Volumetric Flow Rates in the Portal Venous System: Measurement with Cine Phase-Contrast MR Imaging

David J. Burkart[1]
C. Daniel Johnson
Marilyn J. Morton
Ronald L. Wolf
Richard L. Ehman

OBJECTIVE. The purposes of this study were to (1) validate the accuracy of cine phase-contrast MR flow measurements within the portal vein, (2) develop a suitable protocol for using this method to measure volumetric flow rate in the portal venous system, and (3) use this protocol, with Doppler sonography as a reference, to measure portal venous flow in healthy volunteers and in patients with portal venous hypertension.

SUBJECTS AND METHODS. Flow determinations were obtained in a model of fluid movement approximating blood-flow conditions in the portal venous system. A suitable protocol was based on consideration of the theoretical effects of (1) spatial resolution, (2) obliquity of the imaging plane to the direction of flow, and (3) signal-to-noise ratio of the signed quantitative velocity images (in three volunteers) on the accuracy and precision of flow measurements. This protocol was used to obtain cine phase-contrast MR images of the portal venous system in five volunteers and six patients.

RESULTS. Values obtained with a flow phantom showed good accuracy of cine phase-contrast–measured vs actual volumetric flow rate ($r = .995$; $p = .0001$; MR rate = [0.94 $\times$ actual rate] + 65.6 ml/min; standard error of the y estimate = 67.3 ml/min). Velocity encoding and section thickness substantially influenced the signal-to-noise ratio of the velocity images, whereas flip angle and matrix size had only minimal effect. In volunteers and patients, portal volumetric flow rates determined by using MR images and Doppler sonography showed good correlation ($r = .94$; $p = .0003$).

CONCLUSION. Our results indicate that cine phase-contrast MR imaging is a practical noninvasive method for measuring volumetric flow rates in the portal venous system.

***AJR* 1993;160:1113–1118**

Treatment of patients with portal venous hypertension is a challenging clinical problem. Volumetric flow rate in the portal venous system has been used to evaluate the effects of pharmacologic therapy on portal venous hemodynamics [1–3] and may be related to the prevalence of variceal hemorrhage (Burkart DJ et al., presented at the Radiological Society of North America meeting, November 1992). To date, several noninvasive methods [4–11] of measuring this rate have been used to evaluate the hemodynamics of the portal venous system, including Doppler sonography and MR imaging with bolus tracking or with breath-holding phase-contrast techniques (Rubin DL et al., presented at the Society of Magnetic Resonance in Medicine meeting, August 1991).

Doppler sonographic methods have well-known limitations [12]. MR bolus-tracking methods are time-consuming, and neither bolus-tracking nor breath-hold phase-contrast techniques provide volumetric flow measurements throughout the cardiac cycle during normal respiration. This time-resolved quantitative information is a more sophisticated method of analyzing portal venous hemodynamics and may prove to be clinically important. Several studies [13–15] have shown that cine phase-contrast MR imaging can be useful to measure volumetric flow rate in different phases of the cardiac cycle. This method has been used to quantitatively

Received October 5, 1992; accepted after revision December 15, 1992.

[1] All authors: Department of Diagnostic Radiology, Mayo Clinic, 200 1st St. S.W., Rochester, MN 55905. Address correspondence to C. D. Johnson.

0361–803X/93/1605–1113

assess the pulmonary, cardiac, and renal vasculature (Wolf RL et al., presented at the Radiological Society of North America meeting, November 1992). However, to date, use of cine phase-contrast techniques for analysis of flow in the portal venous system has received little attention.

The purposes of this investigation were to (1) validate the accuracy of cine phase-contrast MR measurements in a phantom approximating flow conditions in the portal venous system, (2) develop a suitable protocol for using cine phase-contrast methods for measuring volumetric flow rate in the portal vein, and (3) use this protocol, with Doppler sonography as a reference, to measure volumetric flow rates in the portal veins of healthy volunteers and patients with portal venous hypertension.

Subjects and Methods

Cine Phase-Contrast MR Imaging

Phase-contrast MR methods are based on the principle that the transverse magnetization of spins moving in the presence of a magnetic field gradient develops a velocity-proportional phase shift relative to static spins [16, 17]. Cine phase-contrast MR images were obtained by using a commercially available two-dimensional pulse sequence [18–20]. Velocity encoding could be selected in the frequency, phase, or slice-select directions. The technique typically yields 16 sets of images, spanning the cardiac cycle, in which pixel value is proportional to velocity in the flow-encoded direction.

Phantom Study

Some validation of the quantitative accuracy of cine phase-contrast techniques has been reported [18]. However, additional validation in situations relevant to the envisioned application is desirable [18]. To confirm the accuracy of cine phase-contrast methods for measuring volumetric flow rates in the portal venous system, we constructed a model of fluid movement to simulate vessel geometry, relaxation properties of liver and blood, and blood-flow conditions in the portal venous system. Flexible tubing with an inner diameter of 13 mm was immersed in a fluid with a T1 approximately the same as that of liver tissue. A water solution doped with gadopentetate dimeglumine and $MnCl_2$ to yield a T1/T2 of 847/85 msec was pumped through the tubing in a nonpulsatile fashion at independently measured flow rates of 390, 816, 1213, 1597, 1983, and 2313 ml/min, determined by timed filling of a graduated cylinder. Multiple cine phase-contrast MR measurements (mean, 3.3; range 2–4) were obtained at each flow rate.

Cine phase-contrast MR images perpendicular to the flexible tubing were acquired by using a 1.5-T system (General Electric, Milwaukee, WI) and the following parameters: 33/7.8 (TR/TE), 20° flip angle, two excitations, 256 phase-encoding views, 5-mm section thickness, and 28-cm^2 field of view. Velocity encoding was accomplished along only the section-selection gradient that coincided with the true direction of flow. A simulated electrocardiogram at 100 beats per minute was used to trigger the sequence. Sixteen phases of the cardiac cycle were reconstructed.

In Vivo Studies

Two in vivo series of MR images were obtained using a 1.5-T system. Cine phase-contrast images were acquired with a two-dimensional cine phase-contrast pulse sequence, respiratory-ordered phase encoding and plethysmographic gating, with reconstruction of 16 phases of the cardiac cycle. Localizing sequences were done in order to orient an oblique imaging plane, required to measure flow, perpendicular to the main portal vein. First, a series of axial T1-weighted magnetization-prepared gradient-echo images [21] spanning the abdomen was acquired. Second, a cine phase-contrast angiogram in the coronal plane centered on the main portal vein was obtained by using a repetition time of 33 msec, an echo time of 7.8 msec, a flip angle of 15°, a velocity encoding of 15 cm/sec to cause a π phase shift, 192 phase encodings, a field of view of 34 cm^2, two excitations, and a section thickness of 40 mm. A typical coronal MR angiogram is shown in Figure 1. Velocity encoding was performed along the frequency-encoding, phase-encoding, and slice-selection direction. Angiographic images were reconstructed depicting flowing blood as high intensity regardless of flow direction [18].

The first in vivo series was performed to develop a suitable protocol for using cine phase-contrast methods to measure flow in the portal venous system. Ideally, the optimal protocol would be the one that produced the most accurate and precise measurements of flow. However, a gold standard for the true flow in the portal venous system does not exist. Therefore, the protocol for obtaining these measurements was based on consideration of the theoretical effects of (1) spatial resolution, (2) obliquity of the imaging plane to the direction of flow, and (3) signal-to-noise ratio (SNR) of the signed quantitative velocity images on the accuracy and precision of flow measurements determined by using cine phase-contrast MR imaging (Pelc NJ et al., presented at the Radiological Society of North America meeting, December 1991; Wolf RL et al., presented at the Society of Magnetic Resonance in Medicine meeting, August 1991 and 1992).

The SNR of the signed quantitative velocity images was measured in a series of cine phase-contrast MR studies of three volunteers, 24–34 years old, in which flip angle, velocity encoding, number of phase-encoding views, and section thickness were systematically varied. The flip angles used were 15°, 30°, 45°, and 60°. The velocity encodings used were 40, 80, and 120 cm/sec. Lower velocity encodings were not used in order to ensure that aliasing did not occur. The peak velocity in the portal vein of healthy volunteers has been reported as 26.8 ± 6.9 cm/sec [5]. The number of phase-encoding views evaluated were 128, 192, and 256, and the section thicknesses were varied as 3, 5, and 10 mm. The SNRs were determined in the resulting sets of 16 velocity images used to calculate flow. No accepted conventions exist for measuring the SNR in velocity images. For the purpose of this study, the SNR in a velocity image was defined as the ratio of mean pixel value in the portal vein divided by a measurement of noise in the adjacent liver tissue (standard deviation of the pixel values in a standardized region of interest [ROI] of the liver).

In the second in vivo series, the protocol developed in the first series was used to obtain cine phase-contrast MR images of the portal venous system in five healthy volunteers and six patients with portal venous hypertension in order to assess the feasibility and accuracy of this technique for measuring volumetric flow rate in the portal venous system. As a reference, within 3 hr of the MR study, all subjects had Doppler sonography to estimate portal venous flow. The subjects fasted a minimum of 6 hr before the studies. The mean age of the volunteers and patients was 31 ± 6 years and 68 ± 18 years, respectively. All patients had portal venous hypertension proved by the presence of esophageal varices seen endoscopically. The patient's liver disease was associated with chronic active hepatitis (four cases), primary biliary cirrhosis (one case), and alpha-1 antitrypsin deficiency (one case). From the coronal cine phase-contrast angiogram, the oblique cine phase-contrast image used in flow calculations was acquired perpendicular to the main portal vein, during quiet breathing, by using the optimized protocol developed in this study: 33/7.8 (TR/TE), 30° flip angle, 40 cm/sec velocity

Fig. 1.—Cine phase-contrast MR angiogram of a 40-mm coronal slab (second localizer) centered on main portal vein shows flowing blood as high intensity regardless of flow direction. An oblique section perpendicular to midpoint of main portal vein (*straight arrow*) was acquired to obtain velocity images from which flow rates were calculated. Also shown is splenic vein (*arrowhead*) and superior mesenteric vein (*curved arrow*).

A B

Fig. 2.—Cine phase-contrast MR angiograms of oblique section perpendicular to portal vein.

***A*, Two-dimensional cine phase-contrast modulus image used to manually place a region of interest around main portal vein (*arrow*).**

***B*, Two-dimensional cine phase-contrast velocity image used to calculate flow rates. A region of interest was superimposed from corresponding modulus image to outline main portal vein (*arrow*).**

encoding, two excitations, 256 phase-encoding views, 5-mm section thickness, 28-cm^2 field of view. The rationale for this protocol is outlined in the Discussion. Velocity encoding was accomplished along only the section-selection gradient that coincided with the true direction of flow. The acquisition time was 6–7 min, depending on the subject's heart rate.

Velocity Image Analysis

Volumetric flow rate was calculated by using the signed quantitative velocity images. With cine phase-contrast images, volumetric flow rates were calculated by integrating the area-velocity product of each of the 16 velocity images spanning the cardiac cycle with a user-specified ROI. ROIs encompassing the vessel of interest were manually placed on the modulus images (Fig. 2A). The same ROIs were superimposed from the modulus images to the corresponding velocity images (Fig. 2B).

Doppler Sonographic Technique

All sonographic examinations were performed by the same radiologist. With the subject in the left lateral decubitus position, a 3.5-MHz sector transducer (Acuson, Mountain View, CA) was used to scan the portal vein in the longitudinal plane from a right lateral intercostal approach. Peak flow velocity was measured midstream in the main portal vein midway between the bifurcation of the portal vein and the confluence of the splenic vein and the superior mesenteric vein. The Doppler angle of insonation was less than 60° in each case. The transverse cross-sectional area at the midpoint of the main portal vein was calculated automatically after the vessel edge was traced manually. In order to derive the mean volumetric flow rate in the portal venous system, vessel area (in centimeters squared) was multiplied by mean flow velocity (in centimeters per second). A parabolic velocity profile was assumed, and the mean blood-flow velocity was considered to be half the peak flow velocity. Average values for peak blood-flow velocity and vessel area were calculated from four measurements in each subject.

Results

Phantom Study

Figure 3 shows the linear regression analysis of actual volumetric flow rates vs volumetric flow rates determined by using cine phase-contrast MR imaging in the phantom experiment. A strong linear correlation was found ($r = .995$; $p = .0001$). In addition, agreement was good between rates determined by using the MR images and actual rates (MR rate = [0.94 × actual rate] + 65.6 ml/min; standard error of the y estimate [SEE] = 67.3 ml/min).

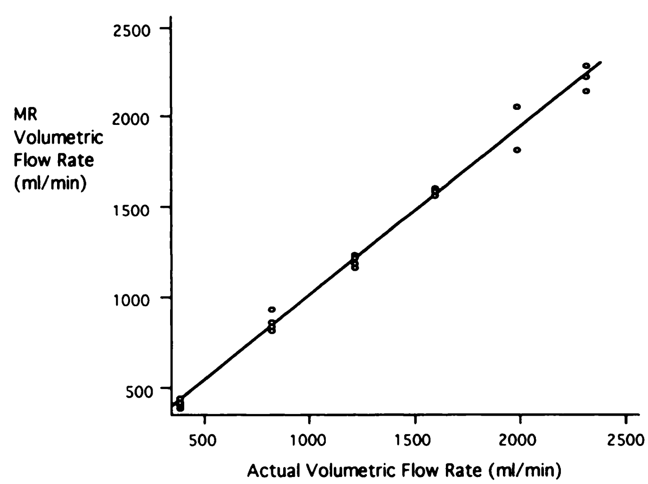

Fig. 3.—Graph shows linear regression of volumetric flow rate in a phantom determined by using cine phase-contrast MR vs actual rates.

Signal-to-Noise Ratios of Velocity Images

Figures 4–7 show the measured SNR of the velocity images of the three volunteers at various flip angles, velocity encodings, numbers of phase-encoding views, and section thicknesses. The SNR ranged from 4.8 ± 1.8 to 5.5 ± 1.8 for flip angles tested between 15° and 60°. The highest SNR of 5.5 was obtained by using a 30° flip angle (Fig. 4). The SNR ranged from 1.3 ± 0.3 to 5.0 ± 1.4 for velocity encodings tested between 40 and 120 cm/sec. The greatest SNR of 5.0 was obtained by using a velocity encoding of 40 cm/sec (Fig. 5). The SNR ranged from 2.9 ± 1.1 to 5.0 ± 1.4 for number of phase-encoding views tested between 128 and 256. The largest SNR of 5.0 was obtained by using 128 phase-encoding views (Fig. 6). The SNR ranged from 2.5 ± 0.9 to 9.7 ± 3.7 for section thicknesses tested between 3 and 10 mm. The highest SNR of 9.7 was obtained by using a section thickness of 10 mm (Fig. 7).

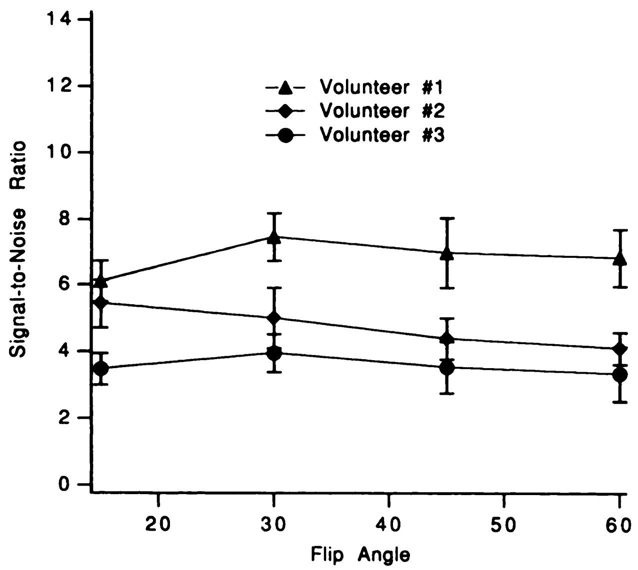

Fig. 4.—Graph shows signal-to-noise ratios of MR velocity images of portal venous system obtained at various flip angles in three volunteers. Highest mean signal-to-noise ratio of 5.5 ± 1.8 was obtained by using a flip angle of 30°.

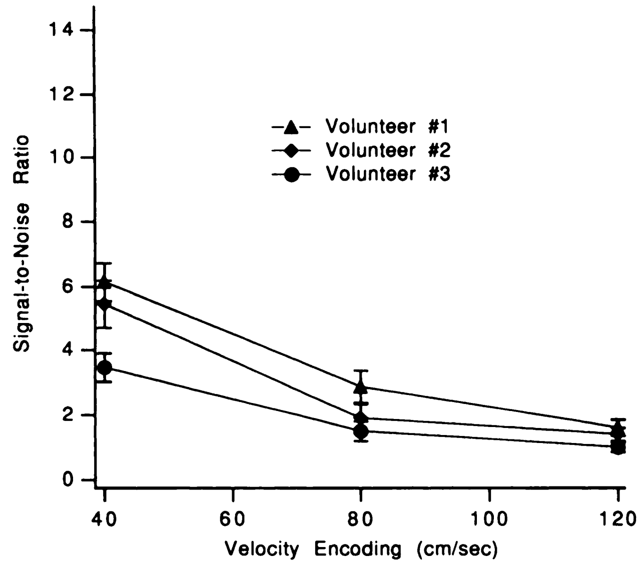

Fig. 5.—Graph shows signal-to-noise ratios of MR velocity images of portal venous system obtained at various velocity encodings in three volunteers. Highest mean signal-to-noise ratio of 5.0 ± 1.4 was obtained by using a velocity encoding of 40 cm/sec.

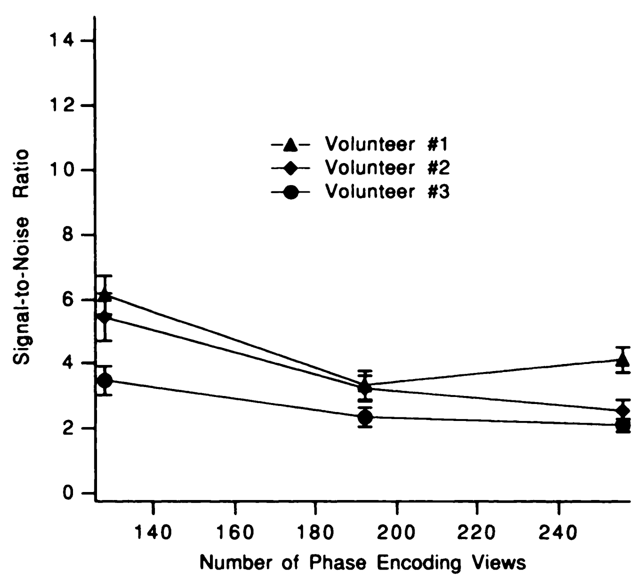

Fig. 6.—Graph shows signal-to-noise ratios of MR velocity images of portal venous system obtained at various numbers of phase-encoding views in three volunteers. Highest mean signal-to-noise ratio of 5.0 ± 1.4 was obtained by using 128 phase-encoding views.

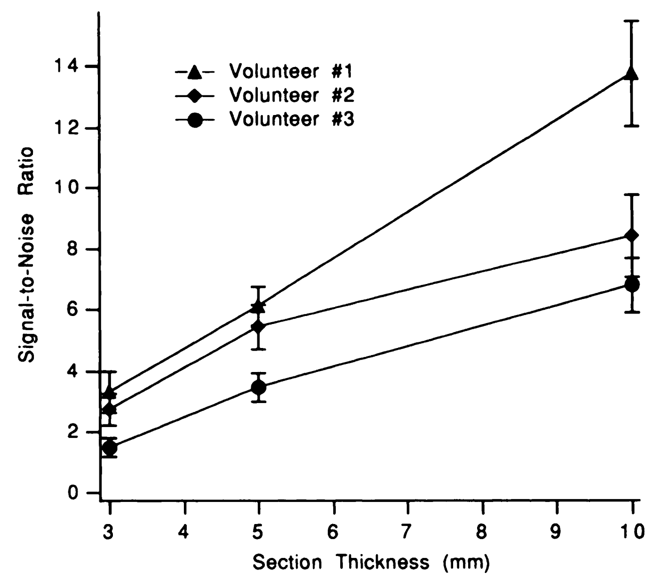

Fig. 7.—Graph shows signal-to-noise ratios of MR velocity images of portal venous system obtained at various section thicknesses in three volunteers. Highest mean signal-to-noise ratio of 9.7 ± 3.7 was obtained by using a 10-mm-thick section.

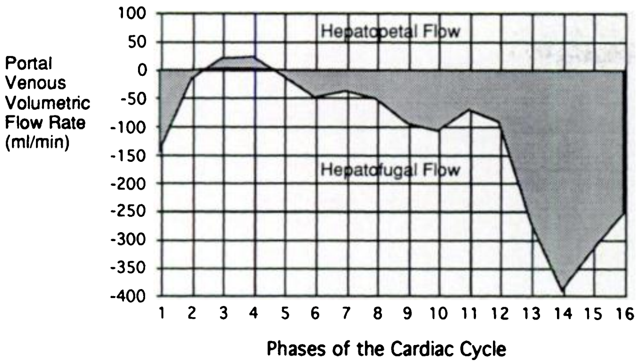

Fig. 8.—Portal venous volumetric flow rate in 16 phases of cardiac cycle in a patient with portal venous hypertension. Graph shows bidirectional flow in the portal vein, with net hepatofugal flow of 116.1 ml/min.

Cine Phase-Contrast MR Measurements of Portal Venous Flow

Calculations based on volumetric flow rates determined by using cine phase-contrast MR images of the portal venous system of five healthy volunteers indicated a mean volumetric flow rate in the portal venous system of 1202.6 ± 303.2 ml/min (14.5 ± 4.1 ml/min per kilogram). The average rate in the patients with portal venous hypertension with hepatopetal flow was 505.0 ± 66.1 ml/min (7.7 ± 1.6 ml/min per kilogram). In one patient, Doppler sonography showed bidirectional flow (both forward and reversed flow in the portal vein), which prevented estimation of the volumetric flow rate. Cine phase-contrast MR images also showed bidirectional flow in this patient (Fig. 8); net hepatofugal flow was 116.1 ml/min.

Comparison of Cine Phase-Contrast MR and Doppler Sonography Flow Measurements

Figure 9 shows the linear regression analysis of volumetric flow rate determined by using cine phase-contrast images vs flow rates determined by using Doppler sonography in the second in vivo series (MR rate = [1.25 × sonographic rate] − 240.7 ml/min; SEE = 151.1 ml/min). A strong linear correlation (r = .94; p = .0003) was found for volumetric flow rate in the portal venous system. The mean difference between measurements determined by using the two imaging methods was 111.2 ± 115.6 ml/min.

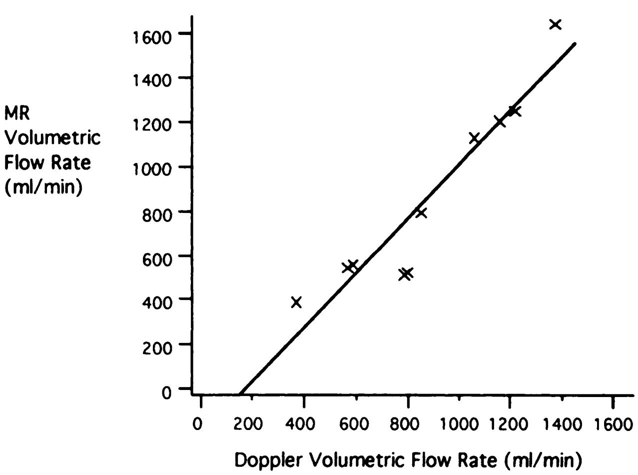

Fig. 9.—Graph shows linear regression of volumetric flow rate in portal venous system determined by using cine phase-contrast MR imaging vs rate based on Doppler sonography. Mean rate was 1202.6 ± 303.2 ml/min in healthy volunteers and 505.0 ± 303.2 ml/min in patients with portal venous hypertension.

Discussion

The results of this study indicate that cine phase-contrast MR techniques can be used to determine volumetric flow rates in the portal venous system in healthy volunteers and in patients with portal venous hypertension. Cine phase-contrast MR methods are advantageous because they are (1) easy to perform, (2) allow temporal resolution of flow determinations throughout the cardiac cycle, and (3) do not require breath-holding, which may introduce variable hemodynamic changes in the portal venous system associated with alterations in intrathoracic and intraabdominal pressures. Assessment of volumetric flow rates in this system has become increasingly important for evaluating the effects of pharmacologic therapy for portal venous hypertension and may contribute to our improved understanding of the complex hemodynamics of the portal venous system.

The data obtained by using cine phase-contrast MR imaging in the phantom model indicate that this method is quite accurate in this model system. We were able to accurately measure even relatively low volumetric flow rates of 400 ml/min, which are commonly seen in patients with portal venous hypertension [4–7]. The average volumetric flow rate determined by using cine phase-contrast MR images of the portal venous system of the volunteers in this study (14.5 ± 4.1 ml/min per kilogram) is consistent with previously reported rates determined by using Doppler sonography [4, 5].

The results of this study indicate that an effective protocol for obtaining velocity images for quantitative evaluation of flow in the portal venous system is a 30° flip angle, 40 cm/sec velocity encoding, 256 phase-encoding views, 28-cm^2 field of view, 5-mm section thickness, two excitations, and respiratory-ordered phase encoding. Flip angle and velocity encoding were chosen solely on the basis of their effect on velocity image SNR. Alternatively, the number of phase-encoding views, field of view, and section thickness were selected because of the results of current studies (Wolf RL et al., SMRM meeting, August 1992) that indicate a section thickness of 5 mm will provide acceptable errors in flow measurements obtained with planes of section not absolutely perpendicular to the direction of flow and that thicker sections give inaccurate measurements when vessels are sectioned obliquely. Spatial resolution should be selected to provide at least 10 pixels across the diameter of the vessel of interest. Velocity encoding and section thickness substantially influenced the SNR of the velocity images. However, when the variability of the SNR measurements was considered, flip angle and matrix size had only minimal effect.

In healthy volunteers and patients with portal venous hypertension, volumetric flow rates determined by using the MR method showed good correlation with those determined by using the Doppler method. Measurements obtained with

Doppler sonography cannot be considered a gold standard; they are only an estimate of volumetric flow rate because they are susceptible to systematic errors related to (1) measurement of the cross-sectional area of the portal vein, (2) determination of the mean blood-flow velocity, and (3) the angle of insonation of the Doppler beam with the portal vein [12]. In addition, the examination can be technically limited by the patient's habitus, intestinal meteorism, and lack of cooperation. The mean difference between flow rates determined by using cine phase-contrast MR and those determined by using Doppler sonography was 111.2 ± 115.6 ml/min. Because of the demonstrated accuracy of flow rates determined by means of the MR method in the model system, we think that the differences in this study between flow rates determined by using these two methods are attributable to the well-known limitations of the Doppler sonographic method. However, the possibility that errors could exist with the MR method cannot be excluded without a gold standard for determining volumetric flow rate in the portal venous system.

Use of cine phase-contrast MR imaging to determine volumetric flow rates throughout the cardiac cycle during normal respiration allows a more complete hemodynamic assessment than use of techniques that measure only average flow within a cardiac cycle. Even in the portal venous system, which is conventionally described as a steady-flow system, this temporal resolution can be helpful, as illustrated in the patient with bidirectional portal venous flow.

In conclusion, cine phase-contrast MR imaging is a readily applied noninvasive method for determining volumetric flow rate in the portal venous system of subjects with normal and abnormal hemodynamics. This method provides detailed determinations of flow throughout the entire cardiac cycle.

REFERENCES

1. Taranto D, Suozzo R, De-Sio I, et al. Effect of metoclopramide on transmural esophageal variceal pressure and portal blood flow in cirrhotic patients. *Digestion* **1990**;47:56–60
2. Gaiani S, Bolondi L, Fenymes D, Zironi G, Rigamonti A, Barbara L. Effect of propranolol on portosystemic collateral circulation in patients with cirrhosis. *Hepatology* **1991**;14:824–829
3. Lfubicic N, Bilic A. The effects of selective and non-selective adrenoceptor blockade on the portal blood flow in patients with liver cirrhosis. *Scand J Gastroenterol* **1991**;26:751–757
4. Zoli M, Marchesini G, Cordiani MR, et al. Echo-Doppler measurement of splanchnic blood flow in control and cirrhotic subjects. *JCU J Clin Ultrasound* **1986**;14:429–435
5. Moriyasu F, Ban N, Nishida O, et al. Clinical application of an ultrasonic duplex system in the quantitative measurement of portal blood flow. *JCU J Clin Ultrasound* **1986**;14:579–588
6. Moriyasu F, Nishida O, Ban N, Nakamura T, Miyake T, Uchino H. "Congestion Index" of the portal vein. *AJR* **1986**;146:735–739
7. Nelson RC, Lovett KE, Chezmar JL, et al. Comparison of pulsed Doppler sonography and angiography in patients with portal hypertension. *AJR* **1987**;149:77–81
8. Becker CD, Cooperberg PL. Sonography of the hepatic vascular system. *AJR* **1988**;150:999–1005
9. Edelman RR, Zhao B, Liu C, et al. MR angiography and dynamic flow evaluation of the portal venous system. *AJR* **1989**;153:755–760
10. Tamada T, Moriyasu F, Ono S, et al. Portal blood flow: measurement with MR imaging. *Radiology* **1989**;173:639–644
11. Spritzer CE, Pelc NJ, Lee JN, Evans AJ, Sostman HD, Riederer SJ. Rapid MR imaging of blood flow with a phase-sensitive, limited-flip-angle, gradient recalled pulse sequence: preliminary experience. *Radiology* **1990**; 176:255–262
12. Burns PN, Jaffe CC. Quantitative flow measurements with Doppler ultrasound: techniques, accuracy, and limitations. *Radiol Clin North Am* **1985**; 23:641–657
13. Mohiaddin RH, Wann SL, Underwood R, Firmin DN, Rees S, Longmore DB. Vena caval flow: assessment with cine MR velocity mapping. *Radiology* **1990**;177:537–541
14. Kondo C, Caputo GR, Semelka R, Foster E, Shimakawa A, Higgins CB. Right and left ventricular stroke volume measurements with velocity-encoded cine MR imaging: in vitro and in vivo validation. *AJR* **1991**; 157:9–16
15. Van Rossum AC, Visser FC, Hofman MBM, Galjee MA, Westerhof N, Valk J. Global left ventricular perfusion: noninvasive measurement with cine MR imaging and phase velocity mapping of coronary venous outflow. *Radiology* **1992**;182:685–691
16. Hahn EL. Detection of sea-water motion by nuclear precession. *J Geophys Res* **1960**;65:776–777
17. Axel L. Blood flow effects in magnetic resonance imaging. *AJR* **1984**;143: 1157–1166
18. Pelc NJ, Herfkens RJ, Shimakawa A, Enzmann DR. Phase contrast cine magnetic resonance imaging. *Magn Reson Q* **1991**;7:229–254
19. Moran PR. A flow zeugmatographic interface for NMR imaging in humans. *Magn Reson Imaging* **1982**;1:197–203
20. Nayler GL, Firmin DN, Longmore DB. Blood flow imaging by cine magnetic resonance. *J Comput Assist Tomogr* **1986**;10:715–722
21. Holsinger-Bampton AE, Riederer SJ, Campeau NG, Ehman RL, Johnson CD. T1-weighted snapshot gradient-echo MR imaging of the abdomen. *Radiology* **1991**;181:25–32