F	100 in CA, 0 in SMA, 100 in IMA	Asymptomatic for 12 mo
5/60/M	90 in CA, 100 in SMA, 100 in IMA	Asymptomatic for 6 mo
6/63/M	0 in CA, 100 in SMA, 100 in IMA	Asymptomatic for 8 mo

* CA = celiac artery, IMA = inferior mesenteric artery. Percentage of stenosis was determined by means of measurement of the luminal diameter at the point of greatest reduction in diameter divided by diameter just proximal or distal to the stenosis as seen at lateral angiography and rounded to the closest 10%. 0 is used to indicate all stenosis less than 50%.

Human Experiments

All procedures that involved humans in the study were approved by the Stanford University Administrative Panel on Human Subjects in Medical Research. Ten patients without symptoms of chronic mesenteric ischemia with correlative x-ray angiographic studies and six patients with symptomatic chronic mesenteric ischemia were studied. The patients without symptoms of chronic mesenteric ischemia included seven men and three women with a mean age of 62.3 years ± 17.6 (mean ± standard deviation; age range, 30–75 years). These patients were referred for angiography for reasons other than mesenteric ischemia. They were recruited for the MR imaging studies as the control population, and informed consent was obtained from each patient. Frontal and lateral aortograms were obtained in every case. The angiograms were interpreted prospectively by the attending radiologists who performed angiography without knowledge of the MR imaging findings. The angiographic findings included aortic atherosclerotic disease with normal mesenteric vessels (four patients), shortened trans-



a. b. c.

Figure 1. Sequential x-ray angiograms **(a)** before, **(b)** 2 days after, and **(c)** 7 days after an ameroid ring was implanted around the SMA in a dog show gradual stenosis of the vessel that resulted in hemodynamically significant stenosis within 7 days after surgery.

planted small bowel with normal mesenteric vessels (one patient), abdominal aortic aneurysm with normal mesenteric vessels (two patients), aortic dissection with normal mesenteric flow (one patient), occluded celiac and inferior mesenteric arteries with a normal SMA (one patient), and occluded superior and inferior mesenteric arteries with 75% stenosis of the celiac artery (one patient).

The symptomatic patients included three men and three women with a mean age of 63.3 years ± 15.3 (range, 37–82 years). These were consecutive patients scheduled for mesenteric revascularization surgery for treatment of chronic mesenteric ischemia. All of these patients had the classic clinical triad of symptoms (postprandial abdominal pain, weight loss, and food aversion) and hemodynamically significant stenosis or occlusion of at least two of three mesenteric vessels. MR imaging findings were not used to influence the decision to perform surgery. The demographic data, angiographic findings, and postoperative follow-up results in the symptomatic patients are summarized in the Table.

MR oximetry measurements of the SMV $\%Hbo_2$ after at least 6 hours of fasting and at 15, 35, and 45 minutes after ingestion of 240 mL of a liquid nutritional supplement (Ensure) were obtained in each subject. The arterial $\%Hbo_2$ was monitored throughout the experiments with a pulse oximeter placed on the fingers or toes of the patients. The maximum change in the postprandial SMV $\%Hbo_2$ was calculated in each subject. All symptomatic patients underwent revascularization surgery after MR imaging studies. Postoperative resolution of symptoms occurred in all patients; this complete resolution confirmed that the symptoms were caused by chronic mesenteric ischemia. One patient underwent MR oximetry measurement of the SMV $\%Hbo_2$ 7 days after revascularization surgery.

Statistical Analysis

The fasting SMV $\%Hbo_2$ in the dogs at the preoperative stage and when stenosis in the SMA first became hemodynamically significant (>70%) after implantation of ameroid rings were compared with the paired Student *t* test (Statview 4.01; Abacus Concepts, Berkeley, Calif). Similarly, the maximum postprandial change in the SMV $\%Hbo_2$ at the two times were also compared by means of the paired Student *t* test. The maximum postprandial change in the SMV $\%Hbo_2$ in the patients without symptoms of chronic mesenteric ischemia and the patients with symptoms were compared by means of the unpaired Student *t* test.

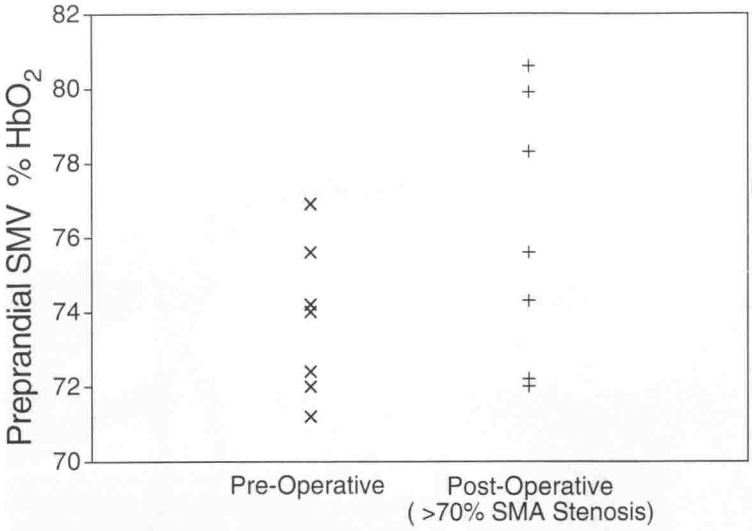
RESULTS

Animal Experiments

In seven of the 10 dogs studied, the implanted ameroid rings resulted in hemodynamically significant (>70%) stenosis of the SMA 7–14 days after surgery. Interval x-ray angiography demonstrated gradual progression of SMA stenosis as predicted (Fig 1). As the stenosis in the SMA became hemodynamically significant, gradual weight loss and increase in time necessary to consume each meal were observed in these dogs, suggesting development of chronic mesenteric ischemia.

The quantitative data for the $\%Hbo_2$ are summarized in Figures 2 and 3. Figure 2 is a scatter plot that shows comparison of the preprandial SMV $\%Hbo_2$ in the seven dogs before ameroid ring implantation and at the time when stenosis of the SMA first became greater than 70% as demonstrated at x-ray angiography. The mean preprandial SMV $\%Hbo_2$ in the seven dogs preoperatively and when stenosis in the SMA first became hemodynamically significant postoperatively was 73.8% ± 0.8 (standard error) and 76.1% ± 1.3, respectively. These values were not statistically significantly different (paired Student *t* test, $P > .5$). Figure 3 is a scatter plot that shows comparison of the maximum postprandial change in the SMV $\%Hbo_2$ in the seven dogs preoperatively and when stenosis in the SMA first became hemodynamically significant. Preoperatively, the SMV $\%Hbo_2$ in the seven dogs increased by an average of 2.5% ± 0.8 after a meal. After stenosis in the SMA became hemodynamically significant, the postprandial SMV $\%Hbo_2$ decreased by 6.3% ± 2.1. These values were statistically significantly different ($P = .007$, paired Student *t* test). Postoperatively, the maximum postprandial change in the SMV $\%Hbo_2$ occurred at 35 and 45 minutes in four and three dogs, respectively.

In the remaining three dogs, the clinical signs were not compatible with chronic mesenteric ischemia, and therefore findings in these dogs were excluded from data analysis. In one



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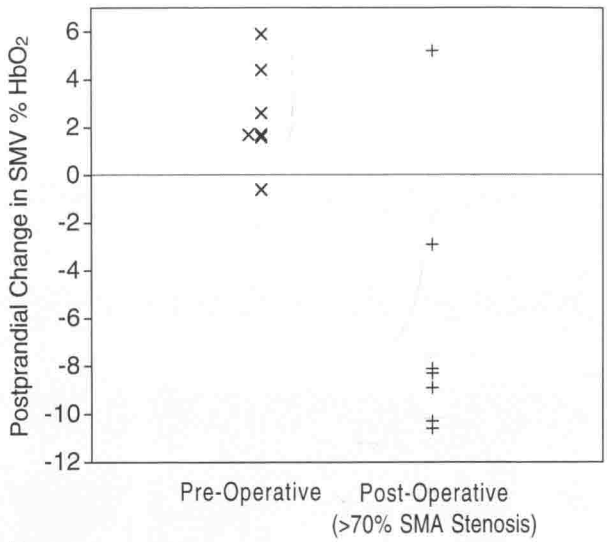

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Figures 2, 3. Scatter plots show comparison of the **(2** preprandial and **(3)** maximum postprandial change in the SMV $\%HbO_2$ at MR imaging in seven dogs before surgery and when stenosis of the SMAs first became hemodynamically significant (>70%) as demonstrated at x-ray angiography. **(2)** All seven dogs developed hemodynamically significant stenosis of the SMAs 7–14 days after surgery. Notice that there is much overlap between the two groups. **(3)** Notice that the SMV $\%HbO_2$ increased in all dogs after a standard meal preoperatively but decreased after a meal in six of seven dogs when stenosis in the SMA first became hemodynamically significant (ie, >70%).

dog, stenosis of the SMA progressed too rapidly. By day 6 after surgery, the SMA was completely occluded as demonstrated at x-ray angiography. In this dog, the fasting SMV $\%HbO_2$ was 48.9%. This percentage was much lower than the fasting SMV $\%HbO_2$ in the seven dogs after stenosis of the SMA became hemodynamically significant more slowly. Clinically, this dog developed rapid weight loss and bloody diarrhea, consistent with acute bowel ischemia and infarction, and was euthanized.

In two of the 10 dogs, stenosis of the SMA progressed very slowly. Stenosis in the SMAs in these dogs was less than 70% after 2 weeks after surgery. Clinically, the dogs did very well with no noticeable weight loss or other symptoms. Preoperatively, the SMV $\%HbO_2$ in the two dogs increased by an average of 3.3% ± 0.9 after a meal. At 2 weeks after surgery, the postprandial SMV $\%HbO_2$ increased by 4.0% ± 0.6.

Human Experiments

A scatter plot of the maximum postprandial change in the SMV $\%HbO_2$ in the patients without symptoms of chronic mesenteric ischemia and the symptomatic patients is illustrated in Figure 4. In the 10 patients without symptoms, the postprandial SMV $\%HbO_2$ increased by 4.6% ± 0.6 (range, 0.7%–7.0%). The maximum change in the $\%HbO_2$ occurred at 15, 35, and 45 minutes postprandially in one patient, seven patients, and two patients, respectively. In the two patients in whom the maximum change occurred 45 minutes postprandially, the difference between the 35- and 45-minute measurements of the SMV $\%HbO_2$ was small (0.1% and 0.9%, respectively).

In the symptomatic patients, the SMV $\%HbO_2$ decreased by 8.8% ± 0.7 postprandially (range, 6.8%–12.0%) (Fig 5). The maximum postprandial change in the SMV $\%HbO_2$ occurred at 15, 35, and 45 minutes in two patients, three patients, and one patient, respectively. In the symptomatic patient in whom the maximum postprandial change occurred at 45 minutes, the SMV $\%HbO_2$ decreased by 5.0% at 35 minutes postprandially and by 9.0% at 45 minutes postprandially. The difference between the maximum postprandial change in the SMV $\%HbO_2$ in the patients without symptoms of chronic mesenteric ischemia and that in symptomatic patients was significant (unpaired two-tailed Student t test, $P <$ .0001). In the patient who underwent MR imaging before and after revascularization surgery, the maximum postprandial change in the SMV $\%HbO_2$ improved from −14.0% preoperatively to −3.3% postoperatively.

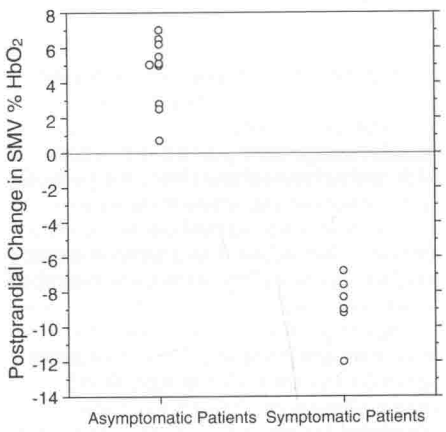

Figure 4. Scatter plot shows comparison of the maximum postprandial change in the SMV $\%HbO_2$ in 10 patients without symptoms of chronic mesenteric ischemia and six patients with symptoms. The SMV $\%HbO_2$ increased in all patients without symptoms after a standard meal but decreased after a meal in all patients with chronic mesenteric ischemia.

DISCUSSION

Since anatomic data alone are often insufficient for confirming the diagnosis of chronic mesenteric ischemia, many investigators began to assess the possibility of using functional data for diagnosis (10–15). Postprandial mesenteric hyperemia has been reported in many animal species including humans, nonhuman primates, dogs, cats, sheep, and rats (16). The latency and duration of postprandial mesenteric hyperemia depend largely on the type and quantity of the meal, with high-fat and protein-containing foods producing the most pronounced and sustained intestinal hyperemia. Studies in anesthetized cats and conscious dogs showed that, in general, the mesenteric hyperemia is most pronounced at about 30–90 minutes after food intake and lasts for 4–6 hours (16). Current evidence indicates that postprandial mesenteric hyperemia is

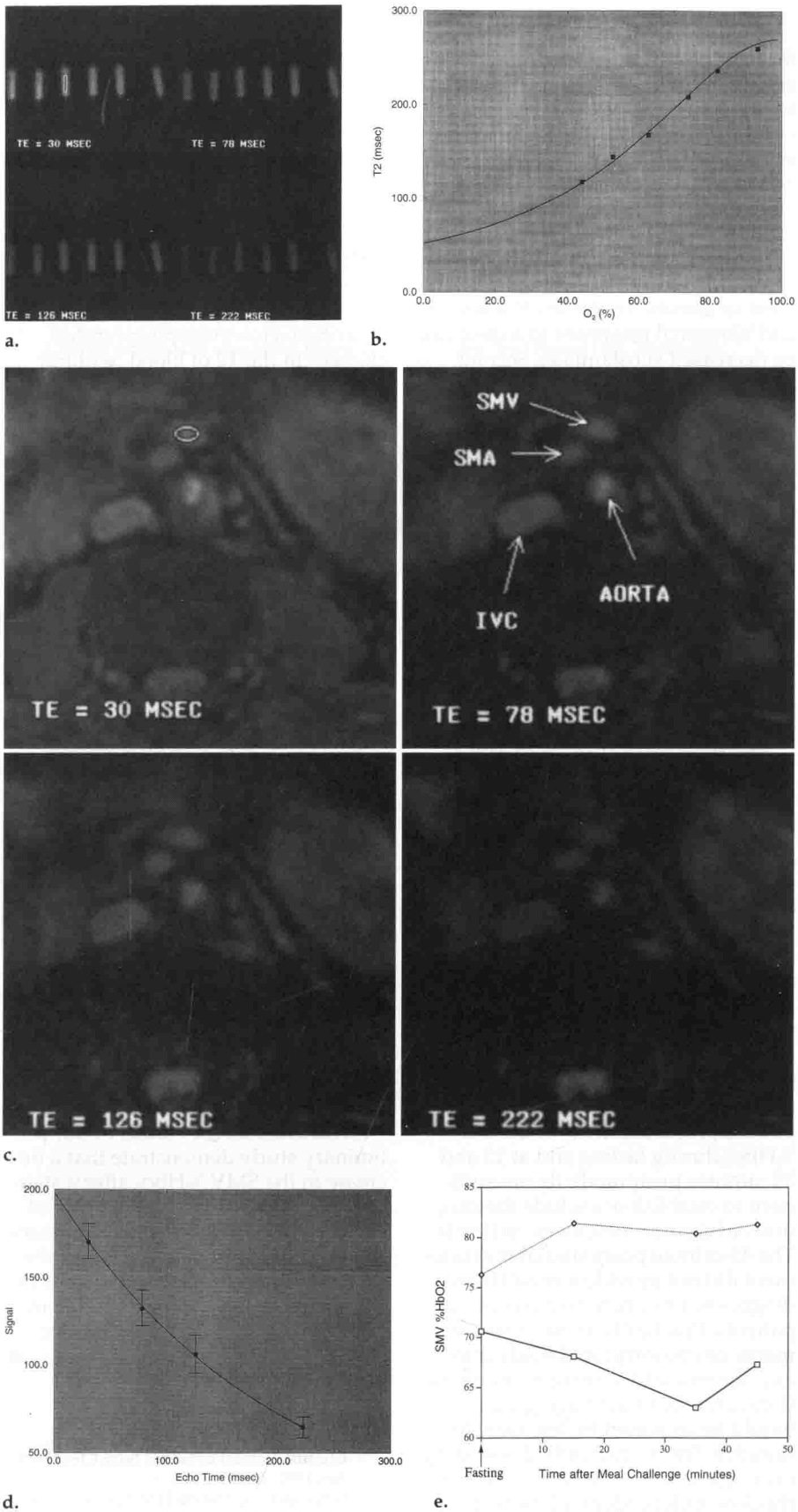

Figure 5. In vivo MR oximetry data from a symptomatic patient. **(a)** Images from in vitro calibration experiment. A typical region of interest is seen on the image obtained with an echo time of 30 msec. **(b)** Graph shows a monoexponential plot of T2 versus O_2 in the blood samples in **a**. **(c)** Images from preprandial MR oximetry measurements obtained in a 63-year-old male symptomatic patient. *IVC* = inferior vena cava. A typical region of interest is seen in the SMV on the image obtained with an echo time of 30 msec. **(d)** Graph shows exponential plot of signal intensity versus echo time for determination of the T2 of SMV blood obtained from the region of interest in **c**. The computed T2 of 198.6 msec corresponds to a $\%Hbo_2$ of 70.6% on the T2-O_2 calibration curve shown in **b**. **(e)** Graph shows SMV $\%Hbo_2$ versus time after a meal in the patient in **a–d** (□) compared with that of a 72-year-old man without symptoms of chronic mesenteric ischemia (◇).

confined to organs involved in the digestive process. This process is highly selective. It has been demonstrated that the postprandial increase in mesenteric blood flow is not shared equally by all the mesenteric organs. For example, if food is introduced into the stomach of conscious dogs, only blood flow in the celiac artery is increased. Similarly, if food is introduced into only the small bowel, little or no hyperemia is observed in the stomach and colon. The selectivity of postprandial hyperemia even extends to the various layers of the intestinal wall, with the mucosa receiving the highest degree of blood flow increase (16).

Many investigators have used isolated intestinal loop models to study the local mechanisms (17–23). Their results indicate that tissue oxygenation and mesenteric blood flow are highly interdependent. Since the intestine has virtually no capability to store oxygen, tissue oxygen demand must be satisfied on a second-to-second basis by means of changes in mesenteric blood flow. It has been shown that once the mesenteric blood flow is increased sufficiently to satisfy the oxygen demand, further increases in blood flow will not increase oxygen consumption. However, if the increase in mesenteric blood flow is insufficient to meet the oxygen demand, oxygen consumption will be a function of blood flow (ie, decrease in mesenteric hyperemic response to the increase in metabolic demand results in lower oxygen consumption and tissue hypoxia) (23). These data suggest that in normal animals with mesenteric vascular reserve sufficient to ensure that the mesenteric hyperemic response is more than adequate to satisfy the oxygen demand, we should expect a decrease in the oxygen extraction after a meal, since oxygen consumption does not increase with increase in blood flow after a threshold value of blood flow is reached. As a result, the mesenteric arterial-venous oxygen saturation difference should decrease, leading to an increase in the venous $\%Hbo_2$, provided that the arterial $\%Hbo_2$ remains constant. This phenomenon has

been observed in the cerebral circulation and has been exploited in the blood oxygenation level–dependent technique for functional MR imaging of the brain (23–26). With this technique, the T2* changes associated with an increase in the venous $\%HbO_2$ in the activated cerebral areas are used for functional MR imaging brain mapping (24–27).

Postprandial mesenteric hyperemia is a complex response that involves not only local mechanisms but also nervous and humoral factors (28). Recently, various investigators began measuring blood flow in the SMA and the SMV with cine phase-contrast MR imaging for the diagnosis of chronic mesenteric ischemia (15,29–31). The initial results are very encouraging. However, measurement of blood flow alone may not be sufficient in all cases, since oxygen uptake is not influenced by blood flow alone. Since many different hormones and drugs can influence the ability of the small intestine to extract oxygen, the same level of blood flow can correspond to different levels of oxygen uptake (32). Therefore, measurements of the mesenteric arterial-venous oxygen saturation difference may be an even more accurate method for diagnosis of mesenteric ischemia than blood flow measurements. Since the arterial $\%HbO_2$ in most patients should be fairly constant and can be monitored easily with pulse oximetry, in vivo MR oximetry monitoring of changes in the SMV $\%HbO_2$ will allow monitoring of changes in the mesenteric arterial-venous oxygen saturation difference in vivo, noninvasively.

Our results show that, preoperatively, in the dogs and the patients without symptoms of chronic mesenteric ischemia, the SMV $\%HbO_2$ increased with food intake as expected. This increase indicated that the postprandial mesenteric hyperemic response was more than sufficient to satisfy the increase in metabolic demand. However, once stenosis in the SMAs became hemodynamically significant in the dogs, postprandial mesenteric hyperemic response became insufficient to satisfy the increase in metabolic demand, and as a result oxygen extraction increased. The increase in oxygen extraction led to a decrease in the SMV $\%HbO_2$ after a meal. In the patient who underwent MR imaging before and after revascularization surgery, the reversal of the change in the postoperative SMV $\%HbO_2$ after a meal added more support to our hypothesis.

The difference in maximum postprandial change in the SMV $\%HbO_2$ between the patients without and those with symptoms of chronic mesenteric ischemia was greater than that between the preoperative and postoperative stages in the dogs. The maximum postprandial change in the SMV $\%HbO_2$ also occurred later in the dogs after surgery compared with symptomatic patients. This is not surprising, since there are several limitations associated with the canine model. First, in anesthetized dogs, the neural and hormonal responses to a meal can be decreased substantially. Second, use of an ameroid ring to induce gradual stenosis of the SMA is not an ideal simulation of chronic mesenteric ischemia in patients because chronic mesenteric ischemia is due usually to atherosclerosis of the mesenteric vessels over a much longer period of time. Third, use of mesenteric angiography and clinical symptoms for diagnosis of the onset of chronic mesenteric ischemia in the dogs may not be accurate enough. Despite these limitations, our results from the canine and human experiments are similar qualitatively, suggesting that our hypothesis is correct.

Results of previous studies suggest that maximum postprandial mesenteric blood flow changes occur at about 30 minutes after food intake (29–31). Since maximum postprandial changes in the mesenteric arterial-venous oxygen saturation difference should occur at about the same time as maximum mesenteric blood flow changes, we decided to measure the SMV $\%HbO_2$ during fasting and at 15, 35, and 45 minutes after food intake. Our data from the human experiments suggest that in the majority of patients, measurements of the SMV $\%HbO_2$ during fasting and at 15 and 35 minutes postprandially are sufficient to establish or exclude the diagnosis of chronic mesenteric ischemia. The 45-minute postprandial measurement did not provide any additional diagnostic information in any of our patients. Practically, these measurements can be integrated easily into any abdominal MR imaging examinations, and the total imaging time would be increased by less than 20 minutes. We are currently developing faster pulse sequences for obtaining the flow-independent T2 measurements to decrease further the total imaging time. Our hope is that the total imaging time for the T2 measurements will be less than 5–10 minutes in the future.

Although the sequence we used for flow-independent T2 measurements is not commercially available, other investigators have successfully used cardiac-triggered, flow-compensated gradient-echo imaging for estimation of the $\%HbO_2$ in vivo (33). Since our technique allows imaging of only a single section per acquisition, careful choice of the imaging plane is necessary. To establish the quantitative relation between the T2 of blood and the $\%HbO_2$, venous blood samples must be obtained in each patient and the calibration procedure performed as described. However, postprandial changes in the T2 of blood, without conversion to $\%HbO_2$, may be useful for the diagnosis of chronic mesenteric ischemia. We are currently collecting data to test this hypothesis, and it may be possible that no calibration will be necessary in the majority of cases. Since the calibration does not need to be performed at the same time as the in vivo examination, in the cases where calibration is deemed necessary it can be performed later. Although blood flow in the SMA and SMV can be measured with cine phase-contrast MR imaging at the same time as in vivo MR imaging monitoring of changes in the SMV $\%HbO_2$ without knowledge of the total mass of small intestine in individual patients, it is still impossible to determine the oxygen uptake, calculated as a product of blood flow per unit mass of tissue and the mesenteric arterial-venous oxygen saturation difference. Without knowledge of the responses of oxygen uptake to different physiologic and pathologic situations in vivo, it is still difficult to directly apply knowledge learned from isolated intestinal loop experiments to clinical situations.

In conclusion, the results of our preliminary study demonstrate that a decrease in the SMV $\%HbO_2$ after a standard meal is an accurate indicator of chronic mesenteric ischemia in humans and dogs. These initial results corroborate pathophysiologic mechanisms of chronic mesenteric ischemia, thus increasing our knowledge and understanding of this important disease. ■

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