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Correlation of Arterial and Venous Blood Flow in the Mesenteric System Based on MR Findings

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OBJECTIVE. The purpose of this study was to determine if a consistent relationship exists between (1) flow in the portal vein and superior mesenteric vein and (2) flow in the mesenteric arteries.

SUBJECTS AND METHODS. Cine phase-contrast methods were used to determine volumetric flow in the celiac axis, superior mesenteric artery, portal vein, and superior mesenteric vein in 11 healthy volunteers.

RESULTS. The mean (±SD) volumetric flow rates in the celiac axis, superior mesenteric artery, superior mesenteric vein, and portal vein were 9.9 ± 3.2, 6.0 ± 1.8, 5.7 ± 2.0, and 13.7 ± 1.8 ml/min per kilogram, respectively. A strong correlation was found between measured mesenteric arterial blood flow, defined as the sum of flow in the celiac axis and the superior mesenteric artery, and portal venous flow ($r = .97$, $p = .00002$). Good agreement was found between flow in the superior mesenteric artery and that in the superior mesenteric vein ($r = .98$; $p = .00001$; bias = 20 ml/min).

CONCLUSION. There is a consistent relationship between MR measurements of flow in the portal or superior mesenteric vein and the measured flow in the arteries supplying those veins. Flow in the superior mesenteric vein is an accurate predictor of flow in the superior mesenteric artery.

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Recently, developments in MR technology have permitted noninvasive measurement of volumetric flow rates in arteries and veins via cine phase-contrast methods [1–3]. Despite the success of these methods in many vessels, application of such techniques to the mesenteric arteries is likely to be technically demanding because of the vessels' relatively small size and flow patterns [4–6]. Assessing global mesenteric blood flow by determining flow in the mesenteric arteries requires measurements of flow in at least three separate vessels. This is time-consuming and may not be practical, especially in patients with mesenteric ischemia who may have numerous collateral vessels.

The purpose of this study was to determine if a consistent relationship exists between (1) flow in the portal and superior mesenteric veins and (2) flow in the mesenteric arteries.

Subjects and Methods

Nine men and two women 23–73 years old (mean, 37 years) with no signs or symptoms of mesenteric ischemia were examined by using cine phase-contrast MR methods. The subjects fasted for at least 8 hr before the MR studies were done.

A 1.5-T system (General Electric, Milwaukee, WI) was used for imaging. Axial localizer images spanning the abdomen were rapidly obtained by using a T1-weighted magnetization-prepared gradient-echo pulse sequence [7]. MR angiographic images of the celiac axis, superior mesenteric artery, and portal vein were then acquired by using cine phase-contrast methods as previously reported [1–3]. Next, a thin-section MR angiogram perpendicular to the vessel in which flow measurements were desired was obtained.

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The software for obtaining the cine phase-contrast images is commercially available; cardiac monitoring is used to control the incrementing of phase encoding during acquisition [2]. The subjects were monitored by using plethysmographic gating, and ordered phase encoding was used to minimize respiratory artifacts. Sixteen phases of the cardiac cycle were constructed. Speed images (images in which flow is displayed as high signal intensity regardless of the direction of flow) were reconstructed to yield the angiographic images [3]. The thin-section angiograms were reconstructed to yield magnitude images as well as signed quantitative velocity images in which a positive or negative pixel value is proportional to flow velocity along the flow-encoding axis in opposite directions.

Anatomic MR Imaging

MR angiograms were obtained so that the appropriate thin-section angiogram used for flow measurements could subsequently be obtained. First, a sagittal image of the upper abdominal aorta was obtained (Figs. 1A and 1B). For this MR angiogram of the celiac axis and superior mesenteric artery, a 15-mm sagittal section was centered on the aorta, and the following parameters were used: 33/8.8 msec TR/TE, 256 × 192 matrix, 32 cm^2 field of view, 15° flip angle, two excitations, and a velocity encoding of 50 cm/sec to cause a π phase shift. A coronal portogram was then obtained (Fig. 1C) by using a 40-mm coronal section centered on the main portal vein and the same sequence parameters except that the velocity encoding was 15 cm/sec. These imaging parameters were chosen because they had been used successfully in imaging of the portal venous system [8]. It is possible that non–cine phase-contrast methods could have been used.

MR Flow Measurements

Thin-section MR angiograms were obtained perpendicular to the vessel of interest so that flow could be accurately calculated. Signed quantitative velocity images perpendicular to the celiac axis and superior mesenteric artery and vein were obtained as shown in Figures 1A and 1B, respectively. The following parameters were used: 5-mm slice thickness, 33/8.8 msec TR/TE, 256 × 256 matrix, 32 cm^2 field of view, 30° flip angle, two excitations, and a velocity encoding of 150 cm/sec to cause a π phase shift. Thin-section angiograms of the portal vein (Figs. 2A and 2B) were acquired perpendicular to the midpoint of the main portal vein (Fig. 1C) by using the same parameters except that the velocity encoding was 40 cm/sec. Measure-

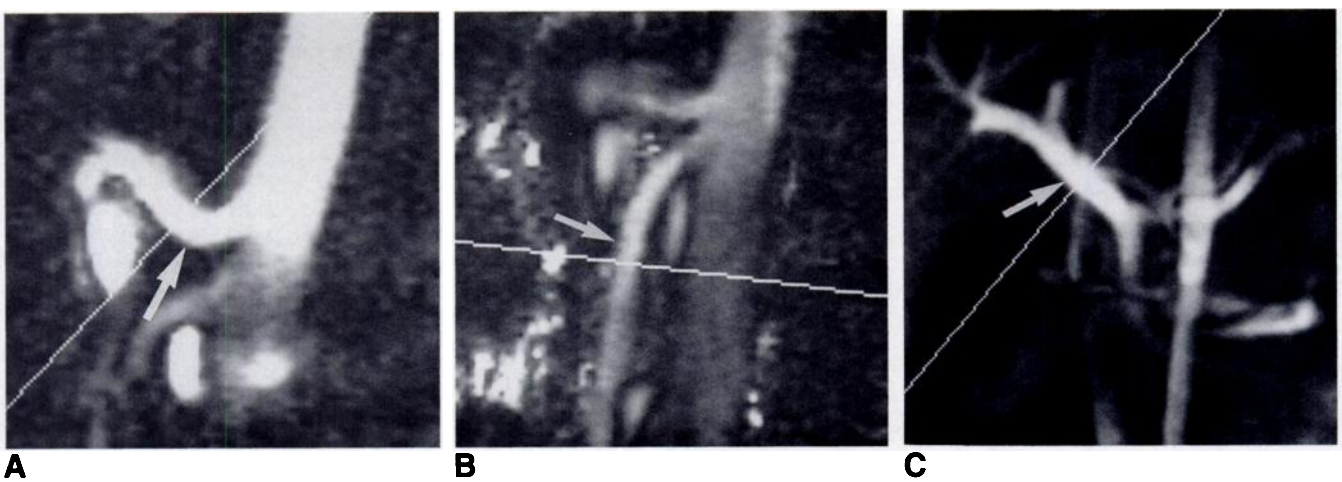

Fig. 1.—MR angiograms ("speed" images) used to determine orientation of thin-section MR angiograms.
***A*, Sagittal aortogram shows orientation (*line*) of thin-section angiogram used to measure flow in celiac axis (*arrow*).**
***B*, Sagittal aortogram shows orientation (*line*) of thin-section angiogram used to measure flow in superior mesenteric artery (*arrow*) and vein.**
***C*, Coronal portogram shows orientation (*line*) of thin-section angiogram used to measure flow in portal vein (*arrow*).**

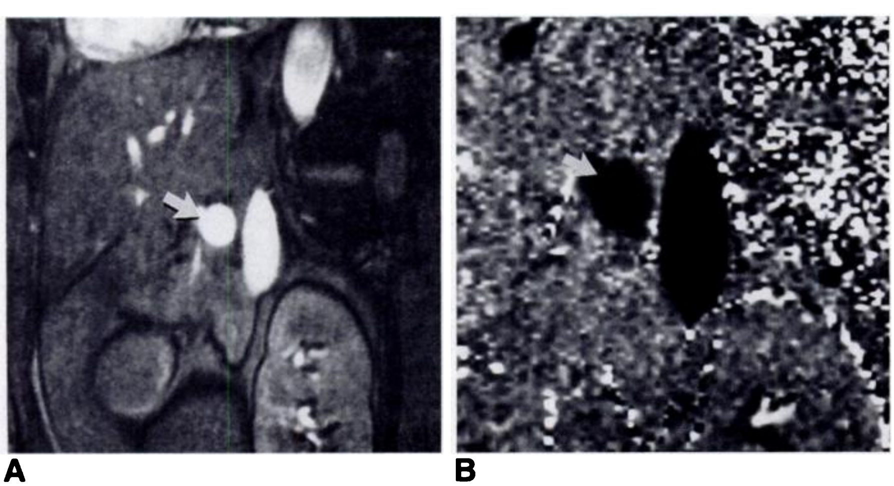

Fig. 2.—Thin-section MR angiograms perpendicular to portal vein.
***A*, Cine phase-contrast magnitude image used to manually place a region of interest around main portal vein (*arrow*).**
***B*, Cine phase-contrast velocity image used to calculate volumetric flow rate in portal vein. In this image, pixel value is proportional to flow velocity. A region of interest was superimposed from corresponding magnitude image (*A*) to outline portal vein (*arrow*).**

ments of flow in the portal vein determined by using this MR technique correlate with measurements obtained by using Doppler sonography [8].

Measurements of flow were determined by using the signed quantitative velocity images during 16 phases of the cardiac cycle. Each of the velocity images was viewed to ensure that aliasing did not occur. Flow rates were calculated by placing a region of interest around the desired vessel as seen on the magnitude image and transposing this region to the velocity image. The area-velocity product of the region of interest determined the volumetric flow rate. A volumetric flow rate was calculated for each of the 16 velocity images, and these rates were averaged to provide the mean flow during the cardiac cycle.

Mesenteric arterial blood flow was defined as the sum of volumetric flow rates in the celiac axis and the superior mesenteric artery, which accounts for the majority of blood supply to the bowel. Although the inferior mesenteric artery provides blood to the large bowel, its contribution was not measured because of the technical limitations of the cine phase-contrast method. Measured mesenteric arterial flow was compared with measured portal venous flow as a ratio and by linear regression analysis. Flow rates in the superior mesenteric artery and vein were also compared as a ratio and by linear regression analysis.

Results

The mean (±SD) volumetric flow rates in the celiac axis, superior mesenteric artery, superior mesenteric vein, and portal vein were 9.9 ± 3.2, 6.0 ± 1.8, 5.7 ± 2.0, and 13.7 ± 1.8 ml/min per kilogram, respectively. The relationship between measured mesenteric arterial blood flow (sum of flow in the celiac axis and superior mesenteric artery) and portal venous flow was consistent. The mean ratio (± SD) was 1.15 ± 0.04. A strong correlation was found by linear regression analysis between measured mesenteric arterial blood flow and portal venous flow as follows: volumetric flow $\text{rate}_{\text{mesenteric artery}} = -2.08$ ml/min per kilogram + 1.31 volumetric flow $\text{rate}_{\text{portal vein}}$ ($r = .97$, $p = .00002$, standard error of the estimate = 0.62 ml/min per kilogram; see Fig. 3).

The mean ratio (±SD) of blood flow in the superior mesenteric artery to blood flow in the superior mesenteric vein was consistent at 1.07 ± 0.08. A strong correlation was found between flow rates in the superior mesenteric artery and the superior mesenteric vein ($r = .98$; $p = .00001$). The linear regression equation showed good agreement between the arterial inflow and venous outflow as follows: volumetric flow $\text{rate}_{\text{superior mesenteric artery}} = 0.96$ ml/min per kilogram + 0.88 volumetric flow $\text{rate}_{\text{superior mesenteric vein}}$ (Fig. 4). Flow in the superior mesenteric vein was an accurate predictor of flow in the superior mesenteric artery; the standard error was 0.37 ml/min per kilogram. When flow in the superior mesenteric artery was compared with flow in the superior mesenteric vein, the bias between these measurements was only 20 ml/min.

Discussion

The major findings of this study were as follows: (1) in healthy volunteers, the relationship between portal venous flow and mesenteric arterial blood flow, defined as the sum of flow in the celiac axis and the superior mesenteric artery, was consistent, and (2) volumetric flow rates in the superior mesenteric vein were an accurate predictor of flow in the superior mesenteric artery. These correlations between arterial inflow and venous outflow were significant.

Use of cine phase-contrast MR imaging to measure flow in the portal vein and the superior mesenteric vein shows promise, and the findings may improve our understanding of mesenteric hemodynamics. This method of using measurements of venous flow to evaluate mesenteric arterial blood flow appears to have several advantages. The large sizes of the portal vein and the superior mesenteric vein relative to the mesenteric arteries increase the likelihood that measurements of flow obtained by using cine phase-contrast methods will be accurate. Some authors [6] have suggested that 10 pixels are needed across the diameter of the vessel in

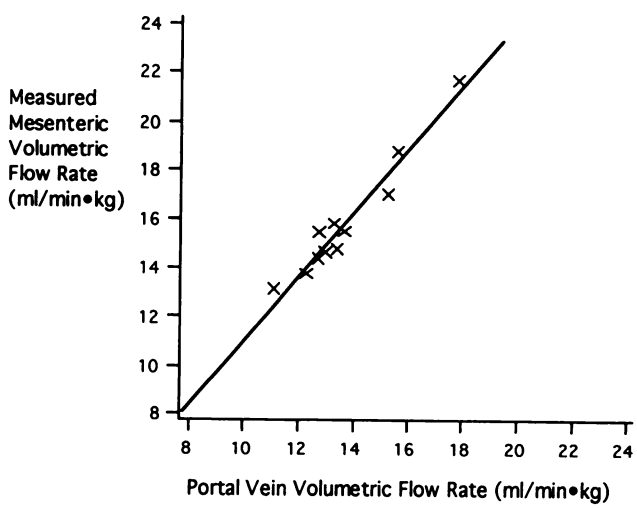

Fig. 3.—Linear regression analysis of measured mesenteric arterial flow vs measured portal venous flow. Graph shows a regular relationship between measured flow in the two vessels. Correlation was significant (*r* = .97, *p* = .00002).

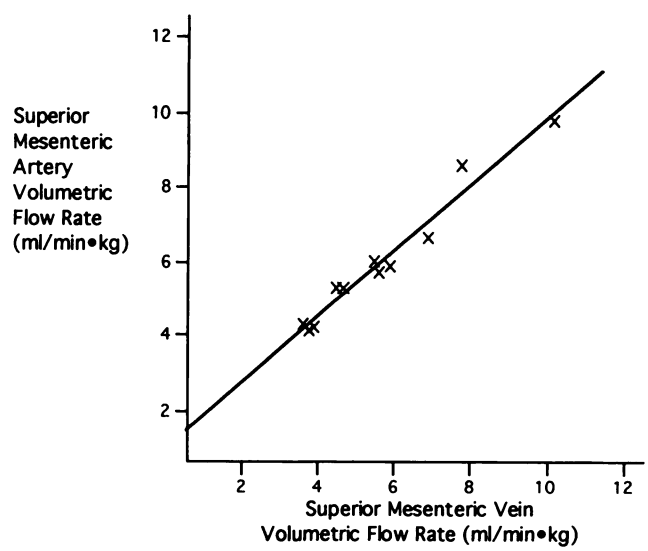

Fig. 4.—Linear regression analysis of flow in superior mesenteric artery vs flow in superior mesenteric vein. Graph shows a strong correlation and good agreement between flow rates in the two vessels (*r* = .98; *p* = .00001; bias = 20 ml/min).

order to obtain accurate measurements. Additionally, measurements of flow in the portal vein are technically less complicated because total mesenteric blood flow is reflected in one measurement of venous flow rather than three measurements of flow in three separate arteries. This is particularly important in patients with mesenteric ischemia, in whom a large number of collaterals may preclude an accurate estimation of mesenteric blood flow if flow is measured in the arteries supplying the mesentery. Steady flow is also preferable, as is found in the portal vein and superior mesenteric vein relative to the pulsatile flow present in the celiac axis and superior mesenteric artery, because measurements of flow by using cine phase-contrast MR imaging are susceptible to errors due to phase shifts caused by higher orders of motion and phase dispersion associated with turbulence [4, 5].

The validity of using measurements of venous flow as an indicator of arterial blood flow is confirmed by the findings of this study. Measurements of flow in the superior mesenteric vein and superior mesenteric artery were in good agreement (bias = 20 ml/min), and measured flow in the mesenteric arteries was strongly associated with measured flow in the portal vein. Additionally, the mean volumetric flow rates in the portal vein and the superior mesenteric vein were consistent with previously reported measurements determined by using Doppler sonography [9–12]. In animal models, the ratio of flow in the superior mesenteric artery to flow in the portal vein, measured directly by using electromagnetic flow probes, was 54% [13]; in our study it was 44%. Also, postprandial increases in flow rates in the superior mesenteric artery and the portal vein in dogs were 65% and 76%, respectively [14, 15]. These results support a linear relationship between mesenteric arterial inflow and portal venous outflow.

Doppler sonography has been used to measure blood flow in the superior mesenteric artery and celiac axis [11, 12]. Because of the curved courses of the mesenteric vessels and the presence of overlying bowel gas, accurate measurements of flow may be difficult to obtain with sonographic techniques in many patients. Other technical impediments to obtaining accurate measurements with sonography include the difficulty of accurately determining the cross-sectional area of these vessels and the mean velocity. To date, measurements of flow by using MR imaging have shown relatively less sensitivity to these limitations compared with Doppler sonography [16, 17].

The role of MR imaging in measurements of flow in patients with suspected mesenteric ischemia requires further investigation. The sensitivity and specificity of measurement of volumetric flow rates in the portal vein and superior mesenteric vein as a screening test to guide the more prudent use of conventional mesenteric angiography in patients with suspected mesenteric ischemia need to be critically evaluated in a prospective study. This technique of assessing flow in the portal venous system as a measure of mesenteric arterial blood flow shows promise to improve the understanding of mesenteric hemodynamics.

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