J Clin Ultrasound 14:429–435, July/August 1986

Echo-Doppler Measurement of Splanchnic Blood Flow in Control and Cirrhotic Subjects

Marco Zoli, MD,* Giulio Marchesini, MD,* Maria Rita Cordiani, MD,* Paolo Pisi, MD,* Alessandra Brunori, MD,* Antonio Trono, EE,† and Emilio Pisi, MD

Abstract: Blood flow in the splanchnic veins was studied in cirrhotics and matched controls by means of a system that combines a mechanical sector scanner with a pulsed Doppler. The measurements were validated in an in vitro model. Echo-doppler studies could be carried out reproducibly in only approximately two-thirds of cases because of poor echo transmission or incomplete cooperation. Portal blood velocity was significantly reduced in cirrhotics (10.5 ± 0.6 cm/s versus 16.0 ± 0.5 in controls; $p < 0.001$), but portal blood flow was normal because of enlarged portal caliber. A complete hemodynamic evaluation of the splenic and superior mesenteric veins was possible in only a few subjects. In selected patients the technique may prove relevant in the study of hemodynamic effects of drugs and surgery on portal blood flow. **Indexing Words:** Echo-Doppler · Liver cirrhosis · Portal hypertension · Splanchnic vein hemodynamics

Real-time ultrasonography (US) is increasingly being used in the evaluation of abdominal organs and vessels. A few recent studies stressed the role of US in the detection of enlarged splanchnic veins as signs of portal hypertension.[1,2] However, no data on splanchnic blood flow can be obtained from a conventional US investigation.

Recent technological developments in pulsed Doppler equipment made it possible to obtain a noninvasive measurement of blood velocity in major vessels.[3,4] When combined with real-time US, which makes the measurement of vessel lumen dimensions possible, blood flow can be calculated. This technique has been used successfully for the evaluation of renal blood flow,[5] but very little data are so far available on the portal venous system in normal populations and in patients with liver disease.[6–8]

The aim of this study was to explore the feasibility of making echo-Doppler measurements of blood flow of the portal trunk. In vivo results were validated by an in vitro study. Problems arising during Doppler measurement of splanchnic vein flow rates were carefully checked. The clinical relevance of data obtained in a large series of patients with liver disease is extensively discussed.

MATERIALS AND METHODS

Eighty-two patients, consecutively admitted to our institution, underwent echo-Doppler examination. These patients suffered from liver cirrhosis of different etiologies, which was documented by liver biopsy, in most cases taken under laparoscopic control. Patients with ascites were not included in the study. For technical reasons, an accurate echo-Doppler flowmetry of the portal vein was obtained in only 50 cirrhotic patients. The leading cause of failure was poor echo transmission (25 cases), partly a result of meteorism, and poor cooperation of the patients in maintaining apnea (seven cases). Pertinent laboratory data in the 50 cirrhotics were as follows: albumin, 3.5 ± 0.1 (SE) g/dl; γ-globulin, 1.9 ± 0.1 g/dl; aspartate transaminase, 55 ± 7 U/liter; prothrombin activity, 79 ± 2%; cholesterol, 161 ± 6 mg/dl; alkaline phosphatase, 184 ± 17 U/liters; total bilirubin 1.3 ± 0.1 mg/dl. All patients underwent an endoscopic examination of the upper gastrointestinal tract; esophageal varices were graded as suggested by Beppu et al.[9] The age of these patients ranged from 22 years to 77 years (median 58 years),

From the *Istituto di Patologia Medica I, University of Bologna, Bologna, and †Sonotron, Milano, Italy. For reprints contact Marco Zoli, MD, Istituto di Patologia Medica I, Policlinico S. Orsola, Via Massarenti 9, 40138-Bologna, Italy.

0091-2751/86/060429-07 $04.00

and their body surface from 1.25 m^2 to 2.12 m^2 (median 1.69 m^2).

Fifty subjects without any clinical or laboratory evidence of liver failure served as controls. They were matched with the cirrhotics with respect to sex, age, and body surface. They were part of a group of 75 control subjects, but in 25 of this larger group good Doppler signals could not be obtained.

Splanchnic venous blood flow was evaluated using a system that combined a mechanical sector scanner (3.5-MHz transducer) and a pulsed Doppler (Aloka SSD-280, UGR 23). The Doppler beam axis can be electronically positioned at any location in the sector scan, and it is possible to vary the depth of the sampling point (from 1 to 20 cm) and the sampling width (from 2 to 25 mm). The Doppler signals are displayed on a TV monitor screen in real time; these signals can also be heard through a loudspeaker.

After the sampling marker had been set in the middle of the lumen along the beam axis, a second marker was positioned along the direction of blood flow. Care was taken to maintain the angle θ (the angle formed by the ultrasonic beam direction and the blood flow direction) below 60°, which is considered the upper limit to obtain an optimal Doppler flow measurement. The system automatically measures the angle θ and every 5 s displays the mean flow velocity calculated according to Gill's formula.[10]

Every measurement was repeatedly performed until good and reproducible spectrum patterns and blood flow sounds were obtained. During the Doppler recording, subjects stopped breathing in expiration for at least 30 s. This allowed four or five consecutive measurements of blood velocity. In all patients, the measurements were carried out during expiration, which can easily be standardized and permits a better visualization of the portal vein for Doppler purposes since the angle θ is reduced to a minimum. Under this experimental condition, the portal flow appears to be constant, whereas it drops temporarily during suspended deep inspiration. The highest and most reproducible value recorded during the investigation, which lasted about 10 min on each vessel, was considered to be the subject's actual blood velocity. Velocity estimates may sometimes be lower than the true velocity because of incorrect location of the sampling volume. Therefore, the highest mean velocity recorded during the examination is the closest to the actual velocity. The blood flow rate was obtained by multiplying the blood velocity by the cross-sectional area of the vessel, calculated on the basis of the inner diameter assuming circular geometry.

The portal vein was scanned longitudinally in the supine position during expiration. The sampling marker was placed in the center of the lumen, approximately midway between the confluence of the splenic and superior mesenteric veins and the bifurcation of the left and right portal branches. The superior mesenteric vein was examined 2 cm before the confluence with the splenic vein. The splenic vein was examined in front of the superior mesenteric artery, in its ascending tract (which is near the tail of the pancreas), and at the hilus of the spleen. The umbilical vein, the left gastric vein, and the short gastric veins were also evaluated with echo Doppler when they were enlarged and clearly visible.

All measurements were performed by two independent, equally skilled investigators on fasting patients during two consecutive mornings. The fasting state was chosen to permit a better visualization of the splanchnic vessels and to avoid changes in the blood flow caused by the absorption of nutrients.[11] Interobserver variations in portal blood velocity measurements were always lower than 10%. The average estimated portal blood flow rate varied within ±10%.

Data in the text and in the tables are the mean ± SE of the mean values of individual patients calculated by the independent operators during the two days of investigations.

Statistical analyses were carried out by Student t test for paired and unpaired data.

In Vitro Validation of Echo-Doppler Measurements

A peristaltic pump was used to generate a pulsed flow in a silicon tube filled with human blood. Blood velocity was calculated by dividing the blood flow rate by the cross-sectional area of the tube. The tube was put in a washing tray filled with water and fixed about 6–7 cm below the surface. The probe was placed on the surface, and blood velocity was measured over a wide range of values (from 7 cm/s to 25 cm/s) (Fig. 1). Blood flow was repeatedly measured with an angle θ of about 40–60° both forward and backward from the probe.

RESULTS

In Vitro Validation

In the in vitro model the blood velocity estimated by echo Doppler correlated very well with the actual values (r = 0.995; Fig. 2). The blood velocity generated by the peristaltic pump was in the same range as that seen in the splanchnic veins.

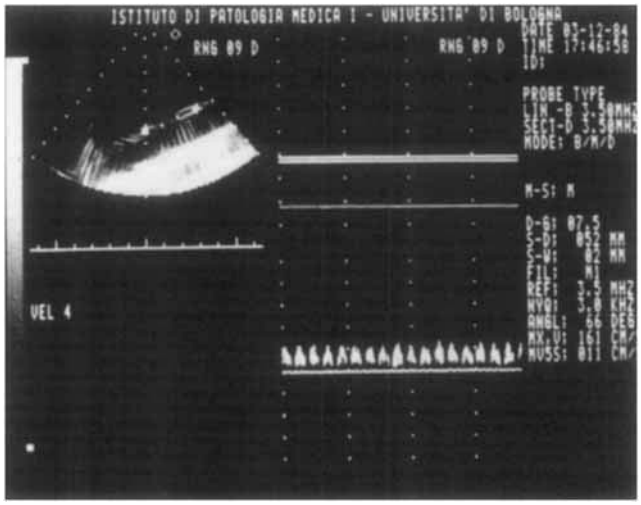

FIGURE 1. Echo-Doppler measurement of blood velocity in the silicon tube filled with human blood during the in vitro experiment of validation.

Splanchnic Blood Flow in Humans

An accurate and reproducible echo-Doppler investigation of the portal vein was possible in 67% of control subjects (50/75). The superior mesenteric vein hemodynamics was estimated in eight of these 50 subjects (16%), and the hemodynamics of the splenic vein in its ascending tract was measurable in 38% (19/50). In the same subjects, the hemodynamics of the splenic vein at the hilus of the spleen and in front of the superior mesenteric artery was never measurable.

In patients with cirrhosis, a reproducible evaluation of portal blood flow was obtained in 61% of cases. The flowmetry of the superior mesenteric vein, splenic vein in the ascending portion, and splenic vein at the hilus was measurable in 15/50 (30%), 22/50 (44%), and 8/50 (16%) patients, respectively. A reproducible echo-Doppler measurement of the splenic vein in front of the superior mesenteric artery was never obtained.

Splanchnic vein hemodynamics are reported in Table 1.

Portal blood flow was always directed towards the liver. In a single patient, not included in the analysis, the portal vein was occluded by a thrombus, and splanchnic blood was directed towards the liver in the splenic vein and backwards in the superior mesenteric vein.

Portal blood velocity was significantly lower in

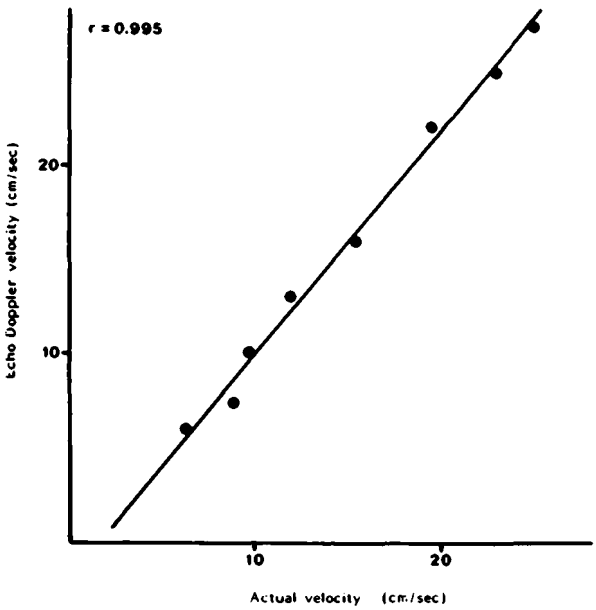

FIGURE 2. *Relationship of actual blood velocity to echo-Doppler-measured blood velocity in in vitro study.*

TABLE 1
Splanchnic Vein Hemodynamics in Cirrhotic Patients and Matched Control Subjects*

Vein	Controls	Cirrhotics	*p*
Portal			
N	50	50	
ϕ	9.6 ± 0.2	12.5 ± 0.3	<0.001
BV	16.0 ± 0.5	10.5 ± 0.6	<0.001
BF	694 ± 23	736 ± 46	NS
Superior mesenteric			
N	8	13	
ϕ	5.3 ± 0.4	7.9 ± 0.7	<0.02
BV	14.8 ± 1.5	9.7 ± 1.1	<0.02
BF	194 ± 25	343 ± 90	NS
Splenic			
N	19	22	
ϕ	6.0 ± 0.2	7.6 ± 0.4	<0.005
BV	13.8 ± 0.6	13.2 ± 0.7	NS
BF	231 ± 19	372 ± 43	<0.01

*ϕ, inner diameter in mm; BV, blood velocity in cm/s; BF, blood flow rate in ml/min. All values are given ± SE. NS, no statistical significance.

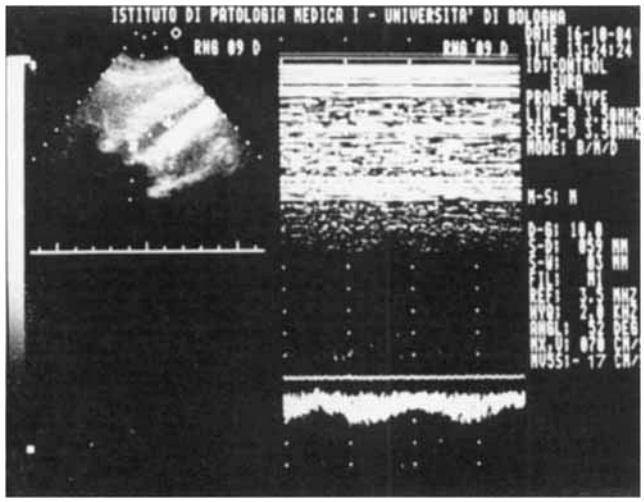

FIGURE 3. Echo-Doppler measurement of blood velocity in the portal vein in a control subject. The echo-Doppler spectrum (right) appears to be wavy continuous.

cirrhotics than in controls. Blood velocity in the control population varied from 10 to 23 cm/s. In 23 of the 50 cirrhotics, blood velocity was <10 cm/s, the lowest value being 3 cm/s. The highest value seen in the cirrhotics was 17 cm/s. The diameter of portal vein was considerably larger in the cirrhotics, so that portal blood flow rates were comparable in the two groups. The portal blood flow rates corrected for body surface were 423 ± 14 $ml \cdot min^{-1} \cdot m^{-2}$ in controls and 440 ± 27 in cirrhotics. It is worth noting that the echo-Doppler spectrum in control subjects showed waves possibly in relation to cardiac activity in 70% of cases (Fig. 3). In patients with cirrhosis, the spectrum was continuous in 72% of cases (Fig. 4) and continuous with waves in only 28%.

It was possible to determine flow direction in the superior mesenteric vein and in the ascending portion of the splenic vein in all subjects, but blood flow rates were reproducibly measured in very few patients. Blood velocity in these vessels was comparable in controls and cirrhotics, whereas blood flow rates appeared to be increased in cirrhotics. In cirrhotics, the sum of blood flow rates in the superior mesenteric and splenic veins grossly approximated the estimated blood flow rate in the portal vein. This was not seen in controls, where the sum of blood flow rates in the superior mesenteric vein and the splenic vein was considerably lower than the estimated portal blood flow rates. The echo-Doppler spectrum of the splenic vein in both groups was wavy continuous (Fig. 5).

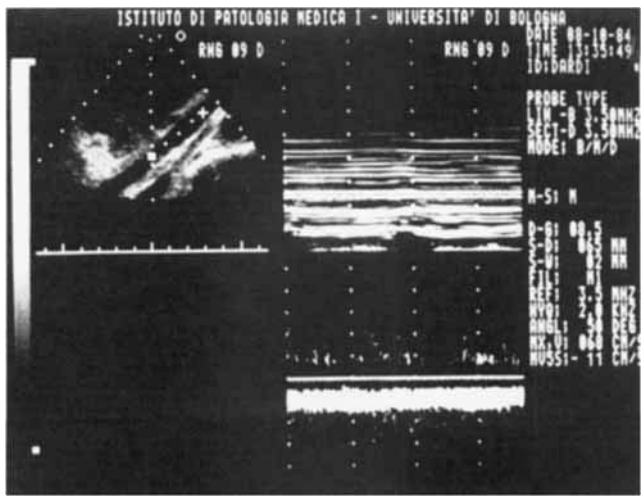

FIGURE 4. Echo-Doppler measurement of blood velocity in the portal vein in a cirrhotic patient, where a continuous echo-Doppler spectrum (right) is clearly visible.

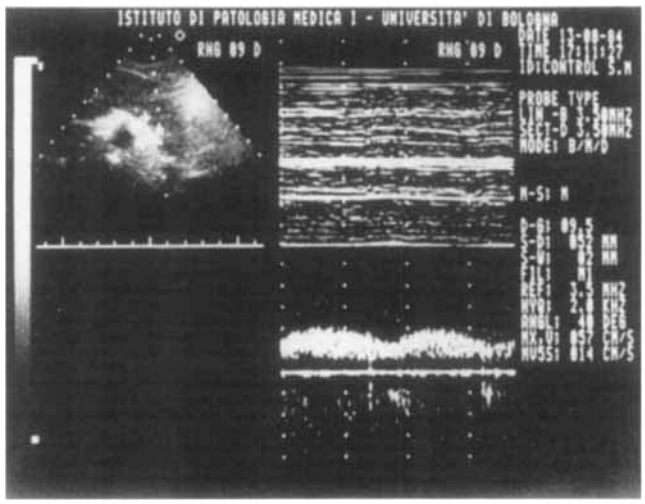

FIGURE 5. Echo-Doppler measurement of blood velocity in the splenic vein in its ascending tract. The echo-Doppler spectrum (right) appears to be wavy continuous.

In three of the 50 patients, the umbilical vein was patent, and the blood flow was directed backwards from the liver. The diameters were 6 mm, 9 mm, and 15 mm, and blood velocities were 13 cm/s, 11 cm/s and 11 cm/s, respectively. The blood flow was inverted through an enlarged left gastric vein in three additional patients and through the short gastric veins in two more.

Portal vein hemodynamics in relation to the size of esophageal varices are reported in Table 2. Portal vein diameters progressively increased with the development of esophageal varices, whereas blood velocity was progressively reduced so that no significant differences in portal blood flow could be detected. In six patients with large varices, the spleen size was markedly increased, and the splenic vein was considerably enlarged (11.5 ± 0.7 mm). The blood velocity in the splenic vein was 12.1 ± 0.5 cm/s. The blood flow rate (766 ± 97 ml/min) was significantly correlated with the area of the maximal section of the spleen ($p < 0.01$).

TABLE 2
Portal Vein Hemodynamics in 50 Cirrhotic Patients Divided in Relation to the Size of Esophageal Varices*

	Esophageal Varices		
	None	Small	Large
N	20	11	19
ϕ	11.5 ± 0.3	12.3 ± 0.6	13.8 ± 0.4†
BV	11.6 ± 0.9	9.4 ± 0.9	8.9 ± 1.1‡
BF	722 ± 60	655 ± 58	805 ± 103

*ϕ, inner caliber in mm; BV, blood velocity in cm/s; BF, blood flow rate in ml/min; all values are given ± SE.
†$p < 0.005$ versus corresponding value for patients without varices.
‡$p < 0.05$ versus corresponding value for patients without varices.

DISCUSSION

The measurement of portal blood flow rate is usually based on invasive or difficult-to-repeat techniques (electromagnetic flowmetry, cineangiography, and radioisotopes).[12–14] These techniques are not routinely employed in clinical practice. Their use is usually confined to experimental surgery or to sophisticated clinical investigations, since they cannot be repeated without risk and discomfort for the patients. The clearance of several substrates massively taken up by the liver (i.e., indocyanine green)[15,16] makes it possible to calculate the functional hepatic blood flow, which has no relation to portal blood flow but also depends on intrahepatic shunting and hepatic artery flow. No direct, noninvasive measurement of portal blood flow rates has been available previously.

Recent developments in US pulsed Doppler flowmetry have proved successful in the measurement of flow velocity in various major blood vessels. Our data prove that pulsed echo Doppler can be used in the study of the splanchnic veins, particularly the portal vein. As for the echo-Doppler measurement of renal hemodynamics,[5] the velocities measured in humans in portal blood vessels are in a range where the US systems appear to give reliable results, as validated by our in vitro studies.

Blood flow rate measurement with echo-Doppler equipment may be biased by two factors: measurements of the angle θ and the blood vessel cross-sectional area. For the calculation of the angle θ, the flow direction is assumed to be streamlined and parallel to the vessel walls. Indirect evidence for a streamlined flow may be derived from the

shape of the spectrum, but no direct evidence has ever been obtained. As for the cross-sectional area, the vessel lumen is assumed to be round, and venous blood vessels may be somewhat compressed by adjacent structures. Moreover the diameters of vessels can be accurately measured in most instances, but in small vessels minor errors may lead to relevant errors in the estimated blood flow rates, which depend on the square of the half-diameter. Some systems, such as the one we used in the present investigation, have additional devices that allow direct measurement of an area. However, it is usually difficult to obtain evidence that the measured area really represents the exact cross-sectional area of the vessel. Moreover, to obtain the cross-sectional area, the operator must obtain a transverse scan of the vessel different from the longitudinal one used to measure blood velocity. This can lead to the area and the blood velocity being measured at different sites along the vessel. Therefore, we preferred to rely on the diameter of the vessel and the assumption of circular geometry for the vessel lumen.

All of these errors may be reduced to a minimum through repeated investigations of the same vessels by two independent, equally skilled investigators. We found good interobserver agreement in blood velocity measurement, suggesting that the error caused by the measurement of angle θ is probably very limited. By contrast, a correct estimation of splanchnic vein cross-sectional area in small vessels is difficult with techniques having a discrimination limit of 1 mm, possibly leading to substantial errors in blood flow rate estimates. This consideration may explain the difference between the estimated portal blood flow rate and the sum of the flow rate of its two major tributaries in controls.

An additional problem for the clinical use of this technique is the limited number of patients who can be correctly and reproducibly scanned. Although in most subjects (98%) a conventional real-time US investigation of splanchnic vessels can be carried out, portal flowmetry was obtained in only 67% of controls and 61% of cirrhotics. The flowmetry in the tributaries of the portal vein is far more difficult and can be obtained in only a small number of patients. The limiting factors for echo Doppler are at least two. First, the vessel must be perfectly transonic so that the Doppler signals are received under optimal conditions. The technique is hindered by meteorism and by adipose tissue. Secondly, the sampling point must be kept in the middle of the lumen for at least 20–30 s. Active cooperation of the patient must be obtained, as he or she must keep absolutely still and stop breathing. This factor is a cause of failure in about 9% of cases. Moreover, the vessel lumen must be at least 4–5 mm in diameter, since the sampling volume cannot be reduced to less than 2 mm, and the vessel cannot be studied near arterial vessels (i.e., aorta, superior mesenteric artery), which move the veins with each cardiac beat.

In our clinical study we proved that the portal blood flow is directed towards the liver in all the cases we screened except in the patients with a portal vein thrombosis. These data are in agreement with previous studies carried out by means of invasive techniques.[13,17] Portal blood velocity appears to be lower in cirrhotics, but portal flow rate is in the normal range because of increased vessel diameter.

Ohnishi et al.,[7] in a small series of patients with cirrhosis, reported a portal venous velocity higher than the one we measured in our large series. It must be pointed out that the equipment we used belongs to a more recent generation of instruments, and our in vitro study indicates the reliability of the data we obtained. It should also be pointed out that our measurements were similar to those obtained by Ohnishi[7] using cineangiography, and these authors were very well aware that their echo-Doppler instrument possibly overestimated the portal blood velocity.

The presence of a normal blood flow, even in patients with an US-documented spontaneous portal systemic shunt, suggests an extensive intrahepatic shunt, which is well established histologically.[18] We did not find any differences in portal blood flow rates between patients with different degrees of esophageal varices, an indirect index of the extent of portal–collateral circulation. Although a general agreement exists on portal flow rates measured by different techniques in the normal population, very large variations are reported for cirrhotic patients.[7,8] This spread is possibly representative of the large differences among cirrhotic patients because of the different hemodynamic changes that take place.

In spite of all the previously mentioned drawbacks, the clinical use of this technique may prove relevant in several fields. The patency of a surgical portal–systemic shunt may be more reliably proved by echo Doppler than by conventional US scanning. Portal flow rate measurements may significantly add to the evaluation of the hemodynamic effects of drugs known to affect portal blood flow, such as β-blocking agents.[19] The simultaneous assessment of portal blood velocity and the spectrum of Doppler signal together with the mea-

surement of portal vein diameters might increase the sensitivity and specificity of US in the evaluation of patients with chronic liver diseases.

ACKNOWLEDGMENT

We are grateful to Miss Chiara Viola for helpful assistance in preparing the manuscript.

REFERENCES

1. Kane RA, Katz SG: The spectrum of sonographic findings in portal hypertension: A subject review and new observations. *Radiology* 142:453, 1982.
2. Bolondi L, Gandolfi L, Arienti V, et al: Ultrasonography in the diagnosis of portal hypertension: Diminished response of portal vessels to respiration. *Radiology* 142:167, 1982.
3. Phillips DJ, Powers JE, Eyer MK, et al: Detection of peripheral vascular disease using the dupplex scanner III. *Ultrasound Med Biol* 6:205, 1980.
4. Blackshear WM, Phillips DJ, Chikos PM, et al: Carotid artery velocity patterns in normal and stenotic vessels. *Stroke* 11:67, 1979.
5. Avasthi PS, Greene ER, Voyles WF, et al: A comparison of echo-Doppler and electromagnetic renal blood flow measurements. *J Ultrasound Med* 3:213, 1984.
6. Taylor KJW, Burns PN, Woodcock JP, et al: Blood flow in deep abdominal and pelvic vessels: Ultrasonic pulsed-Doppler analysis. *Radiology* 154:487, 1985.
7. Ohnishi K, Saito M, Koen H, et al: Pulsed Doppler flow as a criterion of portal venous velocity: Comparison with cineangiographic measurements. *Radiology* 154:495, 1985.
8. Bru C, Bosch J, Mastai R, et al: Non invasive measurement of portal venous blood flow in man by combined Doppler–real time ultrasonography. Effect of propranolol. *Hepatology* 3:855, 1983.
9. Beppu K, Inokuchi K, Koyanagi N, et al: Prediction of variceal hemorrhage by esophageal endoscopy. *Gastrointest Endosc* 27:213, 1981.
10. Gill RW: Pulsed Doppler with B-mode imaging for quantitative blood flow measurement. *Ultrasound Med Biol* 5:223, 1979.
11. Bellamy EA, Bossi MC, Cosgrove DO: Ultrasound demonstration of changes in the normal portal venous system following a meal. *Br J Radiol* 57:147, 1984.
12. Price JB, Britton RC, Peterson LM, et al: The validity of chronic hepatic blood flow measurements obtained by electromagnetic flow meter. *J Surg Res* 5:313, 1965.
13. Viamonte M, Warren WD, Fomon JJ, et al: Angiographic investigations in portal hypertension. *Surg Gynecol Obstet* 130:37, 1970.
14. Kashiwagi T, Kimura K, Suematsu T, et al: Dynamic studies on portal hemodynamics by scintiphotosplenoportography; flow patterns of portal circulation. *Gut* 21:57, 1980.
15. Caesar J, Shaldon S, Chiandussi L, et al: The use of indocyanine green in the measurement of hepatic blood flow as a test of hepatic function. *Clin Sci* 21:43, 1961.
16. Groszmann RJ: The measurement of liver blood flow using clearance techniques. *Hepatology* 3:1039, 1983.
17. Cacciari C, Pisi E, Cavalli GC: *Splenoportografia e Splenomanometria*. Rome, SEU Editori, 1957.
18. Sherlock S: *Diseases of the Liver and Biliary System* (ed 6). Oxford, Blackwell Scientific Publications, 1981.
19. Zoli M, Marchesini G, Marzocchi A, et al: Portal pressure changes induced by medical treatment: US detection. *Radiology* 155:763, 1985.